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Effect of water availability on growth and water use efficiency for biomass and gel production in Aloe Vera (*Aloe barbadensis* M.)

H. Silva[a,f,*], S. Sagardia[a,f], O. Seguel[b,f], C. Torres[c,f], C. Tapia[d,f], N. Franck[a,c,f], L. Cardemil[e,f]

[a] *Laboratorio Relación Suelo Agua Planta, Departamento de Producción Agrícola, Facultad de Ciencias Agronómicas*
[b] *Departamento de Ingeniería y Suelos*
[c] *Estación Experimental Agronómica Las Cardas*
[d] *Laboratorio de Operaciones Unitarias, Facultad de Ciencias Químicas y Farmacéuticas*
[e] *Laboratorio de Biología Molecular Vegetal, Facultad de Ciencias*
[f] *Universidad de Chile*

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ABSTRACT

The cultivation of Aloe Vera (*Aloe barbadensis* Miller) has achieved economic importance due to the products which are obtained from its leaves. However, there is a scarcity of information about its agronomic management and the effect of water availability for its establishment and production. The objective of this study was to evaluate the effect of different irrigation rates on the growth and water use efficiency (WUE) for the production of leaves biomass and gel. We applied four irrigation treatments calculated to be 20, 15, 10 and 5% of the mean evaporative demand (ETo) of last year, equivalent 4 L h^{-1} during 60, 45, 30 and 15 min (8, 6, 4 and 2 L h^{-1}, respectively), designated as T1, T2, T3 and T4. Plants submitted to the low water availability (T4) produced less new leaves and plantlets per plant. The greatest number of new leaves was produced by the plants T1 and the greatest number of plantlets in an intermediate treatment (T2). The extreme treatments (T1 and T4) had lower values of WUE (10.8 and 10.9 g leaf biomass L^{-1} water) than the intermediate treatments T2 and T3 (24.5 and 15.6 g leaves biomass L^{-1} water). The WUE values for gel production were 8.6, 17.1, 13.1 and 6.8 g L^{-1} in T1, T2, T3 and T4; the T2 plants were the most efficient. The precise water requirement under this edapho-climatic condition was obtained. This requirement, based on the interaction among the metabolic pathway, atmospheric evaporative demand and soil water dynamics, was 15% of the reference evapotranspiration. This condition gave the maximum aerial biomass and gel production for unit of water utilized, and thus the greatest water use efficiency for Aloe Vera.

1. Introduction

Biomass production in plant species in arid and semi-arid ecosystems depends directly upon the availability of water and the seasonal fluctuations in its abundance; water is a selective force in the evolution of these plants, stimulating morphological and physiological responses or adaptations. The appropriate species for these degraded areas are those whose characteristics allow them to use water efficiently. It has been suggested that the agronomic management of several introduced species could increase their productivity considerably, even surpassing the traditionally cultivated species under some conditions. One interesting alternative for the arid and semi-arid zones of Chile is Aloe Vera (*Aloe barbadensis* M.), a drought resistant species with crassulacean acid metabolism (CAM) (Rodríguez-Garcia et al., 2007; Hernández et al., 2002). Nobel and Valenzuela (1987) and Nobel (1988) showed that CAM species (Agavaceae and Cactaceae) have high productivity, on the order of 4.5–8.4 ton ha^{-1} $year^{-1}$ dry weight (DW). Assuming that DW is 15% of fresh weight (FW), the aboveground mass productivity would range from 29.7 to 55.4 ton FW ha^{-1} $year^{-1}$ in the arid and semi-arid regions studied.

Aloe Vera is a perennial specie; its biomass is represented mainly by leaves, growth occurs in a rosette around a small portion of stem no greater than 5 cm. The leaves are simple, triangular, succulent, thick, with narrow lanceolate mucro tip, 30–60 cm long, and 5–12 cm wide at the base and 0.8–3 cm thick (Añez and Vásquez, 2005). The margins of the leaves have sharp triangular teeth about 2 mm long. The main root is 4–10 cm long and 4–5 cm in diameter, the rhizosphere is concentrated at a depth of 15–20 cm. Flowers 2.5–3 cm long, yellow, grouped in clusters on a single erect stem about 1 m long. Reproduction is primarily by asexual plantlets.

* Corresponding author at: University of Chile, Departamento de Produccion Agricola, Santa Rosa 11315, La Pintana, Santiago, Region Metroplolitana, Chile. Tel.: +56 2 9785858; fax: +56 2 9785858.
E-mail address: hsilva@uchile.cl (H. Silva).

