Relevance of sprinkler irrigation time of the day on alfalfa forage production

Jose Cavero^{a,*}, Jose M. Faci^b, Antonio Martínez-Cob^{a,c}

^a *Departamento de Suelo y Agua, Estación Experimental de Aula Dei (CSIC),
Avda. Montañana 1005, 50059 Zaragoza, Spain.*

^b *Unidad de Suelos y Riegos (Unidad Asociada EEAD-CSIC), Centro de
Investigación y Tecnología Agroalimentaria (CITA-DGA), Avda. Montañana
930, 50059 Zaragoza, Spain.*

^c *Dr. A. Martínez-Cob passed away during this research.*

* Corresponding author.

E-mail address: jcavero@eead.csic.es (J. Cavero)

ABSTRACT

Nighttime sprinkler irrigation usually results in lower water losses and higher irrigation uniformity compared with daytime sprinkler irrigation due to lower wind speed. However, daytime sprinkler irrigation modifies the microclimatic conditions within the crop canopy which could result in improved crop growth. We studied during three years the effect of daytime and nighttime irrigation on the yield, N content, N uptake, water use efficiency, microclimate and canopy temperature of an alfalfa (*Medicago sativa* L.) crop irrigated with a solid-set sprinkler system in a semiarid Mediterranean climate. Two irrigation treatments were tested: daytime irrigation and nighttime irrigation. The same irrigation amount was applied in both treatments (552 to 757 mm year⁻¹). The water losses of daytime irrigation (10%) tripled the water losses of nighttime

irrigation (3%). In one year, daytime irrigation decreased the mean Christiansen coefficient of uniformity (CU) by 4% and the seasonal CU by 2%. Microclimatic and canopy temperature changes during sprinkler irrigation were higher for daytime irrigation as compared to nighttime irrigation. Daytime irrigation slightly reduced the soil water content of the surface layer (0-0.3 m). The actual seasonal crop evapotranspiration was slightly higher (+3.7%) in the daytime irrigation treatment compared to the nighttime irrigation treatment only in one of the years. The annual alfalfa forage yield (16 to 22 Mg ha⁻¹), N content (3.16 to 3.38 %), N uptake (514 to 740 kg ha⁻¹) and water use efficiency (17.7 to 25.9 kg ha⁻¹ mm⁻¹) were not affected by the irrigation time of the day. Although nighttime sprinkler irrigation results in some water saving, daytime sprinkler irrigation of alfalfa can be performed if necessary.

Keywords: Water losses

Irrigation uniformity

Semiarid

Microclimatic changes,

Water use efficiency

Abbreviations: CIR, crop irrigation requirement; CWSI, crop water stress index; CU, Christiansen coefficient of uniformity; ETo, reference evapotranspiration; ETc, crop evapotranspiration; GMT, Greenwich Mean Time; WDEL, wind drift and evaporation losses.

1- INTRODUCTION

In order to reduce investments costs, sprinkler irrigation systems are usually designed to operate during daytime and nighttime hours. Irrigation efficiency depends on both water losses and uniformity of water distribution. For sprinkler irrigation systems these two factors are affected by the environmental conditions during the irrigation event, which are very different during daytime and nighttime irrigation events (Cavero et al., 2008; Playán et al., 2005).

In sprinkler irrigation wind is the main environmental factor affecting water losses (Playán et al., 2005) and irrigation uniformity (Dechmi et al., 2003; Kincaid et al., 1996; Seginer et al., 1991; Tarjuelo et al., 1999a). It is well known that wind speed is higher during daytime than during nighttime (Doorenbos and Pruitt, 1977). Consequently, higher water losses (Cavero et al., 2008; Playán et al., 2005) and lower irrigation uniformity (Cavero et al., 2008) are found during daytime irrigation compared to nighttime irrigation.

The irrigation water evaporated during the sprinkler irrigation changes the microclimate of the irrigated area during the irrigation event and some time (2-3 hours) after the irrigation event (Cavero et al., 2009; Playán et al., 2005; Robinson, 1970; Tolk et al., 1995; Urrego-Pereira et al., 2013a,b). These changes (decrease of VPD and temperature of the air) are more relevant during daytime irrigation and cause some physiological changes: a decrease of crop transpiration (Cavero et al., 2009; Martínez-Cob et al., 2008; McNaughton, 1981) and crop canopy temperature (Cavero et al., 2009; Saadia et al., 1996; Steiner et al., 1983; Tolk et al., 1995), and an increase of leaf water potential (Cavero et al., 2009; Howell et al., 1971). Moreover, during the daytime

sprinkler irrigation events the net photosynthesis of crops can be affected (Urrego-Pereira et al., 2013c).

Previous work with maize has shown that daytime sprinkler irrigation with a solid-set system in a Mediterranean climate decreased the grain yield by 5 to 13 % compared to nighttime sprinkler irrigation (Cavero et al., 2008; Urrego-Pereira et al., 2013b). This yield decrease was mainly caused by the lower irrigation uniformity of daytime irrigation (Urrego-Pereira et al., 2013b) and by the decrease of maize net photosynthesis during the daytime irrigation events (Urrego-Pereira et al., 2013c). The reduction of net photosynthesis of maize during sprinkler irrigation was related both with the high wettability of maize leaves, which reduced the exchange of CO₂, and with the reduction of canopy and air temperature, which resulted in temperatures below the optimum for photosynthesis of maize (Urrego-Pereira et al., 2013c). Thus, daytime sprinkler irrigation with solid-set systems under similar climatic conditions to that study site should be avoided for maize due to decreased yield.

Alfalfa for forage production is a main irrigated field crop in Mediterranean areas. It is rather different to maize in terms of sensitivity to water stress, crop height, leaf water wettability and optimal temperature for growth. Alfalfa for forage is considered to be less sensitive to water stress than maize due to its deep rooting system and because it does not have a phenological stage very sensitive to water stress as maize (Sheaffer et al., 1988). Sánchez et al. (2010a,b) reported that irrigation uniformity of sprinkler irrigation was higher for alfalfa than for maize due to the lower plant height of alfalfa. They also found higher soil water recharge with sprinkler irrigation in alfalfa compared to maize. This could be related to the higher hydrophobicity of

alfalfa leaves (Holder, 2012; Urrego-Pereira et al., 2013c). Urrego-Pereira et al. (2013c) found that daytime sprinkler irrigation with a solid-set system at the same Mediterranean site did not affect net photosynthesis of alfalfa. The low wettability of alfalfa leaves prevented sprinkler irrigation water from interfering with the CO₂ uptake and therefore did not decrease net photosynthesis. Moreover, sprinkler irrigation did not decrease air and canopy temperature below the optimum range for photosynthesis of alfalfa.

There is no field data about how the sprinkler irrigation time of the day affects the alfalfa forage yield and quality. The main objective of this research was to study the effect of daytime versus nighttime irrigation on the forage yield and quality and water use efficiency of an alfalfa crop using a solid-set sprinkler irrigation system. We also studied the microclimatic and alfalfa canopy temperature changes due to daytime and nighttime sprinkler irrigation.

