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The use of mulch in cultivating the forage cactus optimizes yield in less time and increases the water use efficiency of the crop

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Abstract

Measurements of crop evapotranspiration (ET_C) and crop coefficients (k_C) in cactus have not yet been adjusted for the phenological stage using conservation practices (i.e. mulching). In this study, soil water dynamics, ET_C and k_C were measured in the forage cactus under cultivation systems with (WM) and without (NM) the use of mulch in the semi-arid region of Brazil. *Opuntia stricta* was subjected to irrigation depths based on a percentage of the reference evapotranspiration (ET_0) (rainfed, 25, 50, 75 and 100%) and to two systems of cultivation: WM and NM. Over time, the phenophases ($^{\varphi}$Ph) were established; the soil water balance components were calculated and the crop yield was evaluated at harvest. The use of 8.2 Mg ha^{-1} mulch led to almost no reduced water consumption by the crop when compared to the NM system; however, the mulch did maximize yield, at 839°C day, when irrigated with 50% ET_0. The k_C value was higher under the WM system, with the differences decreasing throughout the cycle ($^{\varphi}$PhI, 36%; $^{\varphi}$PhII, 27%; $^{\varphi}$PhIII, 23%; $^{\varphi}$PhIV-HT, 17%; and $^{\varphi}$PhIV-RF, 14%). Therefore, the use of mulch in cultivating the cactus optimized forage production in less time and significantly increased the water use efficiency of the crop.

KEYWORDS

cladode emission, harvest, *Opuntia stricta*, phenophase, semi-arid

Résumé

Les mesures de l'évapotranspiration des cultures (ET_C) et les coefficients de culture (k_C) chez le cactus n'ont pas encore été ajustées pour le stade

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phénologique en utilisant des pratiques de conservation (le paillage). Dans cette étude, la dynamique de l'eau du sol, l' ET_C et les k_C ont été mesurés dans le cactus fourrage dans le cadre des systèmes agricoles avec (WM) et sans (NM) l'utilisation de paillis dans la région semi-aride du Brésil. L'*Opuntia stricta* a été soumis à des profondeurs d'irrigation basées sur un pourcentage de l'évapotranspiration de référence (ET_0) (pluvial, 25, 50, 75 et 100%) et à deux systèmes agricoles: WM et NM. Au fil du temps, les phénophases ($^{\varphi}$Ph) ont été établies; les composantes du bilan hydrique du sol ont été calculées; et le rendement agricole a été évalué au moment de la récolte. L'utilisation d'un paillis de 8,2 Mg ha^{-1} n'a pratiquement pas réduit la consommation d'eau de la culture par rapport au système NM; cependant, le paillis a maximisé le rendement, à 839°C jour, lorsqu'il a été irrigué avec 50% ET_0. La valeur du k_C était plus élevée dans le système WM, les différences diminuant tout au long du cycle ($^{\varphi}$PhI, 36%; $^{\varphi}$PhII, 27%; $^{\varphi}$PhIII, 23%; $^{\varphi}$PhIV-HT, 17%; et $^{\varphi}$PhIV-RF, 14%). Par conséquent, l'utilisation de paillis dans la culture du cactus a optimisé la production de fourrage en moins de temps et a augmenté de manière significative l'efficacité de l'utilisation de l'eau agricole.

MOTS CLÉS

émissions de cladode, récolte, *Opuntia stricta*, phénophase, semi-aride

1 | INTRODUCTION

Arid and semi-arid regions exhibit strong rainfall seasonality in addition to great atmospheric demand, which results in a negative water balance throughout the year. In addition, climate change, with alterations in air temperature and the intensification of extreme event patterns (i.e. drought), has a significant impact on the agricultural activities and socio-economic indices of these regions (Irisarri et al., 2019).

The use of tolerant crops and techniques of agronomic conservation in stressful environments can maximize forage production (Amorim et al., 2017; Moraes et al., 2019). In the semi-arid region of Brazil, cacti are an important source of food for herds during periods of prolonged drought. Of these, the forage cactus (*Opuntia* sp. and *Nopalea* sp.) is the most used, as it exhibits good phytomass production compared to the native vegetation (i.e. *Caatinga*) (Silva et al., 2015b; Amorim et al., 2017).

Despite the adaptability of the cactus to semi-arid environments, the use of management practices (i.e. fertilization, mulch, cropping treatments and irrigation) (Amorim et al., 2017; Gong et al., 2017) in line with its growth dynamics can boost growth and yield and therefore anticipate harvest (Silva et al., 2014a; Amorim et al., 2017).

Mulching, for example, affords protection, maintenance of the soil moisture and lower thermal amplitude, in addition to providing nutrients and improving physical and biological attributes (Namaghi et al., 2018), while irrigation offers stability of the soil moisture and guarantees adequate crop growth. Some studies have been carried out in the Brazilian semi-arid region on irrigation in the forage cactus (Queiroz et al., 2016; Barbosa et al., 2017a,b), but there are gaps regarding the use of mulch (Carvalho et al., 2017). Furthermore, few studies have reported on the water requirement of the cactus (Queiroz et al., 2016; Lima et al., 2018), which has to be measured under optimal growth conditions (Morais et al., 2017; Lima et al., 2018).

Measurements of crop evapotranspiration (ET_C) and crop coefficients (k_C) in the cactus have not yet been adjusted for phenological stage, whether under traditional systems or using practices of conservation (i.e. mulching). Divincula et al. (2019), Lima et al. (2018) and Queiroz et al. (2016) cite mean values of k_C equal to 0.72, 0.50 and 0.52, respectively, for the cycle, regardless of phenophase. Therefore, there is a gap in the k_C values throughout the forage cactus cycle and whether the use of mulch promotes significant effects on the k_C values of this cactus. Such data are valuable as an aid to action in areas of irrigated forage cactus in the semi-arid region of Brazil, offering improvements for managing the percentage and time applied in irrigation; this can increase water use efficiency and mitigate loss through excess (Peddinti & Kambhammettu, 2019). In this study, the

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aim was to measure the soil water dynamics, evapotranspiration and crop coefficient in cultivating the forage cactus, with and without mulching, aiming at improving irrigation management, yield and water use efficiency of the crop in cropping systems of arid and semi-arid environments.