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Aloe Vera is considered as a constitutive CAM species (Winter et al., 2005). Efficiency of water use, assessed in pots, can reach 54 g H_2O g^{-1} dry matter (Winter et al., 2005). To obtain high yields of biomass, some authors proposed plant densities between 10 and 20,000 plants per hectare; a plant can be harvested 4–6 times per year (Yepes et al., 1993; Añez and Vásquez, 2005). Aloe Vera is an important industrially cultivated species, from which is extracted a gel of proven pharmacological and medicinal value (Yagi and Takeo, 2003; Hamman, 2008). Yepes et al. (1993) showed that the yield of gel improved with a low frequency of watering and a high dose of fertilizer. Abundant water generates greater leaf biomass, although the relation between water, biomass and gel production is unknown. The gel is found in a clear internal zone located between the abaxial and adaxial mesophyll. This central zone has been called by various names, including pulp, mucilaginous tissue, mucilaginous gel and parenchyma tissue. It is composed of cell walls, degenerate organelles and the viscous liquid contained in the cells. The gel has a complex chemical composition, composed primarily of soluble sugars, anthraquinones, polysaccharides, amino acids, vitamins and proteins, many of which are enzymes (Chow et al., 2005; Chun-hui et al., 2007). The best-known uses of the Aloe Vera gel are in cosmetology and medicine; in the latter area it has been used to treat bites, scars, burns and in some cases as a cofactor in the treatment of cancer and even AIDS (Hamman, 2008; Ramachandra and Srinivasa, 2008). Most of the extensive bibliographic references to this plant are oriented to the promotion and marketing of products which include the gel. There is only a small amount of agronomic and physiological information (Rodríguez-Garcia et al., 2000; Zhao-Pu et al., 2006), since most countries which have its germplasm consider it to be a strategic crop. In this report, we studied the effect of irrigation on the growth and water use efficiency (WUE) for the production of aerial biomass and gel in Aloe Vera in a semi-arid zone of the IV Region of Chile. We hypothesized that WUE should increase if there is greater availability of water, and that there is a direct relation among WUE, aerial biomass and gel produced. One of the specific objectives was to determine the minimum quantity of water necessary for the maximum production of aerial biomass and gel.

2. Materials and methods

2.1. Experimental site

The experiment was performed during the 2006–2007 season in the Campo Experimental Las Cardas, located in the IV Region of Coquimbo, Chile, 31°S latitude. The area has an arid Mediterranean climate with a mean annual precipitation of 100 mm and a water deficit of 94%; the atmospheric evaporative demand (ETo) can reach up to 1300 mm per year. Precipitation is concentrated in the winter season, especially in June and July; the ten remaining months are usually dry. The mean maximum temperature is 29 °C in the warmest month; no freezes occur. The mean total annual number cooling degree days is 6 (below 7 °C) (Caviedes and Daget, 1984). The soil is Tambillo Series (Table 1); the site has a slight inclination (1–2%) with micro-relief and abundant pebbles on the surface and in the soil (50%). The soil texture in profile is sandy loam. The N level is low, while the levels of P and K are normal for this type of soil. Some authors recommend nitrogen fertilization for increasing biomass (Yepes et al., 1993), but in this study no fertilizer was applied.

2.2. Plantation and design experimental

Plants were established in May 2006, from 3-year-old plantlets 25 cm high and 35 cm in diameter. Each plot had 30 plants in 5 rows of 6 plants each, with 1 m between plants in a row and 1.5 m between rows. Plots were separated by 2 m. The experimental unit was 16 plots of 45 m^2 with 30 plants each, so the total number of plants was 480 in an area of 720 m^2, equivalent to a density of 6667 plants ha^{-1}

Table 1
Profile of soil between 20 and 80 cm of depth.

Description	Depth (cm)			
	20	40	60	80
Texture	Sandy loam			
Bulk density (g cm^{-3})	1.6	1.7	1.9	1.8
pH	6.3	6.6	6.8	6.7
Organic material (%)	1.7	0.5	0.1	0.3
N (kg ha^{-1})	52.8	27.4	21.0	21.5
P (kg ha^{-1})	105.6	78.7	76.0	50.1
K (kg ha^{-1})	950.4	807.1	441.0	304.3

2.3. Irrigation

The reference evapotranspiration and daily evaporation was recorded manually from a pan evaporimeter Class A tray at the experimental site. The value of ETo (Fig. 1) was accumulated monthly. Plants were irrigated when there was a loss of between 20 and 25 mm from the ETo. With the knowledge of the metabolic route of Aloe Vera and the coefficient of culture (Kc) of other species CAM: *Opuntia ficus indica* (0.23–0.34) (Daruich, 2000), *Agave* sp. (0.40–0.70) and pineapple (0.30–0.50) (Allen et al., 2006), we designed four irrigation treatments of 20, 15, 10 and 5% of the ETo.

The irrigation system was installed with independent electrical valves for each treatment, along with a volumetric water meter to quantify the amounts applied in each. The water was obtained from a deep well using an electric hydraulic pump. Drip irrigation was used, with a double drip line for each row of plants; two emitters per plant was installed to 20 cm from each plant, covering an area of 0.50 m^2. The emission flow was 4 L h^{-1}; which was applied for 60, 45, 30 and 15 min to deliver 8, 6, 4 and 2 L h^{-1} for treatments T1, T2, T3 and T4, respectively.