2- MATERIALS AND METHODS

2.1- Experimental site

The field experiment was carried out during three years (2012-2014) in a 2.34 ha field irrigated with solid-set sprinkler system, located at Zaragoza, Spain (41°43'N, 0°48'W, 225 m altitude). The climate is Mediterranean semiarid with long-term annual averages of 14.1 °C for air temperature, 298 mm for precipitation, and 1243 mm for grass reference crop evapotranspiration (ET_o). The soil is clay loam and classified as Typic Xerofluvent (Table 1).

2.2- Experimental layout

The experimental field was divided in twelve irrigation sectors which were irrigated independently by four sprinklers each (Fig. 1). The borders of the field

were irrigated independently of the main twelve irrigation sectors. The sprinkler spacing was a square of 18 m x 18 m. The impact sprinkler and nozzles were manufactured in brass (RC-130, Riegos Costa, Lérida, Spain). The sprinkler has a vertical throw angle of 25°, the nozzle diameters were 4.4 mm (main) and 2.4 mm (auxiliary), and the nozzle height was 2.50 m above the soil surface. The nozzle operating pressure was kept constant at 0.3 MPa with a hydraulic pressure control valve. Sprinkler application rate was 5 mm h⁻¹ and the wetted radius was 15 m. The irrigation volume was measured with an electromagnetic flow meter (Promag 50, Endress+Hauser, Reinach, Switzerland) with ±0.5% measurement error.

Alfalfa cv. Aragón was planted on 20 Sept. 2011 at a planting rate of 33 kg/ha. The previous crop was wheat (*Triticum aestivum* L.). Several sprinkler irrigation events of 5 to 10 mm were applied on Sept.-Oct. 2011 after planting to promote the emergence of alfalfa. A total of 14 irrigation events and 105 mm were applied. Fertilization consisted of 200 kg ha⁻¹ P₂O₅, and 200 kg ha⁻¹ K₂O applied on March every year. Pests control was carried out following the best management practices provided by the Pest Control Centre of Aragon. No herbicide was applied during the experiment.

2-3- Irrigation treatments

The meteorological data recorded at a weather station over grass located 1 km southwest from the experimental field were used to compute the reference ET_o using the FAO Penman-Monteith method (Allen et al., 1998). Crop coefficients (K_c) were calculated as a function of thermal time considering the duration of the four phases proposed by Allen et al. (1998) and the K_c initial, midterm and final values according to the meteorological conditions of the

location of the experiment (Martínez-Cob and García-Vera, 2004). The use of thermal time to calculate the K_c for alfalfa has been recommended by Sammis et al. (1985). Thermal time was computed as the cumulative daily difference between daily mean air temperature and a basal air temperature of 6 °C (Breazele et al., 1999; Sharrat et al., 1989) and considering a thermal time of 360 °Cday for the first harvest and 500 °Cday for the rest of the harvests. Daily crop evapotranspiration of alfalfa (ET_c) was then obtained as the ET_o multiplied by the K_c .

The crop irrigation requirements (CIR) were calculated weekly as the difference between ET_c and the effective precipitation, which was estimated as 75% of precipitation (Dastane, 1978). The initial soil water content above the wilting point at the 0-1.6 m depth was considered as available for the crop and subtracted from the CIR at the beginning of the crop season. The irrigation amount applied to the crop was equal to the CIR. Two irrigation treatments were tested: daytime and nighttime irrigation. Daytime irrigation generally started at 1000 Greenwich Mean Time (GMT) while nighttime irrigation started at 2200 GMT of the same day. The same irrigation amount was applied to both treatments. The weekly irrigation amount was generally applied in two irrigation events that lasted 4 to 6 hours depending on CIR. The experimental plot was the area surrounded by the four sprinklers of each irrigation sector (Figure 1) and has an area of 324 m². The area outside was not considered because it received water from two different irrigation sectors. The experimental design was randomized with six replicates per treatment. The experimental plots irrigated during daytime in 2012 (Figure 1) were irrigated during nighttime in 2013, and were irrigated during daytime in 2014. In 2014 the soil water content

measured at the beginning of the season indicated that the plots that had been daytime irrigated in 2013 had a lower soil water content (-12 mm) compared to those nighttime irrigated in 2013. Thus, an irrigation of 12 mm was applied in those plots on 24 March 2014 in order to have the same initial soil water content in the two irrigation treatments.

The irrigation efficiency was evaluated determining the wind drift and evaporation losses (WDEL) (Frost and Schwalen, 1955) and the uniformity of application through the coefficient of uniformity (CU) (Christiansen, 1942). For this, one grid of catch cans was placed at one experimental plot irrigated during daytime and another grid of catch cans was placed at one experimental plot irrigated during nighttime (Fig. 1). Each grid had 25 catch cans, which were arranged in five rows and five columns with a distance of 3.6 m between catch cans. The catch cans were made of plastic, with an opening diameter of 0.18 m and a maximum capacity of 45 L m⁻². The catch cans were marked in mm with a resolution of 1 mm in order to read directly the collected irrigation depth just after each irrigation event. The catch cans were placed above the crop canopy at 1 m above the soil surface.

The WDEL were calculated as:

$$WDEL = 100 \left(\frac{I_{fm} - I_{cc}}{I_{fm}} \right) \quad (1)$$

where I_{fm} (mm) is the applied irrigation depth measured with the flow meter; and I_{cc} (mm) is the mean value of collected water depth in the catch cans.

The CU was computed using the methodology described by Christiansen (1942) as:

$$CU = 100 \left[1 - \frac{\sum (x_i - I_{cc})}{I_{cc} n} \right] \quad (2)$$

where $x_i - I_{cc}$ is the deviation of the individual observations from the mean value of collected water depth in the catch cans, and n is the number of catch cans of the grid.

2.4- Soil water content

One soil core of 0.05 m diameter was taken from the centre of each experimental plot on September 2011 to a depth of 1.8 m at 0.30 m intervals and the gravimetric soil water content was determined.

Two 1.80 m plastic tubes were installed in the soil of each experimental plot on March 2012. One was located centred in the 18 m x 18 m square of the plot and the other at 4 m of one corner (Fig. 1). The gravimetric soil water content was determined at 0.3 m intervals in the soil cores taken for the installation of the plastic tubes. A capacitance sensor (Diviner 2000, Sentek Pty Ltd, Stepney, Australia) of 1.60 m length was used to take measurements every 0.10 m. In order to calibrate the capacitance probe, five 1.80 m plastic tubes were located close to the main plots. On 20 May 2012 the capacitance probe was used to get readings of the five tubes every 0.10 m. Immediately undisturbed soil samples were taken to determine the volumetric soil water content. A regression equation was derived from the capacitance readings and the volumetric soil water content. Measurements of soil water content with the capacitance probe were made with a two-three week frequency during the crop season. The average values of the soil water content measured in the two tubes installed in each experimental plot were used for statistical analysis.

2.5- Microclimatic and crop canopy temperature changes

Two automatic weather stations were installed just at the border of two experimental plots (one daytime irrigated and one nighttime irrigated) in order

not to interfere with alfalfa harvesting operations (Fig. 1). These weather stations were used to record the temperature and VPD of the air and the crop canopy temperature during the crop season so comparisons could be made between the plot that was irrigated and the plot that was not irrigated at that time.