2 | MATERIALS AND METHODS

2.1 | Study area and setting up, designing and conducting the experiment

The experiment was conducted in the district of Serra Talhada in the state of Pernambuco, Brazil (7°59′ S, 38°15′ W, at 431 m above mean sea level) (Figures 1(a) and (b)), where the climate is of type BShw′ (semi-arid climate, dry, very hot, with the rainy season between summer and autumn). The soil in the area was classified as a Red–Yellow Argisol with the following physical characteristics: 1.53 g cm^{-3} (bulk density), 40.3% (total porosity), 684 g kg^{-1} (total sand), 253 g kg^{-1} (silt) and 63 g kg^{-1} (clay).

Before setting up the experiment, the soil was prepared by ploughing, harrowing and furrowing. The 'Orelha de Elefante Mexicana' clone [*O. stricta* (Haw.) Haw.] was planted at a spacing of 1.60 × 0.40 m, with a stand of 15 625 plants ha^{-1}. The area was planted on 22 January 2011, with cutting on 28 May 2012 (first cut—length of cycle: 16 months), 14 June 2013 (second cut—length of cycle: 13 months), 15 November 2014 (third cut—length of cycle: 17 months) and 6 November 2015 (fourth cut—length of cycle: 12 months). The present study was prepared using the data collected during the final cycle, i.e. the fourth production cycle of the forage cactus.

During the experimental period, the total rainfall was less than the accumulated reference evapotranspiration (ET_0) (Figure 2). The accumulated rainfall was slightly less than expected for the same period in the region, i.e. 85% of the historical average. The low rainfall (*R*) was associated with the strong hot-phase event of the El Niño-Southern Oscillation (ENSO) (Marengo et al., 2016). In addition, more prolonged rainfall events occurred between 6 June and 3 July 2015, which is uncommon in the region.

The adopted design was a split-plot design in a randomized complete block design (5 × 2) (Figures 1(c)–(f)), and the plots comprised the water regime: the irrigation depths (25, 50, 75 and 100% ET_0, ET_0 = reference evapotranspiration) and a rainfed regime (dependent only on rainfall), and the subplots comprised the two crop systems (with mulch—WM and without mulch—NM), with four replications, giving a total of 40 experimental units (each unit with 6.4 × 6.0 m = 38.4 m^2).

To apply the irrigation depths, a drip system was installed, with tapes 0.25 m from the plant (basal cladode) and emitters spaced 0.40 m apart, operating at a pressure of 100 kPa, a flow rate of 1.32 ± 0.12 L h^{-1} and a coefficient of distribution uniformity of 93%. The mulch used in the subplots consisted of *Urochloa mosambicensis* (Hack.) Dandy and *Sida cordifolia* L. obtained by manual weeding around the experimental area, 8.2 Mg ha^{-1} of this material being placed in each subplot and not replaced during the experimental period (Carvalho et al., 2017).

During the experimental period, two chemical fertilizations of NPK formulation 14-00-18 were given, with an application of 525 kg ha^{-1} and manual weeding.

2.2 | Environmental monitoring

Meteorological data were monitored over time to estimate ET_0 using the Penman–Monteith method parameterized as per FAO Bulletin 56 (Allen et al., 1998). The data were collected from an automatic station of the National Institute of Meteorology located 1.5 km from the area. Rainfall was recorded by an automatic rain gauge installed in the experimental area. Soil moisture (θ) was measured every 0.10 m by means of a capacitive probe (Diviner 2000®, Sentek Pty Ltd, Australia) (Figure 1(g)) between 17 January and 6 November 2015 (294 days). For this purpose, 40 polyvinyl chloride (PVC) access tubes were installed vertically in the soil to a depth of 0.70 m. The access tubes were 0.10 m from the basal cladode. Before use, the probe was calibrated following procedures described by Araújo Primo et al. (2015).

2.3 | Crop productivity on a fresh (FMY) and dry matter (DMY) basis

The FMY and DMY were obtained to identify the irrigation depth that maximized productivity in the forage cactus under cultivation systems with and without mulch. Twenty-two plants from the working area of each experimental plot were harvested to extrapolate yield on a fresh basis (FMY, in Mg ha^{-1}). Two cladodes per plot were dried in a forced-air circulation oven at 55°C to constant weight. The dry matter content (DMC, Mg Mg^{-1}) was obtained from the ratio between the dry and fresh matter of the cladodes. The product of FMY and DMC gave the yield on a dry basis (DMY, in Mg ha^{-1}) (Silva et al., 2014a,b, 2015b; Barbosa et al., 2017b).