2.4. Soil water content (SWC)

Variation in SWC was measured in two repetitions per treatment, using a capacitive probe (Delta-T probe Model PR1, England). Two access tubes were installed perpendicular to the plant row in two plants per treatment, located in the drip line at 15 and 30 cm from the plant. Since there was no specific calibration curve for the probe in the experimental site, a standard calibration curve of the

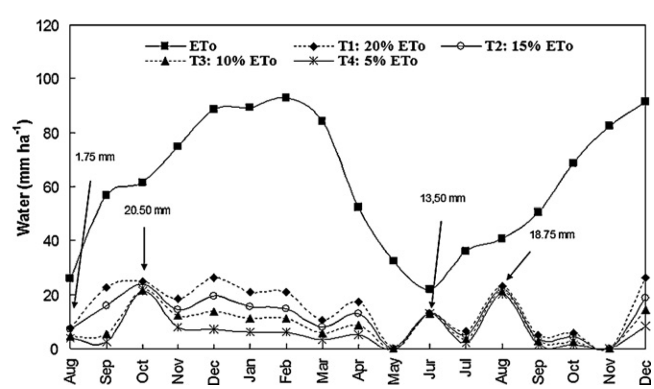

Fig. 1. Relation between evaporative atmospheric demand (ETo) and amount of water applied by irrigation by treatment during 17 months of the experimental period. Arrows indicate precipitation events, which left 1.8, 20.5, 13.5 and 18.8 mm, respectively.

instrument for a sandy loam soil was used for estimating the soil water content. Soil water content was measured weekly at 0.2, 0.3, 0.6 and 1 m depths, and expressed in mm of water. Additionally, the soil characteristic curve of water retention was measured with a pressure plate, determining the field moisture capacity (FMC) at −33 kPa and the permanent wilting point (PWP) at −1500 kPa. Because of the slope and the intensity of precipitation, there is no water runoff.

2.5. Growth, biomass, gel and dry matter production

Once per month the number of new leaves and shoots were counted in 16 plants per treatment (4 plants from each replicate). During the experimental period, we harvested shoots on 3 occasions to determine the number of new plantlets formed per unit time.

Five harvests of leaves were made during the experiment (February, June, July, September and December, 2007); we selected 10 leaves per treatment (1 per plant) from the peripheral part of the plants. Leaves were collected by making a cut in basal area of insertion to the plant without destroying the tissue and placed in a cooler. After measuring total fresh weight, the leaves were filleted to remove the gel from the photosynthetic tissue; the samples were weighed separately on aluminium trays and then dried in an oven at 70° to constant weight. The photosynthetic tissue was the material remaining after gel extraction.

At the end of the experimental period between 21 and 31 leaves per treatment were harvested and sectioned to quantify the photosynthetic tissue and gel.

Water use efficiency (WUE). Water use efficiency was calculated for each harvest as the quotient of leaf biomass production or gel production and the total water applied per treatment, expressed in g L^{-1}. We made five harvest of 10 leaves by treatment (g) during a period of 10 months and the WUE was calculated as a function of the quantity of water registered in a flow meter (L). WUE was also calculated based on dry weight.

2.6. Experimental design

The experimental design used randomized blocks; the experimental unit was a plot with 30 plants. The test consisted of 4 blocks, each composed of 4 plots with the four treatments. Each plot contained 5 rows of 6 plants each; samples were taken from the central rows to avoid edge effects. Data were analyzed using analysis of variance and analysis of covariance using MSTATC (Freed and Eisensmith, 1989) and InfoStat (2009). Significant differences among treatments indicated by ANOVA were further tested with a Tukey multiple range test, using $\alpha = 0.05$.

3. Results

Irrigation was begun in August 2006, on approximately a weekly basis during the summer, biweekly or monthly during the remainder of the year, with a total of 34 irrigations during the experimental period. The frequency of irrigation was 3.75 times per month in summer, while in the winter irrigation was applied 1.25 times per month. Fig. 1 shows the relation between the evapotranspiration and the amounts of water applied by irrigation in each treatment. The total amounts of water (treatments plus 54.6 mm of precipitation) were 348, 260, 180 and 109 L plant^{-1} for T1, T2, T3 and T4, respectively. We found a continuous reduction in the water content of the soil, following the same tendency as the atmospheric evaporative demand. Fig. 2 illustrates soil water content variation in the profile to 50 cm depth before and after irrigation. These values stayed in the range from 55.4 to 88.4 mm of plant available soil water. The values measured at 2-h intervals after irrigation show

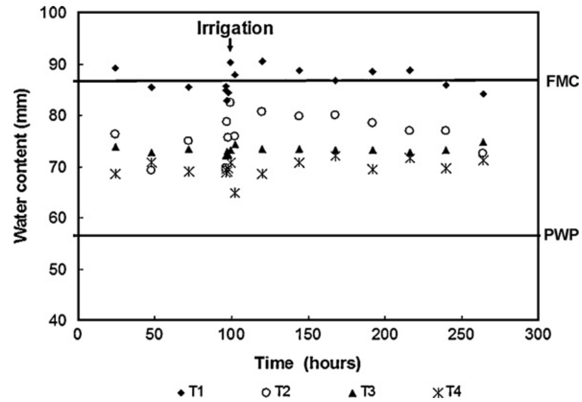

Fig. 2. Average soil water content ($n = 2$) at 15 cm from the plant in the profile just to 50 cm depth during a 11-day period (22/04 to 02/05/2007) with irrigation on day 4 illustrating the effect of an irrigation by treatments. FMC is the field moisture capacity and PWP the permanent wilting point.