Two temperature and relative humidity probes (HMP45C, Vaisala, Helsinki, Finland) were installed at each weather station at two heights: a) 1.0 m above the soil surface, and b) 2.0 m above the soil surface. Each probe was installed inside a shield URS1 (Campbell Scientific, Logan, USA) which protected it from irrigation water. The accuracy of the probes was ± 0.3 °C for temperature and ± 3 % for relative humidity. The maximum crop canopy height was 0.8 m. The air temperature and relative humidity were measured every 10 s and the 5-min mean values were recorded in a datalogger (CR1000, Campbell Scientific Inc, Logan, UT). The VPD was calculated from the air temperature and relative humidity data (Allen et al., 1998). An infrared thermometer (IR120, Apogee Instruments Inc., Roseville, CA, USA) with an accuracy of ± 0.2 °C was installed in each of the automatic weather stations to measure the crop canopy temperature. The infrared thermometer was located at 2.0 m above the soil surface with an angle of 45 ° and was oriented towards the south measuring inside the experimental plot. Canopy temperature measurements were taken at 10 s intervals and average values every 5 min were recorded in the dataloggers.

In one of the weather stations, a pyranometer (LP02, Hukseflux, Delft, The Netherlands) was installed at 2.0 m above the soil surface to measure solar

radiation at 10 s intervals and average values every 5 min, that were recorded in the datalogger.

The crop water stress index (CWSI) was calculated daily for the two irrigation treatments with the data measured in the two experimental plots: air temperature and VPD data measured at 2 m, and canopy temperature. CWSI was calculated for those days that the experiment was not irrigated and considering for each alfalfa harvest cycle that the thermal time was higher than a third of the total to ensure that the alfalfa canopy was covering the soil surface. Cloudy days were excluded from CWSI calculation. The average data measured from 12:00 GMT to 14:00 GMT was used to calculate the daily CWSI. The lower and upper baselines for the relationship between VPD and canopy minus air temperature proposed by Abdul-Jabbar et al. (1985) were used to calculate the CWSI.

2.6- Alfalfa forage yield and N content

Six alfalfa harvests were performed each year. A commercial cutting machine 3-m wide was used to cut the alfalfa at 7 cm above the soil surface. One day after cutting, the alfalfa forage in two samples (2-m x 6-m) was taken at each experimental plot. The alfalfa forage of each sample was weighted and a subsample was taken and dried at 60 °C to determine the moisture content of the alfalfa forage. Once dried, the subsample was grinded and analysed to determine the N content by combustion (TruSpec CN, LECO, St. Joseph, MI, USA). The forage yield and N content average values of the two samples of each experimental plot were used for statistical analysis. The rest of the alfalfa was left in the field for sun drying after cutting during three days and then removed and transported to a dehydration plant. All tillage operations were

made with commercial equipment. The N uptake was obtained from the forage yield and N content.

2.7- Water use efficiency

The water balance was used to calculate the actual alfalfa ET at each plot during each season. Irrigation applied, rainfall and the change in soil water content between the closest measurement date to the start of alfalfa growth at winter time (late February) and to the last harvest cycle (October) were used. Soil water content data suggested that water did not leach below the measurement depth (1.60 m). The water use efficiency was calculated for each plot as the ratio between the seasonal alfalfa forage yield and the seasonal actual ET of alfalfa.

2.8- Statistical analysis

The effect of irrigation time on soil water content, alfalfa forage yield, N content, N uptake, seasonal alfalfa actual ET and water use efficiency was analyzed with ANOVA at a level of significance of $P = 0.05$.

For each irrigation event the air temperature and VPD and the crop canopy temperatures of the experimental plot that was irrigated were compared with that of the experimental plot that was not irrigated. The irrigation events considered were those when thermal time was more than a third of total for each alfalfa harvest cycle. Comparison was made of the average values for the periods: 1 hour before the irrigation event, during the irrigation event, and 1 and 2 hours after the irrigation event. Comparison was made using a paired t-test and a level of significance of $P = 0.05$.

For each alfalfa harvest cycle the daily values of the CWSI calculated for the two irrigation treatments were compared using a paired t-test and a level of significance of $P = 0.05$.

3- RESULTS

3.1- Irrigation applied and characteristics of irrigation events

The soil available water at planting was 41 mm in 2012, 72 mm in 2013, and 84 mm in 2014. The seasonal rainfall was 215 mm in 2012, 271 mm in 2013, and 178 mm in 2014 (Fig. 2). The calculated ET_c ranged from 832 mm to 941 mm and the CIR ranged from 556 mm to 746 mm (Table 2). The seasonal irrigation amount applied was close to the CIR with a difference of only 1 to 11 mm, values that represent less than 1.5 % of the CIR (Table 2; Fig. 2). In general, the weekly applied irrigation amount was close to the CIR (Fig. 2), but some discrepancies occurred during the season, mostly due to rainfall.

The average wind speed during the daytime irrigation events was higher than during the nighttime irrigation events all years and all alfalfa harvest cycles (Table 3). The average daytime wind speed during each alfalfa harvest cycle ranged from 1.5 to 4.4 m s⁻¹, and on 70% of the alfalfa harvest cycles the wind speed was higher than the threshold value of 2.1 m s⁻¹ reported by Faci and Bercero (1991) for adequate irrigation uniformity in our region. However, for the nighttime irrigation events, the average wind speed was only higher than the indicated threshold in one alfalfa harvest cycle period.

The average WDEL of the daytime irrigation events for each alfalfa harvest cycle period ranged from 3.0 to 19.6 %, while the average WDEL of the nighttime irrigation events for each alfalfa harvest cycle period ranged from 0 to

6.5 %. In general, greater losses of water occurred with higher wind speeds during daytime irrigations, but the relationship was not so clear for the nighttime irrigations. The annual average of WDEL was around 10 % for the daytime irrigation events, while it was between 1 and 4 % for the nighttime irrigation events (Table 3). The seasonal value of WDEL ranged from 59 to 71 mm for the daytime irrigation treatment while it ranged from 7 to 29 mm for the nighttime irrigation treatment.

The annual average CU was similar for daytime and nighttime irrigation events in 2012 and 2013 (Table 3). When considering the seasonal irrigation amounts collected at each catch can, the seasonal CU was also the same for both daytime and nighttime irrigation in 2012 and 2013. However, in 2014 the average CU during daytime irrigation events was lower than during nighttime irrigations (Table 3) and, similarly, the seasonal CU was lower for daytime irrigation (92%) compared to nighttime irrigation (94%). The lower CU for daytime irrigation events in 2014 was related to the higher wind speed. Considering the average CU at each alfalfa harvest cycle there were only four harvest cycles where the difference of CU between the irrigation treatments was higher than 5% (one in 2012 and the others in 2014) and in all of them the CU was higher in the nighttime irrigation treatment. The higher difference between the daytime and nighttime irrigation events was found in harvest cycle 4 of 2014, when the CU of daytime irrigation events was only 76% but the CU of nighttime irrigation events was 88%. This high difference was due to the high wind speed at the daytime irrigation events (4.40 m s^{-1}).