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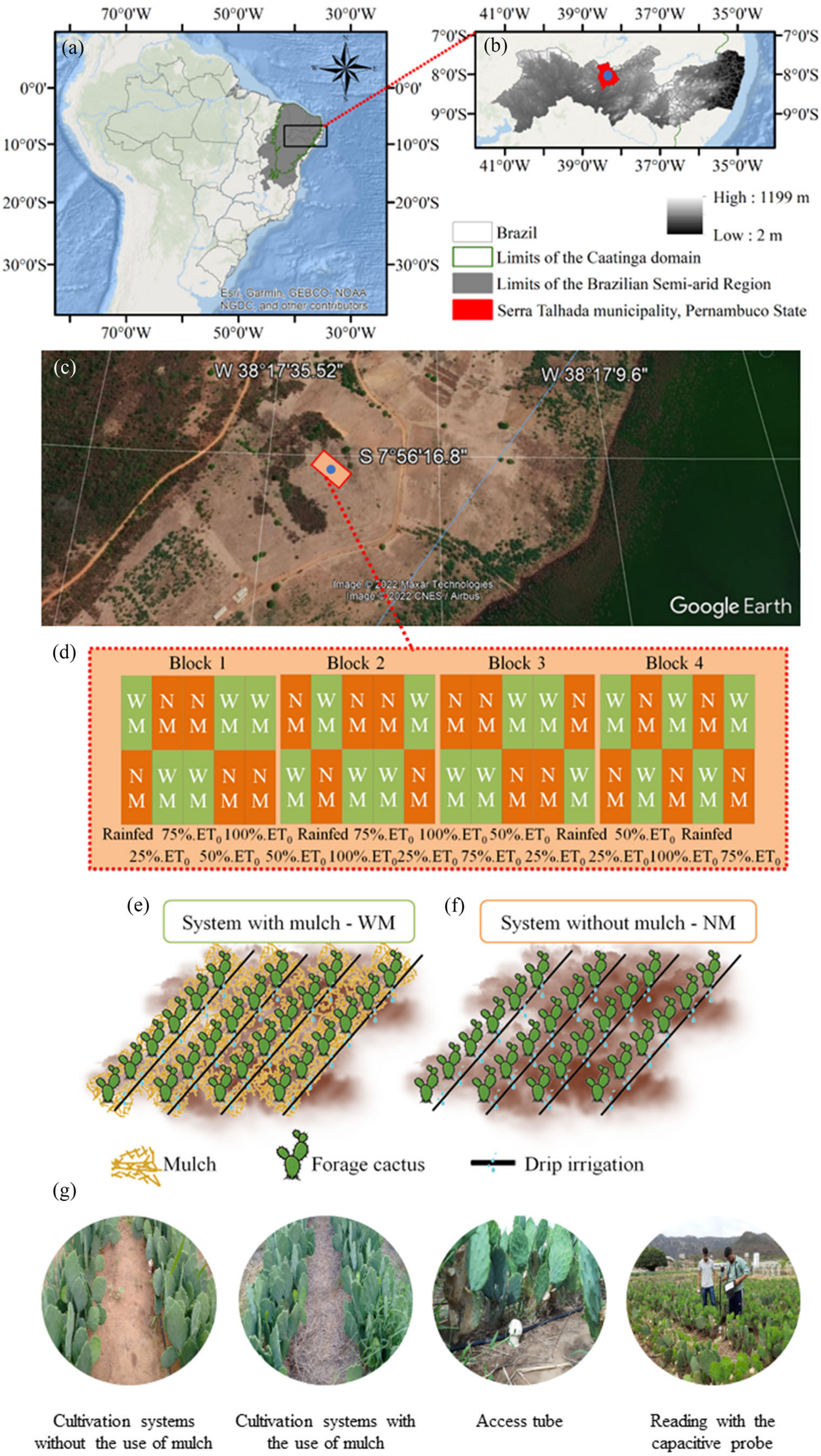

FIGURE 1 Location of the experimental field with forage cactus under two cultivation systems, one with (WM) and one without (NM) the use of mulch, in the district of Serra Talhada in the semi-arid region of the state of Pernambuco, Brazil

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2.4 | Soil water balance (SWB), evapotranspiration (ET_C) and crop coefficient (k_C)

The SWB was applied as the control volume of 0.60 m (Z), as described by Silva et al. (2015a), given by Equation (1):

$$ET_C = R + ID \pm SR \pm Q \pm \Delta H, \quad (1)$$

where ΔH is variation in soil water storage; R, rainfall; ID, irrigation depth; SR, runoff; Q, vertical soil water flow (deep drainage [DD] or capillary rise [CR]); and ET_C, crop evapotranspiration.

ΔH was determined from the difference between the final and initial values for soil water storage. R was integrated from the values recorded by the automatic rain gauge. ID consisted of the integration of the depths applied via irrigation. SR was estimated using the curve number method (CN), considering a CN of 75. Q was obtained using the Buckingham–Darcy equation, which considers the total water potential (Φt) above (0.50 m) and below (0.70 m) the base limit of the control volume Z and the soil hydraulic conductivity $K(\theta)$ at Z, to achieve DD and CR. Φt and $K(\theta)$ were calculated from the data for θ and the adjusted equations by Araújo Primo et al. (2015). ET_C was measured from the residual of the SWB.

The crop coefficient (k_C) was calculated from the ratio between ET_C and ET_0 (Queiroz et al., 2016; Lima et al., 2018). The values for ET_C and k_C were established for both cultivation systems (NM and WM) under the conditions for maximized productivity in the cactus.

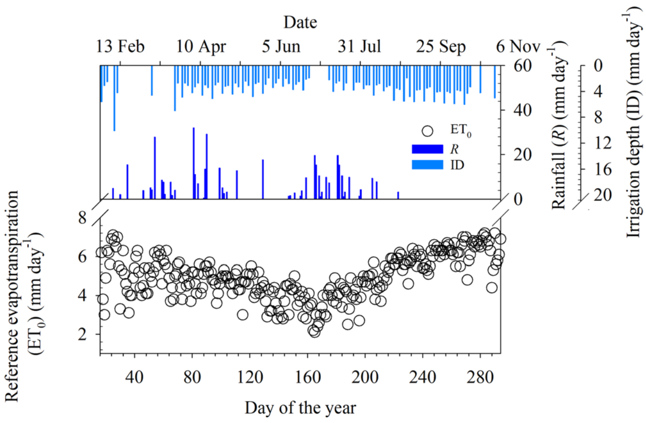

FIGURE 2 Rainfall events and daily reference evapotranspiration from 17 January to 6 November 2015 in the district of Serra Talhada in the semi-arid region of the state of Pernambuco, Brazil

2.5 | Phenophases and ideal harvest time in the forage cactus

The phenophases ($^{\varphi}$Ph) and ideal harvest time were defined based on the rate of cladode emission ($\partial_{TNC}/\partial_t$) from the data on the total number of cladodes (TNC) on the plant (Pinheiro et al., 2014; Silva et al., 2014b). $\partial_{TNC}/\partial_t$ was calculated from the derivative of sigmoid models adjusted between the TNC and accumulated degree days (ADD); the latter was determined using the maximum and minimum air temperatures, with the base temperature equal to 22°C, as cited by Souza et al. (2020). The transition between phenophases and ideal harvest time is described in Table 1.