an accumulation of water in the profile, equivalent to 0.2, 0.4, 0.4 and 0.1 mm h^{-1} for T1, T2, T3 and T4, respectively. The rate of root water absorption was 1.42 mm day^{-1} in T3 plants, 1.00 mm day^{-1} in T2, 0.57 mm day^{-1}, for T1 and 0.28 mm day^{-1} for T1. These values explain why the plants of T4, which were submitted to low water availability, showed little root growth, while the plants of T1 had an excess of water compared to the evaporative atmospheric demand, which would produce root anoxia and thus less growth (Fig. 2). This situation was observed during the summer; the leaf tissue of T1 plants changed color and we observed putrescence (rot) at the neck of the plant; root rot was also observed by digging into the ground. The weekly frequency of irrigation which was associated with the characteristics of soil water retention (19%) were the factors identified as associated with this phenomenon.

A study in parallel with this report (Sagardía, 2009, personal communications) demonstrates that the effective root depth in Aloe Vera was 40 cm and that the greatest root density (N° cm^{-2}) was registered in T2 plants, while the greatest superficial horizontal root extension was found in T1 plants, which reached up to 50 cm from the plants. Analysis of water content distribution in the profile allowed us to confirm that water runoff and water flow below the root zone (below 60 cm) is negligible for the water balance (Fig. 3).

These results demonstrate that the amounts of water applied by irrigation in treatments T2 and T3 were adequate for the root growth of Aloe Vera, given the greater rate of absorption in the range of water availability. By contrast, the amounts of water applied to the plants of T1 and T4 were not optimal for root growth;

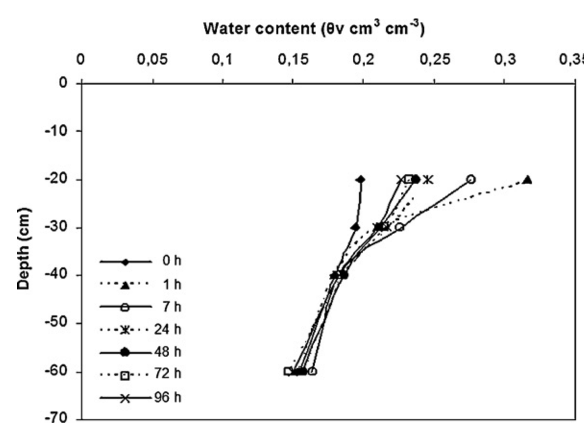

Fig. 3. Average soil water content (θv), 1 h before the irrigation up to 96 h later in plants T1. $n = 2$ (09/10 to 13/10/2007).

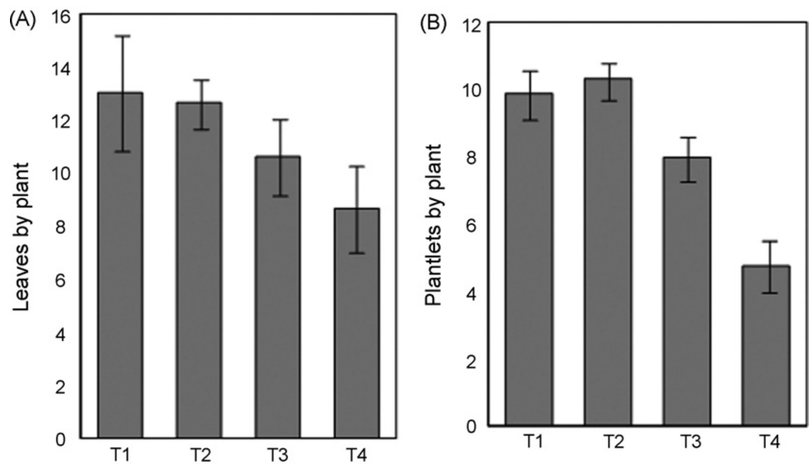

Fig. 4. Number of leaves (A) and plantlets by plant (B) in a 245-day period. Bars indicate the standard error. $n = 16$ plants by treatment.

the former because of an excess and the latter because of insufficient water availability.

3.1. Number of leaves and plantlets

Water availability affected the number of leaves and plantlets produced (Fig. 4A and B). Plants of T1 and T2 produced 209 and 202 leaves respectively, significantly greater ($P < 0.05$) than T3 and T4 plants, which produced 170 and 139 leaves, respectively, during the experimental period. The number of leaves per plant was 13.0, 12.6, 10.6 and 8.6 for T1, T2, T3 and T4, respectively (Fig. 4A). The highest rate of new leaf production occurred in summer, during February and March, 2007, which were the months with highest temperature; in this period the rates of new leaves production per plant were 0.85, 0.82, 0.69 and 0.56 for T1, T2, T3 and T4, respectively. At the individual plant level the differences between T1, T2 and T3 were not significant, while all 3 were significantly greater than T4 plants ($P < 0.05$, Fig. 4A).