3.2- Soil water content

The soil water content was close to the wilting point in the 0-0.6m depth before starting the irrigation the first year of the experiment (2012) (Fig. 3). However, it was above the wilting point at deeper soil layers. During the first year of the experiment, after the irrigation started the soil water content in the 0-0.3 m soil layer was higher in the daytime irrigation treatment compared to the nighttime irrigation treatment in two out of twelve dates (Fig. 3). However, in one date the soil water content in the 0.3-0.6 m soil layer was higher in the nighttime irrigation treatment compared to the daytime irrigated treatment. At deeper soil depths, there were not differences of soil water content between the irrigation treatments.

During the second year of the experiment (2013), after the irrigation started the soil water content in the 0-0.3 m soil layer was higher in the nighttime irrigation treatment compared to the daytime irrigation treatment in six out of ten dates (Fig. 3). At deeper soil depths, there were not differences of soil water content between the irrigation treatments.

As explained in the Materials and Methods, before starting the irrigation treatments in 2014 the soil water content measured at the plots that had been daytime irrigated in 2013 (nighttime irrigated in 2014) had a lower soil water content compared to those nighttime irrigated in 2013 (daytime irrigated in 2014) (Fig. 3). Thus, an irrigation was applied in those plots on 24 March 2014 in order to have the same initial soil water content before starting the irrigation treatments. During the third year of the experiment (2014), after the irrigation started the soil water content in the 0-0.3 m soil layer was higher in the nighttime irrigation treatment compared to the daytime irrigation treatment in

three out of ten dates (Fig. 3). Moreover, in one date the soil water content in the 0.3-0.6 m soil layer was also higher in the nighttime irrigation treatment compared to the daytime irrigation treatment. At deeper soil depths, there were no differences of soil water content between the irrigation treatments.

3.3- Microclimatic and crop canopy temperature changes

During the daytime irrigation events the air temperature above the crop canopy, at 1 m and 2 m above the soil surface, significantly decreased (Table 4). The decrease of air temperature due to the irrigation was slightly higher as the measurement height was closer to the soil surface and ranged from 0.9 to 1.3°C at 1 m and from 0.4 to 1.3°C at 2 m. During the hour following the irrigation events the decrease of air temperature was significant at 1 m all years but only one year at 2 m, and its magnitude (0.3 to 0.8°C) was lower than during the irrigation events (Table 4). The decrease of air temperature almost disappeared 2 h after the irrigation event finished. During the nighttime irrigation events the air temperature significantly decreased in two years but the decrease was lower than in the daytime irrigations, ranging from 0.3 to 0.9°C (Table 5). This decrease lasted for 2 h after the irrigation event finished.

During the daytime irrigation events the air VPD at the different measurement heights significantly decreased and its magnitude ranged from 0.19 to 0.33 kPa (Table 4). The decrease of air VPD due to the irrigation was slightly higher as the measurement height was closer to the soil surface in 2014. During the hour following the irrigation events the decrease of air VPD was significant but its magnitude was lower than during the irrigation event. The decrease of air temperature disappeared 2 h after the irrigation event finished.

During the nighttime irrigation events, the air VPD at the different measurement heights significantly decreased but the decrease was much lower than in the daytime irrigations, ranging from 0.04 to 0.11 kPa (Table 5). In general, this decrease lasted for 2 h after the irrigation event finished.

Alfalfa canopy temperature was significantly reduced during the daytime sprinkler irrigation events (Table 4). The mean reduction ranged from 0.7°C (2013) to 2.1°C (2014). Once the daytime irrigation finished the decrease of alfalfa canopy temperature disappeared (except in 2014 one hour after the irrigation). However, during the nighttime irrigation events the alfalfa canopy temperature was significantly reduced by the irrigation only in one year but it was decreased after the irrigation finished all years (Table 5).

In the first alfalfa harvest cycle, that generally corresponded to the period of March-mid April, the average daily value of CWSI was high and in two years (2012 and 2014) was slightly higher in the nighttime irrigated treatment while in 2013 was clearly higher in the daytime irrigated treatment (Table 6). The average daily value of CWSI in the harvest cycles 2 (mid April-May), 3 (June) and 4 (July) was not affected by the irrigation treatment in 2012 and 2014 but it was higher in the daytime irrigated treatment in 2013. The average daily value of CWSI in the harvest cycles 5 (August) and 6 (September-mid October) was not affected by the irrigation treatment in 2013 and 2014 but it was slightly higher in the nighttime irrigated treatment in 2012.

3.4- Alfalfa forage yield and N content

The annual alfalfa forage yield was not affected by the irrigation time of the day in any of the three years of the experiment (Table 7). When analysing the yield at each harvest cycle only in one out of 18 harvests the irrigation

1 treatment affected the alfalfa forage yield. It was in harvest 4 on 2014, when the
2 daytime irrigation reduced by 10 % the alfalfa yield compared to the nighttime
3 irrigation. As explained before, at this harvest the CU of the daytime irrigation
4 treatment was much lower than the CU of the nighttime irrigation treatment. In
5 any case, this difference found in one harvest did not result in differences in the
6 annual alfalfa forage yield between the two irrigation treatments.

7 The annual yield weighted average N content of the alfalfa forage was
8 not affected by the irrigation time of the day in any of the three years of the
9 experiment (Table 8). The N content was higher than 3% (considered as good)
10 in 88% of the alfalfa harvest cycles and the annual yield weighted average was,
11 generally, higher than 3.2%, which is considered as premium (Putnam et al.,
12 2008). Only in one out of 18 alfalfa harvest cycles the irrigation treatment
13 affected the alfalfa forage N content. It was in harvest 4 on 2014, when the
14 nighttime irrigation reduced the N content of alfalfa forage compared to the
15 daytime irrigation. The N uptake of the alfalfa forage was not affected by the
16 irrigation time of the day in any of the three years of the experiment and in any
17 of the alfalfa harvest cycles.

18 **3.5- Water use efficiency**

19 In one of the years the seasonal actual evapotranspiration calculated
20 with the water balance was slightly higher in the daytime irrigation treatment
21 compared to the nighttime irrigation treatment (Table 9). However, the water
22 use efficiency was not affected by the irrigation treatment in any year (Table 9).

4- DISCUSSION

The microclimatic changes caused by the sprinkler irrigation (decreased air temperature and VPD) were more pronounced during daytime irrigation events as found by others (Cavero et al., 2009; Liu and Kang, 2006). This was related with the higher WDEL during daytime irrigation. The microclimatic changes induced plant physiological responses such as the decrease in canopy temperature (Cavero et al., 2009; Liu and Kang, 2006; Saadia et al., 1996; Steiner et al., 1983; Tolk et al., 1995). The decrease in canopy temperature of alfalfa during the daytime irrigation events found in our study was lower to that found by Cavero et al. (2009) in the same plot for maize. This could be related to the fact that maize leaves are wettable while alfalfa leaves are non wettable (Urrego-Pereira et al., 2013c). Thus, water drops do not cover the alfalfa leaves during the irrigation, differently from maize, which could result in a lower cooling of alfalfa leaves.

The alfalfa forage yield obtained, 16 Mg ha⁻¹ in the first year and 20-22 Mg ha⁻¹ in the following years, is in the high range of reported from semiarid areas (Grimes et al., 1992; Isla and Aragüés, 2009; Lindenmayer et al., 2011; Lloveras et al., 2008; Sheaffer et al., 1988; Smeal et al., 1992). The irrigation time of the day did not affect the seasonal forage yield and its N content in any of the three experimental years. This is different from the 5-13% reduction of maize yield found with daytime sprinkler irrigation compared to nighttime sprinkler irrigation at the same plots (Cavero et al., 2008; Urrego-Pereira et al., 2013b). The different response of alfalfa to sprinkler irrigation time of the day compared to maize is due to several facts.