2.6 | Secondary analyses

Since the SWB was applied for intervals of 14 days, 21 periods were generated from 17 January to 6 November 2015, which were used to express the results for ΔH, R, ID, SR, DD, CR and ET, as well as ET_C and k_C. The measured values for k_C and the accumulated degree days were used to adjust Gaussian models. These models were applied to estimate the values for k_C prior to the start of the SWB (15 November 2014 to 16 January 2015), as well as to smooth the variation in the k_C data during the period of the SWB (17 January to 6 November 2015). The ET_C for each day of the crop cycle (15 November 2014 to 6 November 2015) was calculated from the product of the estimated values for k_C and ET_0, as per the procedure suggested by Silva et al. (2014b). From the ratio between the DMY and the sum of the ET_C for the cycle,

TABLE 1 Definition of the initial and final limits of the phenophases and ideal harvest time based on the rate of cladode emission ($\partial_{TNC}/\partial_t$)

Moment	Phenophases I	Phenophases II	Phenophases III	Phenophases IV	Harvest time
Initial	First value $\partial_{TNC}/\partial_t$	Double the first value $\partial_{TNC}/\partial_t$	Peak $\partial_{TNC}/\partial_t$	50% of the peak $\partial_{TNC}/\partial_t$	$\partial_{TNC}/\partial_t$ equal to zero
Final	Double the first value $\partial_{TNC}/\partial_t$	Peak $\partial_{TNC}/\partial_t$	50% of the peak $\partial_{TNC}/\partial_t$	$\partial_{TNC}/\partial_t$ equal to zero	

the water use efficiency (WUE) was calculated in kg ha^{-1} mm^{-1}. Each of the values for ET_C and k_C from the beginning of the fourth crop cycle were submitted to descriptive statistics and expressed per phenophase.

2.7 | Statistical analysis

The FMY, DMY, DMC and WUE data at the time of harvest and the ET_C and k_C per period were submitted to tests of normality (Shapiro–Wilk's test) and homoscedasticity (Levene's test) and analysis of variance (ANOVA two-way) by the F-test ($P < 0.05$) (Queiroz et al., 2015), considering the two factors: the water regime and crop systems. When significant, the mean values were compared by Tukey's test at a level of 0.05 probability. All statistical procedures were carried out using statistical software and data analysis in Excel software XLSTAT v2018 (Addinsoft, Paris, France, www.xlstat.com).

3 | RESULTS

3.1 | Yield on a fresh (FMY) and dry matter (DMY) basis and water use efficiency (WUE)

Table 2 shows that the interaction between the factors (water regime and cultivation system) did not affect the variables analysed ($P > 0.05$). The water regime affected only the DMC ($P < 0.05$). The DMC was higher for the 0% ET_0 (rainfed) water regime. The FMY, DMY, DMC and WUE values were affected by crop system, with higher values for system WM. Although the water regime factor affected only the DMC variable, higher values for FMY and WUE in the forage cactus were obtained at the irrigation depth of 50% ET_0 under the NM and WM cultivation systems. For this reason, the data for the soil water balance in this irrigation regime under both cultivation systems (NM and WM) were used to define the values for the evapotranspiration and crop coefficient. Under the conditions of 50% ET_0, mulching also significantly increased the FMY (114 versus 47 Mg ha^{-1}) and DMY (18 versus 5 Mg ha^{-1}), as well as the dry matter content (0.16 versus 0.11 Mg Mg^{-1}) compared to the NM cropping system.

3.2 | Accumulated soil water balance components

Table 3 shows the duration of the 21 periods (P) for carrying out the soil water balance (SWB) (17 January to 6 November 2015). Neither deep drainage (DD) nor capillary rise (CR) was affected by the presence of mulch ($P > 0.05$) (Table 3). Between P1 and P7, the DD was low, despite 54% of the rainfall volume and 30% of the total applied irrigation depth having occurred during this

TABLE 2 Analysis of variance (two-way ANOVA) for productivity on a fresh (FMY) and dry matter (DMY) basis and dry matter content (DMC) in the forage cactus under two cultivation systems, one with (WM) and one without (NM) mulch

	P-value			
Source of variation	**FMY**	**DMY**	**DMC**	**WUE**
Water regime (WR)	0.1713	0.1860	<0.0001**	0.4252
Crop system (CS)	0.0067**	<0.0001**	<0.0001**	0.0002**
WR versus CS	0.9318	0.3032	0.1231	0.5091
	Mean values			
Water regime	**FMY**	**DMY**	**DMC**	**WUE**
Rainfed (0% ET_0)	41	9	0.20a	8
25% ET_0	71	11	0.14b	11
50% ET_0	80	11	0.13b	15
75% ET_0	69	8	0.11b	8
100% ET_0	71	8	0.11b	8
Crop system	FMY	DMY	DMC	WUE
NM	44b	5b	0.11b	5b
WM	88a	14a	0.16a	15a

Note: Mean values followed by the same lower-case letter do not differ statistically by Tukey's test ($P < 0.05$). The asterisks (**) denote 0.01 significance.

Abbreviations: DM, dry matter (Mg ha^{-1}); DMC, dry matter content; MF, fresh matter (Mg ha^{-1}); WUE, water use efficiency (kg ha^{-1} mm^{-1}).

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TABLE 3 Water balance components (SWB) in soil cultivated with the forage cactus under a cultivation system with (WM) and without (NM) mulch in a semi-arid environment[a]