The number of plantlets produced was similar in treatments T1 and T2 (Fig. 4B), with a mean of 10 plantlets per plant, and significantly different from T3 and T4 ($P < 0.05$). The daily production rate varied from nearly 0.08 to 0.03 plantlets plant^{-1} day^{-1}. Plants of T1 and T2 produced 0.07 and 0.078 plantlets plant^{-1} day^{-1}, while T3 and T4 produced 0.06 and 0.03, respectively. The total number of plantlets harvested was 1200, 1340, 910 and 550 for treatments T1, T2, T3 and T4, respectively. We thus estimate that one could expect to harvest 10 plantlets per year from each plant, which means that in the second year of cultivation the area planted could be increased by a factor of 10.

3.2. Distribution of leaf biomass

Fig. 5 shows the relation between the production of photosynthetic tissue and gel as a function of fresh tissue mass and total leaf weight for the different treatments, demonstrating that a greater proportion of gel was formed by the plants of treatments T2 and T3.

The relation between fresh leaf weight and gel and photosynthetic tissue (Ph) was linear for all treatments. The production of gel was greater in treatments T2 and T3 than in T1, while in T4 the

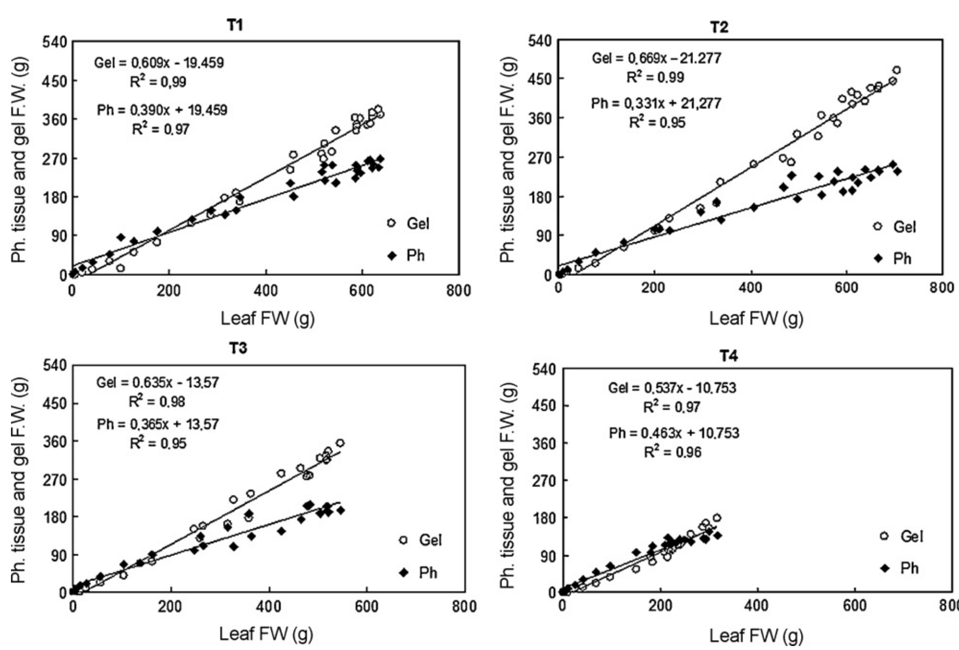

Fig. 5. Relation between fresh weight (FW) gel and photosynthetic tissue (Ph) produced as a function of total leaf weight by treatments of Aloe Vera. $n_{T1} = 32$, $n_{T2} = 31$, $n_{T3} = 27$, $n_{T4} = 25$.

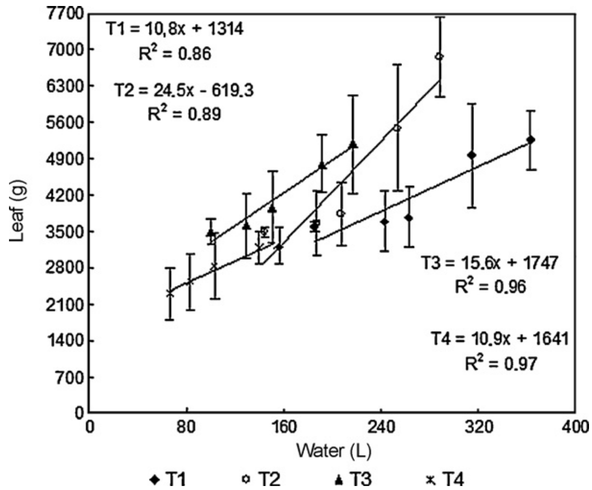

Fig. 6. Relation between biomass produced and water applied by irrigation in plants of Aloe Vera. $n = 10$ leaf by treatment. Bars indicate the standard error. The slopes of the relations represent the values of WUE ($g L^{-1}$).

production of gel was the same as the production of photosynthetic tissue, that is, the slopes coincided. In proportional terms, the quantity of gel produced per unit of fresh leaf was 60.9, 66.9, 63.5 and 53.7% for treatments T1, T2, T3 and T4, respectively; thus the plants of T2 and T3 showed the greatest photosynthetic efficiency for gel production.