1 First, the average WDEL were lower in alfalfa (3% for nighttime irrigation
2 to 10% for daytime irrigation) as compared to maize (8% for nighttime irrigation
3 and to 20% for daytime irrigation) (Cavero et al., 2008; Stambouli et al., 2013;
4 Urrego-Pereira et al., 2013b), which resulted in more water available for the
5 alfalfa crop. Moreover, the difference of WDEL between the daytime and
6 nighttime irrigation was also lower for alfalfa (7%) than for maize (14%). The
7 lower WDEL for alfalfa compared to maize has also been reported by Sánchez
8 et al. (2010a), who found that this resulted in more soil water in alfalfa after
9 sprinkler irrigation.

10 Second, in alfalfa the average and seasonal irrigation CU was similar
11 between the daytime and nighttime irrigation in two years and only was reduced
12 with daytime irrigation in one year. This is similar to what was found by
13 Stambouli (2012) in alfalfa, but different from what was found for maize, where
14 CU was lower with daytime irrigation in three out of four years (Cavero et al.,
15 2008; Urrego-Pereira et al., 2013b). Besides, the average CU for alfalfa (85-
16 89%) was higher than for maize (75 to 84%), and higher than 85%, that is
17 considered as slightly affecting yield (López-Mata et al., 2010; Tarjuelo et al.,
18 1999b; Urrego-Pereira et al., 2013b). Sánchez et al. (2010a) also found higher
19 CU for sprinkler irrigated alfalfa compared to sprinkler irrigated maize, which
20 was due to the lower plant height of alfalfa that decreased the water interception
21 plane and allowed a better overlap of water emitted by the sprinklers (Sánchez
22 et al., 2010b). In this sense it is interesting to notice that the only harvest cycle
23 (one out of eighteen) when irrigation time of the day affected the alfalfa forage
24 yield was the one when the average of daytime irrigation CU was 76% while the
25 average of nighttime irrigation CU was 88%. The relevance of the reduction of

CU in the yield reduction of some crops has been studied by experimental and simulation work (Bruckler et al., 2000; Mantovani et al., 1995; Salmeron et al., 2012; Stern and Bresler, 1983). Thus, the maize yield reduction of 3 to 8% with a decrease of CU from 88% to 76% reported (Salmeron et al., 2012; Stern and Bresler, 1983) is close to the 10% alfalfa yield reduction found in our work at that harvest cycle.

Third, a previous study at the same location found that daytime sprinkler irrigation did not affect the net photosynthesis of alfalfa while it reduced the net photosynthesis of maize (Urrego-Pereira et al., 2013c). This result agrees with the similar forage alfalfa yield found in our work with daytime and nighttime sprinkler irrigation and with the reduction of maize grain yield with daytime sprinkler irrigation found in the above mentioned previous studies (Cavero et al., 2008; Urrego-Pereira et al., 2013b).

Finally, although daytime sprinkler irrigation decreased the soil water content in the surface soil layer on some dates and increased the CWSI in the summer alfalfa harvest cycles in one of the years, its deep rooting system and moderate sensitivity to waters stress (Sheaffer et al., 1988) could also explain that the alfalfa forage yield was not affected by the irrigation time of the day.

The actual seasonal crop evapotranspiration was slightly higher (+3.7%) in the daytime irrigation treatment compared to the nighttime irrigation treatment only in one of the years, probably due to the higher difference of the WDEL this year between the two irrigation treatments (11% for daytime and 1% for nighttime). Although nighttime irrigation could result in some water saving, the similar alfalfa forage yield, N content, and water use efficiency found in this

work indicates that daytime sprinkler irrigation of alfalfa can be performed if necessary.

5- CONCLUSIONS

In a similar previous work with maize at the same site we had found that daytime sprinkler irrigation decreased maize yield as compared to nighttime sprinkler irrigation. However, this work has shown that the alfalfa forage yield, N content, N uptake and water use efficiency were not affected by the sprinkler irrigation time of the day (daytime versus nighttime). This lack of influence of sprinkler irrigation time of the day on the alfalfa crop was related to the low sprinkler water losses (10% for daytime and 3% for nighttime), the slight effect of irrigation time of the day on the uniformity of irrigation, the null effect of daytime sprinkler irrigation on photosynthesis found in a previous work, and the moderate sensitivity of alfalfa to water stress.

For those farms that grow alfalfa and maize, when daytime sprinkler irrigation is necessary due to constraints of the irrigation system, alfalfa should be the crop daytime irrigated. Given that the effect of sprinkler irrigation time of the day on crop production depends on crop species, further studies are needed for other crops.

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7- REFERENCES

- Abdul-Jabbar, A.S., Lugg, D.G., Sammis, T.W., Gay, L.W., 1985. Relationships between crop water stress index and alfalfa yield and evapotranspiration. Trans. ASAE 28, 454-461.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrig. and Drain. Paper 56. FAO, Rome.
- Breazeale, D., Kettle, R., Munk, G., 1999. Using growing degree days for alfalfa production. Fact Sheet 99-7. University of Reno, Nevada.
- Bruckler, L., Lafolie, F., Ruy, S., Granier, J., Baudequin, D., 2000. Modeling the agricultural and environmental consequences of non-uniform irrigation on a corn crop. 1. Water balance and yield. Agronomie 20, 609-624.
- Cavero, J., Jiménez, L., Puig, M., Faci, J.M., Martínez-Cob, A., 2008. Maize growth and yield under daytime and nighttime solid-set sprinkler irrigation. Agron. J. 100, 1573-1579.
- Cavero, J., Medina, E.T., Puig, M., Martínez-Cob, A., 2009. Sprinkler irrigation changes maize canopy microclimate and crop water status, transpiration, and temperature. Agron. J. 101, 854-864.

1 Christiansen, J.E., 1942. Irrigation by sprinkling. Agric. Exp. Stn. Bull. 670. Univ.
2 of California, Berkeley.

3 Dastane, N.G., 1978. Effective rainfall in irrigated agriculture. Irrig. and Drain.
4 Paper 25. FAO, Rome.

5 Dechmi, F., Playan, E., Caverro, J., Faci, J.M., Martínez-Cob, A., 2003. Wind
6 effects on solid-set sprinkler irrigation depth and yield of maize (*Zea mays*).
7 Irrig. Sci 22, 67-77.

8 Doorenbos, J., Pruitt, W.O., 1977. Crop water requirements. Irrigation and
9 Drainage Paper 24. FAO, Rome.

10 Faci, J.M., Bercero, A., 1991. Efecto del viento en la uniformidad y en las
11 pérdidas por evaporación y arrastre en el riego por aspersión. Inv. Agr.:
12 Prod. Prot. Veg. 6, 97-117.

13 Frost, K.R., Schwalen, H.C., 1955. Sprinkler evaporation losses. Agric. Eng. 36,
14 526-528.

15 Grimes, D.W., Wiley, P.L., Sheesley, W.R., 1992. Alfalfa yield and plant water
16 relations with variable irrigation. Crop Sci. 32, 1381-1387.