					Without mulch					With mulch				
Period	Start	End	R mm	ID mm	DD mm	CR mm	SR mm	ΔH mm	ET_C mm	DD mm	CR mm	SR mm	ΔH mm	ET_C mm
1	17 Jan 15	30 Jan 15	7.0	25.5	0.0	0.9	0.0	1.6[b]	46.2	−2.0	0.0	0.0	−13.3[a]	43.8
2	31 Jan 15	13 Feb 15	15.5	0.0	0.0	1.6	−3.0	14.0	38.1	0.0	5.5	−3.0	16.7	39.1
3	14 Feb 2015	27 Feb 15	41.0	4.6	0.0	0.5	−1.4	−0.9	45.6	0.0	2.1	−1.4	1.9	44.4
4	28 Feb 2015	13 Mar 15	32.0	9.7	−0.5	0.0	−5.5	−8.2	44.0	−1.9	0.0	−5.5	−5.4	39.7
5	14 Mar 15	27 Mar 15	50.1	20.9	−0.1	0.9	−13.0	8.2	50.6	0.0	1.6	−13.0	7.1	52.5
6	28 Mar 15	10 Apr 15	43.2	21.8	0.0	1.7[a]	−3.7	10.5	70.8	−0.2	0.0[b]	−3.7	4.4	66.5
7	11 Apr 2015	24 Apr 15	37.9	21.1	−0.3	0.3	−0.2	1.7	43.0	0.0	2.5	−0.2	2.7	44.6
8	25 Apr 2015	8 May 15	0.0	19.9	−1.6	0.0	0.0	10.9	29.2	−2.6	0.0	0.0	10.8	28.1
9	09 May 2015	22 May 15	17.6	17.1	−0.9	0.0	0.0	−10.0	43.8	0.0	1.1	0.0	6.8	29.1
10	23 May 2015	5 Jun 15	5.9	17.2	−0.9	0.2	0.0	16.4	24.0[b]	−0.4	0.3	0.0	1.7	26.5[a]
11	6 Jun 15	19 Jun 15	60.5	7.9	−0.1	0.9	−13.7	1.8[a]	52.9	−1.3	0.0	−13.7	−1.5[b]	54.0
12	20 Jun 15	3 Jul 15	56.6	11.3	0.0	5.3	−4.7	10.8	64.0	0.0	4.6	−4.7	11.4	62.6
13	4 Jul 15	17 Jul 15	26.2	15.6	−3.6	0.0	0.0	11.6	43.4	−2.5	0.0	0.0	11.1	44.1
14	18 Jul 15	31 Jul 15	22.9	22.7	−1.1	0.0	0.0	−4.8	40.9	0.0	0.8	0.0	−2.2	40.2
15	1 Jul 15	14 Aug 15	3.2	23.0	−0.9	0.1	0.0	−1.6	27.0	−1.4	0.0	0.0	−1.4	26.1
16	15 Aug 2015	28 Aug 15	0.0	25.5	−0.5	0.0	0.0	3.5	28.4	−1.0	0.0	0.0	0.3	24.7
17	29 Aug 2015	11 Sep 15	0.0	25.9	0.0	1.0	0.0	6.4[a]	20.5	−0.5	1.0	0.0	4.4[b]	22.0
18	12 Sep 2015	25 Sep 15	0.0	27.5	0.0	1.2	0.0	4.7	24.0[b]	0.0	4.1	0.0	6.7	24.9[a]
19	26 Sep 2015	9 Oct 15	0.0	17.8	0.1	1.4	0.0	1.3	17.9	−0.8	0.3	0.0	−1.4	18.8
20	10 Oct2015	23 Oct 15	0.0	5.0	−4.6	0.8	0.0	−5.2	15.2[b]	−0.6	1.7	0.0	−4.6	19.4[a]
21	24 Oct 2015	6 Nov 15	0.0	6.7	−9.0	0.2	0.0	−11.7	12.5[b]	−0.5	3.2	0.0	−7.7	19.9[a]
Total			418.0	373.0	−24.3	17.2	−45.1	60.8	782.0	−15.7	28.9	−45.1	48.6	771.2

Note: Mean values followed by different letters on a line indicate no difference between cultivation systems (NM and WM) within the same period by Tukey's test ($P < 0.05$).
Abbreviations: ΔH, variation in soil water storage; CR, capillary rise; DD, deep drainage; ET_C, crop evapotranspiration; ID, irrigation depth; R, rainfall; SR = runoff.
[a]Values defined for the crop systems WM and NM mulch irrigated from 50% ET_0 (water regime that provided greater productivity and efficiency of water use for both crop systems).

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period, giving a total of 330 mm (R + ID), and only 8% of the total rainfall having been lost to runoff (SR). For the remaining periods, there was an increase in DD under both cultivation systems due to more regular irrigation (243 mm), which together with R (191 mm) totalled 434 mm.

Positive values for the variation in water storage (ΔH) occurred during periods of more intense rainfall events or during subsequent periods (P2, P6, P8, P10, P12 and P13). There was less fluctuation of ΔH under the WM system (60.8 versus 48.6 mm) (Table 3).

Table 3 also shows the accumulated values for crop evapotranspiration (ET_C) during all 21 periods. Only during P10, P18, P20 and P21 was there any difference between the two systems, NM and WM. From P1 to P16, the ET_C values were higher under the NM system than under WM. However, for all 21 periods, the accumulated ET_C values were 782 and 771 mm (NM and WM, respectively), indicating a very small reduction in water consumption by the crop due to the use of mulch. From P17 to P21, the value of the accumulated ET_C values was reversed, with the WM system surpassing the NM system by 14%.

3.3 | Phenophases and ideal harvest time

Four phenophases were observed during the crop cycle (Figure 3) based on the rate of cladode emission ($\partial_{TNC}/\partial_t$). $\partial_{TNC}/\partial_t$ was superior under the WM system (Figure 3(b)) throughout the cycle, which culminated in a total of 15 cladode units per plant, while under the NM system (Figure 3(a)), it reached an average of 11 units.

As a consequence, phenophase $^{\varphi}$PhI lasted 12 days (53°C day) under the NM system and 16 days (71°C day) under the WM system (Table 4). $^{\varphi}$PhII, with a longer duration than $^{\varphi}$PhI, reached 31 days (145°C day) and 30 days (143°C day) under the NM and WM systems, respectively. $^{\varphi}$PhIII was superior under the WM system, with a duration of 41 days (212°C day) compared to the NM system (32 days and 165°C day). $^{\varphi}$PhIV was subdivided into two phases, one up to the ideal harvest time ($^{\varphi}$PhIV-HT) considered in this study and the other during the subsequent period ($^{\varphi}$PhIV-RF), known as the 'period of reserve forage' when the crop is kept in the field even after reaching harvest age.

This practice is fairly common among producers as a way of maintaining a reserve of forage for the herd during the dry season. Based on the rate of cladode emission, it is suggested that under the NM system, the cactus be harvested during the fourth cycle at 553°C day. Under the WM system, the cactus should be harvested at 687°C day, with a longer thermal time than under the NM system to maximize productivity. On the other hand, if the crop is kept in the field until reaching a cycle of close to a year, an additional 971°C day and 839°C day will be required under the NM and WM systems, respectively.