Based on an analysis of the slopes of Fig. 5, the ratio of gel accumulation per unit quantity of photosynthetic tissue was greatest in T2 plants, followed by T3 and T1, with a significantly lower accumulation in T4; the rates were 2.02, 1.73, 1.56 and 1.15 for T2, T3, T1 and T4, respectively. The molecules that form the gel are polysaccharides such as acemannans, glucans, fructans and sugars, all molecules which retain water (Femenia et al., 2003; Im et al., 2005; Chow et al., 2005).

3.3. Seasonal WUE

Fig. 6 shows the seasonal relation between leaf biomass produced and the amount of water used for this production, in five evaluations during the experimental period. In each case there was a linear relation between the variables, but with different slopes. The total production of aerial biomass is a function of water availability; more water produces more aerial biomass. However, plants of T2 had the greatest production of total green biomass, followed by the plants of T3, T1 and T4. The slope of the biomass produced per quantity of water applied corresponds to WUE, thus the greatest values of WUE were those of the T2 and T3 plants, which were 24.5 and 15.6 $g L^{-1}$, while the lowest values were those of the T4 and T1 plants, with 10.9 and 10.8 $g L^{-1}$, respectively.

Water supply equivalent to 20% of the evaporative atmospheric demand had a negative influence on the value of WUE due to water excess, while as expected, the lower water availability had a negative influence on WUE in the plants of T4, due to deficit. Watering to produce 15% of ETo proved to be the minimum quantity of water to obtain the maximum production of aerial biomass. We suggest that in these conditions Aloe Vera reached its potential yield.

Similar to the above results, the linear relation between gel produced and water utilized during the experimental period varied as a function of water availability; the slopes are the WUE for gel production per unit quantity of water applied by plant (Fig. 6). The least efficient treatments were the extremes, T1 and T4. The maximum gel production was registered in T2 plants, followed by T3 plants, with values of 17.7 and 13.1 $g L^{-1}$; the differences were not significant. The amount of water applied in these cases was close to the minimum to achieve maximum gel production in these edapho-climatic conditions.

Table 2
Percentage (%) of squares sum of variance combined for leaf biomass and gel ($n = 10$).

	% sum of square	
	Biomass	Gel
Date (D)	47.6***	48.7***
Treatment (T)	41.1***	40.0***
D × T	11.3**	11.3***

*$P \leq 0.05$.
** $P \leq 0.01$.
*** $P \leq 0.001$.

We performed two way ANOVAs both for leaf biomass and gel production. In both cases, both sampling date, treatment and their interactions were significant (Table 2). This indicates that there were differences between treatments, but that the effect of the treatments was different over samples. The ranking of the treatments for leaf biomass changed over time; in the first sample T1 plants had the greatest biomass, but by the fifth sample T2 plants had the largest value (Fig. 6). Quantitative differences between samples were observed for gel production (Fig. 7), but not differences in ranking; the increase in gel in T2 plants was greater than that for T1 plants, as the slopes of their regressions indicate (Figs. 6 and 7).

3.4. WUE at the level of marketable leaves

Another way to express WUE is in terms of marketable leaves (60–70 cm long; 14 cm wide and 2–3 cm thick; mean weight 650 g). Considering only 10 leaves per plant per treatment and the same volume of water for this production, the values of WUE were reduced by about 50%, if we consider that the maximum number of leaves per plant should be 21.

About 95% of the leaf biomass of Aloe Vera was water and gel in the plants of T2 and T3, and 94% in T1 and T4. The remaining 5–6% was photosynthetic tissue, cuticle and the spines which surround the leaf. However, 60 and 59% of the total was gel in T2 and T3 plants, reducing to 54 and 46% in T1 and T4, respectively. Thus both at the level of the individual plant and at the harvestable leaf level the same tendency is maintained; the plants of T3 and T2 had greater production and greater efficiency in water use, followed by, T4 and T1 in that order (Table 3).

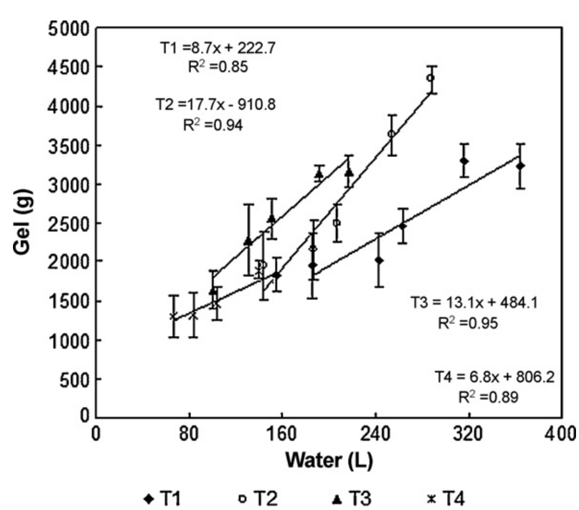

Fig. 7. Relation between gel produced and water applied by irrigation in plants of Aloe Vera. $n = 10$ leaf by treatment. Bars indicate standard error. The slopes of the relations represent the values of WUE ($g L^{-1}$).