17 Holder, C.D., 2012. The relationship between leaf hydrophobicity, water droplet
18 retention, and leaf angle of common species in a semi-arid region of the
19 western United States. Agric. Forest Meteo. 152, 11-16.

20 Howell, T.A., Hiler, E.A., van Bavel, C.H.M., 1971. Crop response to mist.
21 Trans. ASAE 14, 906-910.

22 Isla, R., Aragües, R., 2009. Response of alfalfa (*Medicago sativa* L.) to diurnal
23 and nocturnal saline sprinkler irrigations. I: total dry matter and hay quality.
24 Irrig. Sci. 27, 497-505.

1 Kincaid, D.C., Solomon, K.H., Oliphant, J.C., 1996. Drop size distributions for
2 irrigation sprinklers. Trans. ASAE 39, 839-845.

3 Lindenmayer, R.B, Hansen, N.C., Brummer, J., Pritchett, J.G., 2011. Deficit
4 irrigation of alfalfa for water-savings in the Great Plains and Intermountain
5 West: a review and analysis of the literature. Agron. J. 103, 45-50.

6 Liu, H.J., Kang, Y., 2006. Effect of sprinkler irrigation on microclimate in the
7 winter wheat field in the North China plain. Agric. Water Manage. 84, 3-19.

8 Lloveras, J., Chocarro, C., Freixes, O., Arqué, E., Moreno, A., Santiveri, F.,
9 2008. Yield, yield components, and forage nutritive value of alfalfa as
10 affected by seeding rate under irrigated conditions. Agron. J. 100, 191-197.

11 López-Mata, E., Tarjuelo, J.M., de Juan, J.A., Ballesteros, R., Domínguez, A.,
12 2010. Effect of irrigation uniformity on the profitability of crops. Agric. Water
13 Manage. 98, 190-198.

14 Mantovani, E.C., Villalobos, F.J., Orgaz, F., Fereres, E., 1995. Modelling the
15 effects of sprinkler irrigation uniformity on crop yield. Agric. Water Manage.
16 27, 243-257.

17 Martínez-Cob, A., García-Vera, M.A., 2004. Revisión de las necesidades
18 hídricas netas de los cultivos de la cuenca del Ebro. Internal Technical
19 Report 2004-PH-12.I. Confederación Hidrográfica del Ebro, Zaragoza.

20 Martínez-Cob, A., Playan, E., Zapata, N., Caverro, J., Medina, E.T., Puig, M.,
21 2008. Contribution of evapotranspiration reduction during sprinkler irrigation
22 to application efficiency. J. Irrig. Drain. Eng. ASCE 134, 745-756.

23 McNaughton, K.G., 1981. Net interception losses during sprinkler irrigation.
24 Agric. For. Meteorol. 24, 11-27.

- 1 Playán, E., Salvador, R., Faci, J.M., Zapata, N., Martínez-Cob, A., Sanchez, I.,
2 2005. Day and night wind drift and evaporation losses in sprinkler solid-sets
3 and moving laterals. *Agric. Water Manage.* 76, 139-159.
- 4 Putnam, D.H., Robinson, P., DePeters, E., 2008. Forage quality and testing, in:
5 Summers, C.G., Putnam, D.H. (Eds.), *Irrigated alfalfa management for*
6 *Mediterranean and desert zones*, Chapter 16, pp. 25. Oakland, Univ. of
7 California. Agricultural and Natural resources publication nº 8302.
- 8 Robinson, F.E., 1970. Modifying an arid microclimate with sprinklers. *Agric.*
9 *Eng.* 51, 465.
- 10 Saadia, R., Huber, L., Lacroix, B., 1996. Modification du microclimat d'un
11 couvert de maïs au moyen de l'irrigation par aspersion en vue de la gestion
12 des stress thermiques des organes reproducteurs. *Agronomie* 16, 465-477.
- 13 Salmeron, M., Urrego, Y.F., Isla, R., Cavero, J., 2012. Effect of non-uniform
14 sprinkler irrigation and plant density on simulated maize yield. *Agric. Water*
15 *Manage.* 113, 1-9.
- 16 Sammis, T.W., Mapel, C.L., Lugg, D.G., Lansford, R.R., McGuckin, J.T., 1985.
17 Evapotranspiration crop coefficients predicted using growing degree days.
18 *Trans. ASAE* 28, 773-780.
- 19 Sanchez, I., Zapata, N., Faci, J.M., 2010a. Combined effect of technical,
20 meteorological and agronomical factors on solid-set sprinkler irrigation: I.
21 Irrigation performance and soil water recharge in alfalfa and maize. *Agric.*
22 *Water Manage.* 97, 1571-1581.

1 Sanchez, I., Zapata, N., Faci, J.M., 2010b. Combined effect of technical,
2 meteorological and agronomical factors on solid-set sprinkler irrigation: II.
3 Modifications of the wind velocity and of the water interception plane by the
4 crop canopy. *Agric. Water Manage.* 97, 1591-1601.

5 Seginer, I., Kantz., D., Nir, D., 1991. The distortion by wind of the distribution
6 patterns of single sprinklers. *Agric. Water Manage.* 19, 341-359.

7 Sharratt, B.S., Sheaffer, C.C., Baker, D.G., 1989. Base temperature for the
8 application of the growing degree day model to field grown alfalfa. *Field*
9 *Crops Res.* 21, 95-102.

10 Sheaffer, C.C., Tanner, C.B., Kirkham, M.B., 1988. Alfalfa water relations and
11 irrigation, in: Hanson, A.A., Barnes, D.K., Hill, R.R. (Eds.), *Alfalfa and alfalfa*
12 *improvement. Agronomy Monograph* 29, 373-409. ASA, Madison, WI, USA.

13 Smeal, D., Gregory, E.J., Arnold, R.N., 1992. Interseasonal variability in the
14 water use-production function of alfalfa. *J. Prod. Agric.* 5, 576-580.

15 Stambouli, T., 2012. Gestión avanzada del riego por aspersión en parcela:
16 aplicación en el valle medio del Ebro. Ph. D. Dissertation. Universidad de
17 Zaragoza, Spain. 191 pp.

18 Stambouli, T., Martínez-Cob, A., Faci, J.M., Howell, T., Zapata, N., 2013.
19 Sprinkler evaporation losses in alfalfa during solid-set sprinkler irrigation in
20 semiarid areas. *Irrig. Sci.* 31, 1075-1089.

21 Steiner, J.L., Kanemasu, E.T., Hasza, D., 1983. Microclimatic and crop
22 responses to center pivot sprinkler and to surface irrigation. *Irrig. Sci.* 4, 201-
23 214.