3.4 | Mean daily crop evapotranspiration (ET_C) and crop coefficient (k_C)

The daily ET_C showed greater intensity during P6, P11 and P12 under both the NM and WM systems (5.1 and 4.8 mm, 3.8 and 3.9 mm and 4.6 and 4.5 mm, respectively) (Figure 4(a)). The lowest daily ET_C occurred during the last three periods, P19, P20 and P21, with mean values of 1.1 and 1.3 mm, 1.1 and 1.4 mm, and 0.9 and 1.4 mm under the NM and WM systems, respectively. The ET_C differed between systems only during P10, P18, P20 and P21. Similar to the ET_C, the highest crop coefficients (k_C) were observed during P6, P11 and P12, with a mean value of 1.14, and the lowest were observed during P19, P20 and P21, with a mean of 0.17 (Figure 4(b)). Differences between the k_C values of the systems were found for P10, P18, P20 and P21.

The ET_C varied based on the water regime, atmospheric demand and crop growth. In daily terms, the ET_C increased until phenophase IV-HT with a subsequent reduction under both systems. In accumulated terms, the ET_C of the cactus increased up to the end of the cycle due to the increased duration of the phenophases (Table 4).

During phenophase I ($^{\varphi}$PhI), the ET_C was 0.49 and 0.65 mm day^{-1} under the NM and WM systems, respectively, with an accumulated ET_C of 6 and 10 mm. During $^{\varphi}$PhII, the mean ET_C was 0.81 mm day^{-1} (176°C day) under the NM system and 1.06 mm day^{-1} under the WM system, totalling 25 and 32 mm, respectively. The ET_C during $^{\varphi}$PhIII was 1.84 and 2.08 mm day^{-1} under the NM and WM systems, respectively, accumulating 59 and 85 mm. During $^{\varphi}$PhIV, up to the ideal harvest time considered in this study ($^{\varphi}$PhIV-HT), the ET_C was equal to 2.81 and 3.31 mm day^{-1}, with a total of 109 and 182 mm. During the subsequent $^{\varphi}$PhIV-RF period, the reduction in ET_C reached an average of 2.76 and 2.59 mm day^{-1}, with a total of 679 and 564 mm. On average, $^{\varphi}$PhIV had an ET_C of 2.78 and 2.95 mm day^{-1} under the NM and WM systems, respectively.

In cumulative terms, the ET_C of the cactus showed little difference between the NM and WM systems (878 and 874 mm, respectively, over 360 days). However, it can be seen that up to the ideal harvest time, the ET_C was 199 mm under the NM system (114 days) and 310 mm under the WM system (142 days). Because of the significant increase (DMY, 18 versus 5 Mg ha^{-1}) and small increase in ET_C, the crop efficiency was

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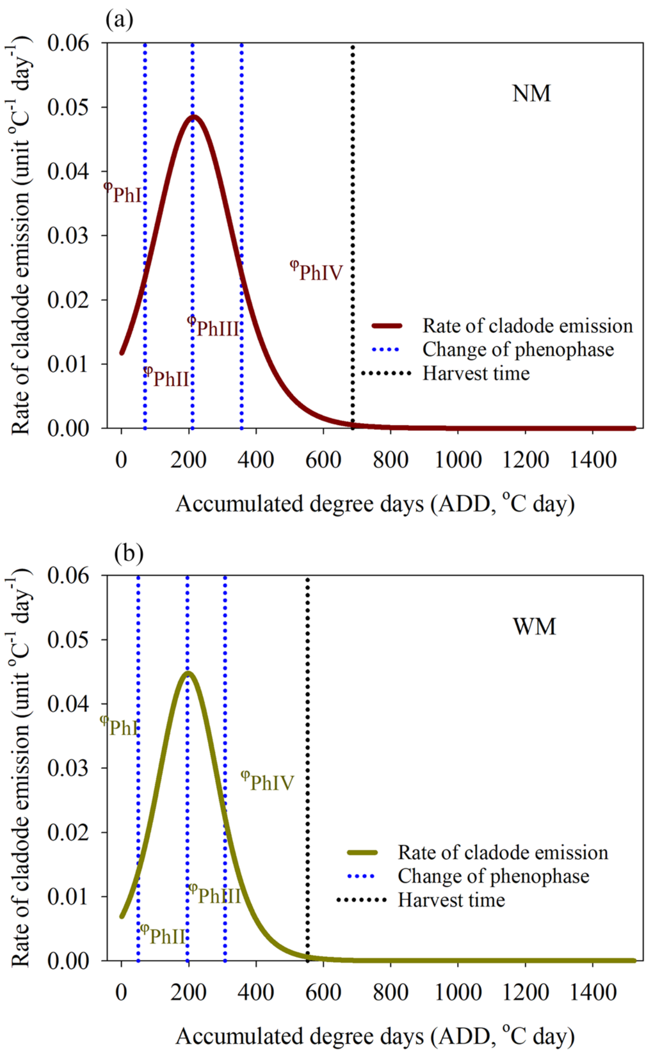

FIGURE 3 Cladode emission rate and phenological stages (ᵠPh) in the forage cactus as a function of degree days under two cultivation systems, one without (NM) (a) and the other with (WM) the use of mulch (b)

21 kg ha^{-1} mm^{-1}, much higher than that under the NM system (DMY, 6 kg ha^{-1} mm^{-1}).

Figure 5 shows the adjusted values for k_C in the cactus, where the same tendency to vary throughout the cycle can be seen under both cultivation systems. Analysing k_C by phenophase, the values changed more due to their duration, which is different between the systems. On average, therefore, k_C was always higher under the WM system, with the differences decreasing throughout the cycle (ᵠPhI, 0.09 versus 0.12, a difference of 36%; ᵠPhII, 27%; ᵠPIII, 23%; ᵠPIV-HT, 17%; and ᵠPhIV-RF, 14%).

4 | DISCUSSION

Under optimal growing conditions (water regime of 50% ET_0), the cactus under the WM system showed 59% more fresh matter, 72% more dry matter and 200% more water use efficiency than under the NM system. Mulching usually increases crop yield due to improved nutrient cycling from the mineralization of organic matter (Prosdocimi et al., 2016), a better soil structure (Kader et al., 2017), a reduction in soil temperature (Namaghi et al., 2018) and maintenance of the soil moisture (Carvalho et al., 2017; Gong et al., 2017) because it protects the most superficial layers of the soil against the direct incidence of solar radiation, reducing soil water evaporation (Li et al., 2018; Zhang et al., 2018).