Table 3
Mean WUE values at the stage of harvestable leaf in Aloe Vera at the end of experimental period ($n = 10$).

Variable	WUE ($g L^{-1}$)					
	T1	T2	T3	T4	CV	R^2
Fresh leaf biomass	16.61 a	24.33 c	27.34 d	22.60 b	7.65	0.94
Photosynthetic tissue	7.13 a	8.97 a	10.94 b	11.53 c	6.15	0.94
Gel	9.07 a	14.90 b	16.43 b	11.12 c	12.31	0.90
Dry leaf biomass	1.10 a	1.27 b	1.48 c	1.58 d	11.91	0.84
Photosynthetic tissue	0.92 a	1.04 a	1.22 b	1.22 b	13.37	0.80
Gel	0.18 a	0.23 b	0.25 c	0.25 c	11.63	0.88

(a,b,c,d) Means in the same row with different letters are different ($P \leq 0.05$). CV: coefficient of variation and R^2 coefficient of determination.

4. Discussion

Many factors determine crop production. Thus, in order to decide how much irrigation should be applied, not only water availability and the species must be considered, but also the physical properties of the soil related to water retention, and the climatic conditions that determine the atmospheric evaporative demand. The definition of the amount of water per treatment in terms of the atmospheric evaporative demand, the capacity of water retention of this soil and information on the metabolic pathway of Aloe Vera allowed us to determine that in one of the intermediate water treatments (T2) we managed to produce the maximum growth and greatest gel production with the minimum quantity of water. In these conditions, the growth, productivity and efficiency in water use followed a model of a normal distribution, in that the expected responses had their maximum expression in treatments 2 and 3, while in treatment 1 the responses reflected an excess of water and in T4 a deficiency of water.

The daily variation in soil water content allowed us to register the differential response of water uptake by roots in the treatments. These conditions demonstrated the plasticity of roots to absorb at different rates. This water absorption was in direct relation with the water requirements of the plant. Apparently the plants of T2 represent the optimum rate of water absorption. This is because treatment 1, which received water equivalent to 20% of the ETo had an excess of water, producing root anoxia, and because the plants of T4, which received water equivalent to 5% of the ETo, did not receive enough water for root growth. Thus in these conditions there was an excess of water in one case and a water deficit in the other. Root development and characteristics of the root system depend on the species, however this can be altered by environmental conditions, including soil physical conditions (Richards, 1983); this in conjunction with soil hydraulic properties are important factors that affect the absorption process (Acevedo, 1979; Steudle, 2000). Between environmental conditions are the physical and chemical properties of soil, in addition to the variables that affect the aerial development of cultures. Water is essential for root growth, as in any other physiological process that depends on cell elongation, to provide a force that causes expansion (Acevedo, 1979). Under normal conditions, roots receive the oxygen needed for respiration from the soil. However, when the soil is saturated with water, gas exchange is reduced to only the most superficial portion of the soil, leading to a situation of root anoxia. The available oxygen is quickly consumed by the microbial flora of the soil, stopping the absorption and transport of water and salts into the root (Richards, 1983; Azcon-Bieto and Talón, 2000).

The lower availability of soil water was accompanied by a reduction in the number of new leaves and plantlets. The processes associated with vegetative and reproductive growth are thermodependent; temperature is the main factor controlling normal growth of the crop, and determines the yield. At the individual plant level the differences between T1, T2 and T3 were not significant, while all 3 were different significantly to T4 plants ($P < 0.05$, Fig. 4A). To maintain productivity over time, the number of leaves harvested should be equivalent to the number of new produced during the year and for the conditions of the experimental site. The greatest production of leaf biomass was recorded during the summer, harvested leaves were of commercial size and weight, and were located on the periphery. The leaf optimal number per plant should be 21. The number of leaves usually harvested for market purposes is from 4 to 6 per plant per year, these are from 50 to 70 cm long and have a mean weight of about 650 g, and the experimental plan can utilized by farmers

Gel content and photosynthetic tissue increased linearly with the increase in fresh leaf weight. As the leaves grew, the conversion of assimilates to gel increased significantly in the plants of T2 and T3 compared to T1; however, in T4 plants a large part of the aerial biomass was maintained as photosynthetic tissue. During the experimental period, the plants with least water availability (T4) maintained their metabolic activity and no mortality was registered, which shows their natural resistance to conditions of low water availability.