24 Stern, J., and Bresler, E., 1983. Nonuniform sprinkler irrigation and crop yield.
25 *Irrig. Sci.* 4, 17-29

- 1 Tarjuelo, J.M., Montero, J., Valiente, M., Honrubia, F., Ortiz, J., 1999a. Irrigation
2 uniformity with medium size sprinklers. Part II: Influence of wind and other
3 factors on water distribution. Trans. ASAE 42, 677-689.
- 4 Tarjuelo, J.M., Montero, J., Honrubia, F.T., Ortiz, J.J., Ortega, J.F., 1999b.
5 Analysis of uniformity of sprinkle irrigation in a semi-arid area. Agric. Water
6 Manage. 40, 315-331.
- 7 Tolk, J.A., Howell, T.A., Steiner, J.L., Krieg, D.R., Schneider, A.D., 1995. Role
8 of transpiration suppression by evaporation of intercepted water in improving
9 irrigation efficiency. Irrig. Sci. 16, 89-95.
- 10 Urrego-Pereira, Y., Caverro, J., Medina, E.T., Martínez-Cob, A., 2013a.
11 Microclimatic and physiological changes under a center pivot system
12 irrigating maize. Agric. Water Manage. 119, 19-31.
- 13 Urrego-Pereira, Y., Martínez-Cob, A., Caverro, J., 2013b. Relevance of sprinkler
14 irrigation time and water losses on maize yield. Agron. J. 105, 845-853.
- 15 Urrego-Pereira, Y., Martínez-Cob, A., Fernández, V., Caverro, J., 2013c.
16 Daytime sprinkler irrigation effects on net photosynthesis of maize and
17 alfalfa. Agron. J. 105, 1515-1528.

Figure 1. General experimental layout, with 12 irrigation sectors (1-12) irrigated independently by four sprinklers each. The irrigation sectors with even numbers were irrigated during nighttime in 2012, during daytime in 2013, and during nighttime in 2014. The irrigation sectors with odd numbers were irrigated during daytime in 2012, during nighttime in 2013, and during daytime in 2014. The shaded areas are the experimental plots where irrigation events were characterized and alfalfa yield and soil water content were measured. IE, experimental plots where irrigation was characterized. The location of the two access tubes for soil water measurement installed in all the plots is shown in one of them. Two automatic weather stations were located in irrigation sectors 5 and 6 in the sprinklers line.

Figure 2. Cumulative weekly values of calculated evapotranspiration of the crop (ETc), rainfall, crop irrigation requirement (CIR), and irrigation amount applied to alfalfa for daytime and nighttime irrigation treatments (Irrigation) during the 2012, 2013 and 2014 seasons.

Figure 3. Soil water content at different depths for the daytime and nighttime irrigation treatments during the experiment. For each date and soil depth, the star symbol indicates statistical difference after ANOVA at $P=0.05$ (black colour indicates higher value in the nighttime treatment and red colour indicates higher value in the daytime treatment). For each soil layer, the horizontal dashed lines indicate the soil water content at field capacity (upper) and wilting point (lower). The three irrigation seasons (2012, 2013 and 2014) duration are shown.

Table 1. Soil characteristics of the experimental field.

Depth (m)	pH	C (%)	N (%)	CaCO ₃ (%)	Sand (%)	Silt (%)	Clay (%)	FC ^a (m ³ m ⁻³)	WP ^b (m ³ m ⁻³)
0.0-0.3	8.2	1.12	0.14	35.0	19.6	50.2	30.2	0.351	0.189
0.3-0.6	8.3	0.77	0.11	35.0	14.9	47.5	37.6	0.381	0.227
0.6-0.9	8.3	0.54	0.10	32.0	7.7	47.5	44.8	0.364	0.207
0.9-1.2	8.2	0.43	0.08	31.0	11.9	47.1	41.0	0.359	0.187
1.2-1.6	8.3	0.43	0.07	33.0	20.3	49.2	30.5	0.344	0.187

^a FC, field capacity (-0.033 MPa)

^b WP, wilting point (-1.5 MPa)

Table 2. Calculated crop evapotranspiration (ET_c), crop irrigation requirement (CIR) and irrigation water applied in the crop seasons of 2012, 2013 and 2014.

Season	ET_c (mm)	CIR (mm)	Irrigation (mm)
2012	941	746	757
2013	832	556	552
2014	929	711	710

Table 3. Average values of wind speed, wind drift and evaporation losses (WDEL), and Christiansen coefficient of uniformity (CU) for the daytime and nighttime irrigations events at each harvest cycle of alfalfa in the three years of the experiment. The average values of wind speed and WDEL for all the irrigation events in each year and the seasonal CU are also given.

Year	Harvest cycle	Irrigation (N ^a)	Wind speed (m s ⁻¹)		WDEL (%)		CU (%)	
			Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime
2012	1	4	2.98	2.30	9.74	3.99	84	85
	2	6	2.13	1.83	9.32	4.47	85	88
	3	4	1.60	1.30	6.51	3.43	89	91
	4	6	2.15	1.70	7.55	5.60	91	91
	5	7	3.07	1.61	13.56	4.40	85	87
	6	3	2.13	1.67	6.96	0.00	85	90
	All	30	2.40	1.73	9.40	4.03	87	88
	Seasonal						94	94
2013	1	0						
	2	3	2.04	1.60	7.46	1.17	89	86
	3	4	1.55	1.33	5.66	0.39	91	88
	4	6	1.66	0.72	9.75	0.95	90	88
	5	7	2.68	1.57	13.39	1.55	87	88
	6	6	2.95	1.56	14.70	1.86	82	83
	All	26	2.26	1.34	10.97	1.26	87	87
	Seasonal						92	92
2014	1	2	1.70	1.05	6.23	1.19	87	93
	2	6	2.21	2.00	7.22	5.08	88	88
	3	4	2.13	0.86	7.05	2.14	89	91
	4	7	4.40	1.88	19.60	6.49	76	88
	5	7	2.39	1.45	8.86	2.90	85	90
	6	4	1.59	0.80	3.02	3.30	91	90
	All	30	2.63	1.45	9.84	3.92	85	89
	Seasonal						92	94

^a Number of irrigation events

Table 4. Average air temperature and vapor pressure deficit (VPD) measured above the crop canopy at 1 and 2 m above the soil surface and canopy temperature of alfalfa in the irrigated (Irrig) and not irrigated (Not irrig) plots during and after the daytime irrigation events for each year. The irrigation events considered were those when thermal time was more than a third of total for each alfalfa harvest cycle.

Variable and year	N ^a	During irrigation		1 h after irrigation		2 h after irrigation	
		Irrig	Not irrig	Irrig	Not irrig	Irrig	Not irrig
Air temperature (°C) at 1m							
2012	18	26.0 b ^b	27.3 a	28.9 b	29.7 a	29.5 b	29.8 a
2013	18	23.6 b	24.5 a	26.5 b	26.8 a	27.1 a	27.0 a
2014	24	22.5 b	23.4 a	25.4 b	26.1 a	26.1 a	26.1 a
Air temperature (°C) at 2m							
2012	22	24.4 b	25.1 a	27.8 a	27.9 a	28.3 a	28.2 a
2013	18	23.2 b	24.5 a	26.4 b	27.2 a	27.2 b	27.5 a
2014	24	22.6 b	23.0 a	25.9 a	25.9 a	26.5 a	26.1 b
VPD (kPa) at 1m							
2012	18	1.65 b	1.98 a	2.42 b	2.61 a	2.66 a	2.73 a
2013	18	1.17 b	1.36 a	1.85 a	1.87 a	2.04 a	1.99 a
2014	24	1.10 b	1.39 a	1.75 b	1.96 a	1.95 b	2.02 a
VPD (kPa) at 2m							
2012	22	1.63 b	1.95 a	2.52 b	2.66 a	2.71 a	2.76 a
2013	18	1.23 b	1.46 a	2.00 b	2.10 a	2.25 a	2.23 a
2014	24	1.24 b	1.43 a	2.00 b	2.08 a	2.16 a	2.16 a
Canopy temperature (°C)							
2012	22	23.3 b	24.2 a	23.8 a	24.2 a	23.2 a	23.3 a
2013	18	23.3 b	24.0 a	24.8 a	24.7 a	24.4 a	24.3 a
2014	24	21.9 b	23.9 a	23.8 b	24.6 a	23.7 a	23.9 a

^a Number of irrigation events.