The presence of mulch on the ground did not affect the accumulated values of DD or CR ($P < 0.05$). DD and CR depend on the water regime, the water retention capacity of the soil, its hydraulic properties, and the water dynamics at the soil–atmosphere interface that control the vertical flow of water (Kool et al., 2013; Queiroz et al., 2016).

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TABLE 4 Duration, accumulated degree days, mean daily and accumulated evapotranspiration, and crop coefficient in the forage cactus by phenophase under cultivation systems with (WM) and without (NM) the use of mulch[a]

	No mulch							With mulch						
	Duration	ADD[b]	ET	ΣET	k_C			Duration	ADD[b]	ET	ΣET	k_C		
Phenophase	**Days**	**°C day**	**mm day^{-1}**	**mm**	**Initial**	**Final**	***M***	**Days**	**°C day**	**mm day^{-1}**	**mm**	**Initial**	**Final**	***M***
$^{\varphi}$ PhI	12	53	0.49	6	0.08	0.10	0.09	16	71	0.65	10	0.10	0.14	0.12
$^{\varphi}$ PhII	31	145	0.81	25	0.10	0.21	0.16	30	143	1.06	32	0.14	0.26	0.20
$^{\varphi}$ PhII	32	165	1.84	59	0.21	0.41	0.31	41	212	2.08	85	0.26	0.51	0.39
$^{\varphi}$ PhIV-HT	39	190	2.81	109	0.41	0.68	0.55	55	259	3.31	182	0.51	0.76	0.64
$^{\varphi}$ PhIV-RF	246	971	2.76	679	0.68	0.09	0.38	218	839	2.59	564	0.76	0.11	0.44
Average/sum	360	1,523	1.74	878				360	1,523	1.94	874			

Abbreviations: Initial, final and *M*, initial, final and mean values for the phenophase; $^{\varphi}$Ph, phenophases; HT, harvest time; RF, period of reserve forage, maintaining the crop in the field.

[a]Values defined for the crop systems WM and NM mulch irrigated from 50% ET_0 (water regime that provided greater productivity and efficiency of water use for both crop systems).

[b]Accumulated degree days (ADD) calculated with a base temperature of 22°C.

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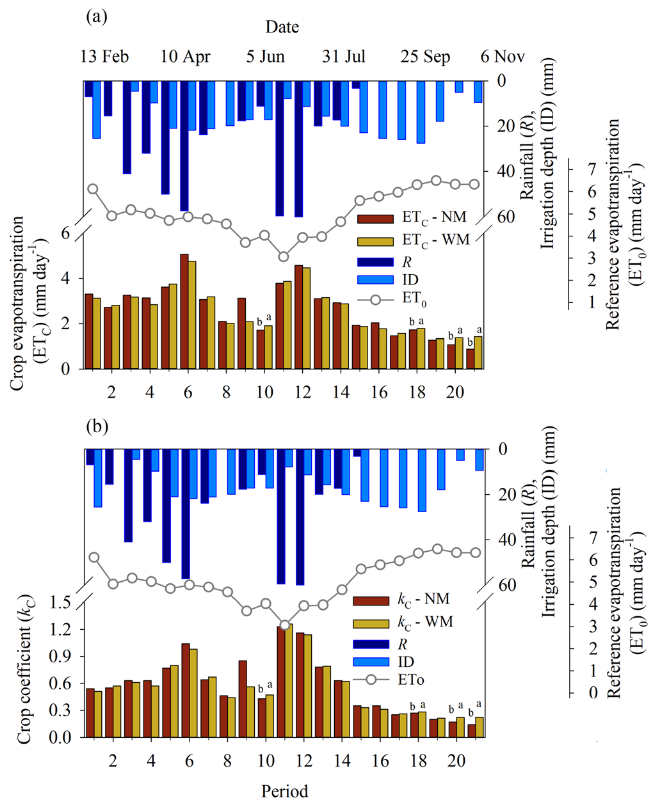

FIGURE 4 (a) Maximum evapotranspiration and (b) crop coefficient (k_C) in the forage cactus under two cultivation systems, one with mulch (WM) and one without mulch (NM)

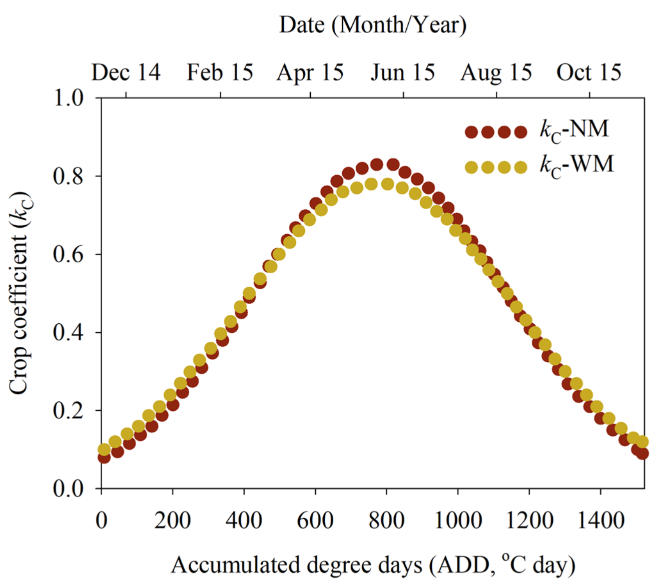

FIGURE 5 Crop coefficient (k_C) adjusted for the forage cactus as a function of accumulated degree days (ADD) from experimental data under two cultivation systems, one with (WM) and one without (NM) the use of mulch. Models adjusted and applied to the entire crop cycle: k_C (NM) = 0.83*exp(−0.5*([ADD-779.66]/353.69)^2); and k_C (WM) = 0.78*exp(−0.5*([ADD-776.35]/379.19)^2)

ET_C and k_C fluctuated according to the growth dynamics of the crop and the influence of more intense rainfall events. Barbosa et al. (2017a) state that evapotranspiration in the forage cactus depends on the seasonality of the weather conditions and the morphological characteristics of the species. Under full growth and maximum productivity, the ET_C and k_C reflect the water requirement of the crop to be adopted under irrigation

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management (Pereira et al., 2017). Their values exhibited the same tendency to vary over time, with greater values only at peak rainfall during the period under evaluation.