Our results suggest that the WUE of Aloe Vera under these levels of water availability represent the highest values ever recorded, only at the level of marketable leaves. There was a linear relation between biomass production and water supplied; the effect of the treatment is given by the slope of the relation and represents the water use efficiency.

The differences in the WUE for the production of leaf biomass and for the production of gel produced by the treatments were not determined by the amount of water, but rather by the use of the available water; the plants of T2 and T3 were the most efficient compared to those of T1 with the maximum, and T4 with the minimum availability of water. At the individual plant level, the values of WUE of Aloe Vera are comparable to those reported in *Opuntia* and *Agave* (Silva and Acevedo, 1995; Nobel, 1994). These values confirm the high WUE of CAM plants compared to C3 and C4 species. The biomass reduced significantly under water stress, which tended to increase the value of WUE. Martínez et al. (2003) suggested that high yields under conditions of limited of water availability are associated with low WUE values, due mainly to high rates of evapotranspiration. The characteristics associated with a low potential yield, such as small plants or a short growing period, are associated with high WUE since they reduce the use of water (Anderson et al., 2003; Liu et al., 2005). Our results show that in Aloe Vera high yield may be associated with high water use efficiency, which contradicts this idea.

Mean values of WUE ranged from 27 to 10 $g L^{-1}$; the most efficient plants were T2 and T3 the least efficient were the T1 plants, with intermediate values for T4, given that in plants lower water availability tends to increase WUE. Nobel (2001) reported that WUE values in CAM plants may be five or more times greater than C3 plants and two to three times greater than C4 plants. However, the values we report in Aloe Vera are even greater (Table 3), an order of magnitude greater than the WUE of C4 plants, only comparable to the values reported by Silva and Acevedo (1995) for ten provenances of *Opuntia* sp. (22–54 $g L^{-1}$). A high WUE may be associated with a low growth and yield (Clavel et al., 2005; Fengjun et al., 2006; Wu et al., 2008). However, our results show that a high WUE may be associated with a high productivity in terms of leaf biomass. The determination of WUE is important, because it gives an idea of the intraspecific variation in the capacity of a plant species to produce under limiting water conditions. A number of authors have reported increments in WUE in C3, C4 and CAM plants challenged by water stress, indicating a greater effect of water deficit in transpiration than in the incorporation of CO_2 into tissues (Silva, 1990; Martínez et al., 2003). Other investigators have reported decreases in WUE values (Anderson et al., 2003); however, it has also been suggested that this value is constant for a species and does not change because of lack of water (Silva, 1990; Hsiao et al., 2007). It should be noted that these increases or decreases in WUE were not obtained under optimum conditions (minimum amount of water necessary for maximum production of aerial biomass) considering soil water retention, the metabolic pathway of the species and the atmospheric evaporative demand.

At a commercial density of 10,000 plants ha^{-1} and for similar edapho-climatic conditions, the maximum productivity should reach 127 ton ha^{-1} $year^{-1}$, which is comparable to the value of 108 ton ha^{-1} $year^{-1}$estimated for the production of green biomass in *Opuntia ficus indica* (Flores-Hernández et al., 2004). Rodríguez-Garcia et al. (2007), in a greenhouse experiment with Aloe Vera, found a significant reduction in leaf biomass yield due to lower water availability; they estimated yields of 44.5–58.5 ton ha^{-1} $year^{-1}$ for a density of 10,000 plants ha^{-1}. We found the highest yield of gel in T2 plants, with a mean of 7.6 kg $plant^{-1}$. At a density of 10,000 plants ha^{-1}, this would give a productivity of 76.2 ton ha^{-1} $year^{-1}$ in 4-year-old plants if all aerial biomass were harvested.

Blum (2005) concluded that it is mainly constitutive characters which affect water use and avoid dehydration under stress, and that a high WUE is more a function of low water use than a net improvement in the production in biomass and/or the biochemistry of assimilation.

The range of water treatments used in this experiment included sufficiently severe treatments to reduce WUE in both extremes, one from an excess and the other from a deficiency (T1 and T4). The results suggested that the success of a crop in conditions of limited water availability can only be evaluated by considering the total soil–plant–atmosphere system in terms of potential yield, water use efficiency and resistance to drought. We suggest that we considered the total system of Aloe Vera, and that by giving the plants of T2 the minimum necessary quantity of water we obtained the maximum yield in green biomass and gel, as well as the maximum water use efficiency.

5. Conclusions

The results of this study show that Aloe Vera is a promising crop for arid zones, with high yield of leaf biomass production and thus a high gel production, associated with a high WUE and low water requirements.

The principal conclusion of this experiment was the precise definition of the water requirement for this species under this edapho-climatic condition. This definition, based on the interaction among metabolic pathway, atmospheric evaporative demand and soil water retention characteristics, was 15% of the reference evapotranspiration. This condition gave the maximum aerial biomass and gel production for unit of water utilized, and thus the greatest water use efficiency.

This report contributes to the understanding of the key factors of potential yield and water use efficiency; we conclude that in the case of Aloe Vera, these factors are not mutually exclusive, but rather are complimentary if the total system is considered.

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