^b For each variable, year and period of measurement the values followed by different letters are significantly different according to a paired *t*-test at the 0.05 level.

Table 5. Average air temperature and vapor pressure deficit (VPD) measured above the crop canopy at 1 and 2 m above the soil surface and canopy temperature of alfalfa in the irrigated (Irrig) and not irrigated (Not irrig) plots during and after the nighttime irrigation events for each year. The irrigation events considered were those when thermal time was more than a third of total for each alfalfa harvest.

Variable and year	N ^a	During irrigation		1 h after irrigation		2 h after irrigation	
		Irrig	Not irrig	Irrig	Not irrig	Irrig	Not irrig
Air temperature (°C) at 1m							
2012	18	17.0 b ^b	17.5 a	15.4 b	15.8 a	16.7 a	16.9 a
2013	19	15.6 a	15.5 a	14.9 a	14.8 a	15.6 a	15.5 a
2014	22	14.0 b	14.7 a	13.2 b	13.8 a	13.8 b	14.4 a
Air temperature (°C) at 2m							
2012	22	15.8 b	16.6 a	14.4 b	15.0 a	15.2 b	15.7 a
2013	19	16.2 a	16.1 a	15.4 a	15.3 a	15.8 a	15.7 a
2014	22	14.5 b	15.4 a	13.5 b	14.3 a	14.1 b	14.8 a
VPD (kPa) at 1m							
2012	18	0.39 b	0.49 a	0.25 b	0.32 a	0.35 b	0.39 a
2013	19	0.24 b	0.28 a	0.18 b	0.21 a	0.20 b	0.24 a
2014	22	0.24 b	0.30 a	0.19 b	0.24 a	0.22 b	0.28 a
VPD (kPa) at 2m							
2012	22	0.44 b	0.51 a	0.31 b	0.34 a	0.37 a	0.38 a
2013	19	0.28 b	0.34 a	0.21 b	0.26 a	0.22 b	0.27 a
2014	22	0.25 b	0.36 a	0.20 b	0.28 a	0.24 b	0.31 a
Canopy temperature (°C)							
2012	22	13.6 a	13.8 a	12.3 b	12.6 a	13.7 b	14.0 a
2013	19	14.2 a	14.4 a	13.6 b	14.0 a	14.8 b	15.0 a
2014	22	12.8 b	13.0 a	12.1 b	12.5 a	13.2 b	13.5 a

^a Number of irrigation events.

^b For each variable, year and period of measurement the values followed by different letters are significantly different according to a paired *t*-test at the 0.05 level.

Table 6. Average values of daily crop water stress index in the daytime and nighttime irrigation treatments at each alfalfa harvest cycle of the three years of the experiment.

Harvest cycle	Crop water stress index					
	2012		2013		2014	
	Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime
1	0.51 b ^a	0.55 a	0.62 a	0.47 b	0.53 b	0.60 a
2	0.20 a	0.28 a	0.47 a	0.32 b	0.43 a	0.36 a
3	0.20 a	0.18 a	0.47 a	0.27 b	0.39 a	0.39 a
4	0.17 a	0.18 a	0.25 a	0.13 b	0.30 a	0.26 a
5	0.07 b	0.15 a	0.26 a	0.14 b	0.20 a	0.25 a
6	0.12 b	0.17 a	0.21 a	0.07 a	0.18 a	0.19 a

^a For each year and harvest the values followed by different letters are significantly

different according to a paired *t*-test at the 0.05 level.

Table 7. Alfalfa forage yield (dry matter) in the daytime and nighttime irrigation treatments at each harvest cycle of the three years of the experiment.

Harvest cycle	Forage yield (Mg ha ⁻¹)					
	2012		2013		2014	
	Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime
1	3.02 a ^a	2.83 a	3.59 a	3.48 a	3.12 a	3.19 a
2	3.26 a	3.48 a	4.05 a	4.05 a	4.26 a	3.92 a
3	3.10 a	3.07 a	3.85 a	3.89 a	3.85 a	4.09 a
4	3.13 a	2.93 a	4.02 a	4.02 a	3.97 b	4.41 a
5	2.50 a	2.60 a	2.87 a	3.10 a	4.09 a	4.02 a
6	1.00 a	1.11 a	2.11 a	2.25 a	2.34 a	2.35 a
All	16.02 a	16.02 a	20.48 a	20.79 a	21.64 a	22.00 a

^a For each year and harvest cycle the numbers with different letters are significantly different after ANOVA at the P=0.05 level.

Table 8. Alfalfa forage N content (yield weighted) and N uptake in the daytime (Day) and nighttime (Night) irrigation treatments at each harvest of the three years of the experiment.

Harvest	N content (%)						N uptake (kg ha ⁻¹)					
	2012		2013		2014		2012		2013		2014	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
1	3.49 a ^a	3.48 a	3.48 a	3.48 a	3.39 a	3.44 a	105 a	99 a	125 a	121 a	106 a	110 a
2	3.47 a	3.46 a	2.98 a	2.84 a	3.31 a	3.31 a	113 a	120 a	120 a	115 a	140 a	130 a
3	3.30 a	3.19 a	3.20 a	3.20 a	3.45 a	3.46 a	102 a	98 a	123 a	124 a	132 a	141 a
4	3.22 a	3.13 a	3.10 a	3.06 a	3.31 a	3.17 b	101 a	92 b	125 a	123 a	131 a	140 a
5	3.06 a	3.00 a	3.10 a	3.10 a	3.34 a	3.42 a	76 a	78 a	88 a	95 a	136 a	138 a
6	2.67 a	2.53 a	3.60 a	3.43 a	3.58 a	3.47 a	27 a	28 a	76 a	77 a	84 a	82 a
All	3.28 a	3.21 a	3.21 a	3.16 a	3.38 a	3.37 a	524 a	514 a	657 a	655 a	729 a	740 a

^a For each variable, year and harvest the numbers with different letters are significantly different after ANOVA at the P=0.05 level.

Table 9. Seasonal alfalfa actual evapotranspiration (calculated with a water balance) and water use efficiency in the daytime and nighttime irrigation treatments of the three years of the experiment.

Variable	2012		2013		2014	
	Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime
Evapotranspiration (mm)	878 a ^a	867 a	832 a	802 b	891 a	885 a
Water use efficiency (kg ha ⁻¹ mm ⁻¹)	17.71 a	18.59 a	24.62 a	25.94 a	24.28 a	24.85 a

^a For each variable and year the numbers with different letters are significantly different after ANOVA at the P=0.05 level.