The differences during P10, P18, P20 and P21 revealed higher values under the WM system; however, cumulatively, mulch barely reduced the water consumption of the cactus. This difference may be related to the compensatory effects of transpiration in the process of evapotranspiration, since mulch helped to reduce water evaporation but also favoured greater crop development, increasing the leaf area index, which is directly reflected in plant transpiration (Carvalho et al., 2017; Unkovich et al., 2018).

As the cactus showed greatly increased productivity under the WM system, even with the small change in accumulated ET_C, this resulted in a significant increase in water use efficiency (WUE). High WUE in the cactus has been reported in the literature (Silva et al., 2014a; Morais et al., 2017; Lima et al., 2018) and is a reflection of the crassulacean acid metabolism, permitting stomatal opening mainly at night, when the water vapour-pressure deficit is lower, thereby reducing water loss through transpiration (Liu et al., 2018). However, Barbosa et al. (2017b) also state that productivity in the cactus does not always respond linearly to the water supply or to the actual evapotranspiration of the crop but rather to the peculiarities of the morphological characteristics of its clones.

From periods 17, 18, 19 and 21 onwards, there was a reversal in values and in the ET_C between the NM and WM systems, where the ET_C of the WM system exceeded that of the NM system by 14%. This is due to an increase in the soil water evaporation component from the decomposing mulch and because of increased transpiration due to the cladode area index being higher under the WM system (data not shown). For Rosas-Anderson et al. (2018), soil evaporation can reach significant values depending on the crop (i.e. 80% of the total ET_C). Evaporation is directly related to the ground-cover index (GCI). Because the cactus has a low GCI (Queiroz et al., 2016), replacing the mulch throughout the cycle can be very useful to further increase the efficiency of the production system.The greatest values for ET_C and k_C (P6, P11 and P12) under the NM and WM systems were associated with more intense rainfall events, which significantly increased the value of the evaporation component, whereas the lowest values for ET_C and k_C occurred at the beginning (before 17 January 2015) and end of the crop cycle (P19, P20 and P21), when the cladode area index was low and there was a reduction in cladode emission, respectively. On average, k_C under the WM system was greater per phenophase than under the NM system, with the difference decreasing as the cycle progressed due to the duration of the phenophases, which under the WM system are longer until the ideal harvest time is reached.

The faster phenological advance up to this time increased the water requirement of the crop under the WM system due to the greater emission of cladodes, ensuring a significant increase in yield. On the other hand, by the end of the cycle, with a reduction in the emission of new cladodes during phenophase IV-RF, there was a decrease in the water requirement, so that where the producer chooses not to harvest the crop after the significant reduction in growth, the irrigation depths to be replaced should be smaller. Amorim et al. (2017) state that practices such as irrigation and mulching in the forage cactus bring crop cutting forward, eliminating maintenance in the field, which can be costly to the production system.

Regardless of the cultivation system, the mean values for k_C (0.50) obtained here are lower than those quoted by Queiroz et al. (2015) in *O. stricta* during the second production cycle ($k_C = 0.52$, 13 month cycle) and by Divincula et al. (2019) in *O. ficus-indica* (L.), who obtained a mean value for k_C of 0.72 for a cycle of just 5 months. The values for k_C obtained here are also much lower than those reported for C3 and C4 plants (Souza et al., 2015), a reflection of the CAM process (crassulacean acid metabolism) (Liu et al., 2018). Obtaining the k_C for each region is essential for irrigation management, as the climate, soil and management affect the water depth to be replaced (Queiroz et al., 2016).

5 | CONCLUSION

In this study, soil water dynamics, evapotranspiration and crop coefficients in the forage cactus were measured in cultivation systems with and without the use of mulch. The use of 8.2 Mg ha^{-1} mulch had almost no effect on soil water dynamics nor did it reduce water consumption by the crop when compared to the system without the use of mulch; however, the mulch did significantly increase yield and water use efficiency in less time (839°C day). Greater cladode emission, when irrigated with 50% of the reference evapotranspiration, suggests anticipating the harvest, with a consequent saving in the water applied via irrigation. A mean complementary water depth of 1.3 mm day^{-1} regularly applied to the forage cactus maximizes productivity. On average, the crop coefficient per cycle is not significantly affected by the presence of mulch but varies strongly per phenophase due to the duration of the phenological stage, with higher values for k_C seen under the system with mulch. Greater

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attention should be given to the ideal time for cutting the cactus, as the reduction in cladode emission and greater water storage by the plant reduce the water requirement and the need for irrigation. It is proposed that further studies be conducted, including more irrigation depths and different times for replacing mulch during the crop cycle, in addition to combining irrigation depths and the frequency of application and mulching, to assess the impact on soil water dynamics and suggest the best water management for a system of cactus production.

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CONFLICT OF INTEREST

On behalf of all the authors, the corresponding author confirms that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available on request due to privacy/ethical restrictions. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

LIST OF SYMBOLS

$\partial_{TNC}/\partial_t$	rate of cladode emission
ADD	accumulated degree days
CR	capillary rise
DD	deep drainage
DMY	yield on a dry basis
ET_0	reference evapotranspiration
ET_C	evapotranspiration
FMY	yield on a fresh basis
HT	harvest time
ID	irrigation depth
$K(\theta)$	soil hydraulic conductivity
k_C	crop coefficient
NM	without mulch
P	period
$^{\varphi}$PhI	phenophases I
$^{\varphi}$PhII	phenophases II
$^{\varphi}$PhIII	phenophases III
$^{\varphi}$PhIV	phenophases IV
Q	vertical soil water flow
R	rainfall
RF	Period of reserve forage, maintaining the crop in the field
SR	superficial runoff
SWB	soil water balance
TNC	total number of cladodes on the plant
WM	with mulch
WUE	water use efficiency
ΔH	variation in soil water storage
Φt	total water potential

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