MICROCLIMATIC AND PHYSIOLOGICAL CHANGES UNDER A CENTER PIVOT SYSTEM IRRIGATING MAIZE

Yenny Urrego-Pereira[a*]; José Cavero[a], Eva T. Medina[b] and Antonio Martínez-Cob[a]

[a] *Departamento de Suelo y Agua, Estación Experimental de Aula Dei (EEAD), Consejo Superior de Investigaciones Científicas (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.*

ABSTRACT

The microclimatic (air temperature and vapour pressure deficit (VPD)) and physiological (canopy temperature and plant transpiration) changes due to center pivot sprinkle irrigation were monitored at a commercial plot of maize (*Zea mays* L.). Two treatments were considered: a) *moist*, measurements taken at three spots on a transect when the pivot was running over it; b) *dry*, measurements taken simultaneously at a fourth spot D, 270 m apart. A total of 34 irrigation events were monitored, seven of which included plant transpiration measurements. For the *transpiration-measured* irrigation events, significant (P = 0.05) reductions in the monitored variables for the *moist* treatment were observed for 0.6 to 2.1 h *before*, *during* and 0.5 to 2.4 h *after* the irrigation. The average decreases for the phase *during* were 1.8 to 2.1 ºC for air temperature, 0.53 to

---

[*] Corresponding author: *Tel.: +34-976716075*; *Fax: +34-976716145;* E-mail: yurrego@eead.csic.es (*Yenny Urrego-Pereira).*

0.61 kPa for VPD, 3.1 to 3.8 ºC for canopy temperature, and 0.22 to 0.28 mm h^{-1} (30 to 36 %) for transpiration. Lower reductions were found for the phases *before* and *after*. The duration of the microclimatic changes decreased as the distance from the centre of the pivot increased (from 3.9 to 2.2 h), but the duration of the physiological changes was similar in the different pivot arm portions (≈4 h). Microclimatic and physiological changes were higher in drier and warmer days. Transpiration reduction due to irrigation was higher as closer to the center of the pivot and represented 5 to 7% of the applied water. The estimated reduction of ET represented 1.5 to 1.8% of the applied water. The reduction of transpiration and ET is positive because it represents a reduction in irrigation requirements.

The decrease in maize canopy temperature could be positive or negative depending on its effect on photosynthesis.

Abbreviations

VPD, vapor pressure deficit; PAP, pivot arm portion; GMT, Greenwich Mean Time; SIAR, Spanish Irrigation Advisory System; CV, coefficient of variation.

KEYWORDS

Air temperature; Vapor pressure deficit; Canopy temperature; Transpiration; Center pivot sprinkler irrigation

1. INTRODUCTION

The acreage irrigated by sprinkler irrigation systems has increased in order to better meet the crop water requirements and increase the water application efficiency and the crop yield. For instance, sprinkler irrigation systems represent about 23% of the 3.5 Mha of irrigated land in Spain. Among the different types of sprinkler irrigation systems, the center pivot offers several advantages such as the lower invest cost compared to solid-set, the high degree of automation and the high water application efficiency. Due to these factors, their use has become widespread around the world (Allen et al., 2000). Thus, center pivot is used in about 32 to 40 % of the irrigated land in several Spanish Irrigation Districts (MAGRAMA 2011). In USA, the land irrigated by center pivot has increased by more than 50% from 1986 to 1996 (Evans 2001), while it accounted for 83% of the sprinkler systems on 2008, i.e. about 47% of the 22.2 Mha of irrigated land (USDA 2008).

Thompson et al. (1993) reported that during solid-set sprinkler irrigation a total amount of energy equivalent to 24% of the net radiation was transferred from the plant environment to the water droplets as they warmed during flight and after they impacted the canopy and soil. This leads to sprinkler irrigation water losses by evaporation during and after the irrigation. This evaporation of water modifies the crop microclimate. A decrease of air temperature and air vapor pressure deficit (VPD) has been reported (Robinson 1970; Steiner et al. 1983; Thompson et al. 1993; Tolk et al. 1995; Liu and Kang 2006a; Cavero et al. 2009). The microclimatic changes can also cause several crop responses. Howell et al. (1971) reported that during mist irrigation of peas (*Vigna unguiculata* (L.) Walp.), the air and canopy temperature decreased and the leaf water potential increased; in addition, a higher yield was observed as compared to the non-mist irrigated treatment. Liu and Kang (2006b) also reported decreases of canopy temperature of wheat (*Triticum aestivum* L.) of 0.3 to 2.8 °C in a sprinkler irrigated field as compared to a non-sprinkled field.

In maize (*Zea mays* L.), microclimatic (air temperature and air VPD) and plant physiological (canopy temperature, plant transpiration, leaf water potential) changes have been reported during sprinkler irrigation. Steiner et al. (1983) compared the microclimatic and physiological conditions of crop maize under two types of irrigation system: center pivot sprinkler and surface irrigation. They reported that long-term daily average canopy and air temperatures at the center pivot field were 1.0 ºC and 1.5 ºC, respectively, cooler than at the surface irrigation field. This cooling effect of the center pivot irrigation was higher during days of high evaporative demand. Using a lateral move sprinkler irrigation system, Tolk et al. (1995) observed that during daytime irrigations the VPD decreased about 1.4 KPa, the canopy temperature decreased about 5.3ºC, and the transpiration rates decreased by 32%. Finally, Cavero et al. (2009) reported that during daytime solid-set sprinkler irrigation the air temperature and the VPD (measured at 0.5 m below crop canopy height) decreased between 3.3 and 4.4 ºC, and between 1.0 and 1.2 KPa, respectively; these decreases were lower when monitored at higher measurement heights. Cavero et al. (2009) also reported that canopy temperature decreased between 4 to 6 ºC, the crop transpiration rate was reduced by 58%, and leaf water potential increased from values of -1.2 to -1.4 MPa to values of -0.52 to -0.57 MPa. In general, these studies report that these microclimatic and plant physiological changes during the sprinkler irrigation event only last for a few hours after the irrigation finishes.

These microclimatic and physiological changes affect the efficiency of the sprinkler irrigation application (Tolk et al., 1995; Martínez-Cob et al., 2008), so they are relevant to the modeling of sprinkler irrigation efficiency (Zhao et al., 2012). It is important to gather information of those changes under different irrigation systems and meteorological, crop and land conditions so a larger database can be obtained to test those models under different scenarios.

In center pivots due to its rotation movement, the water application rates and irrigation duration vary along the pivot arm portions. As the abovementioned microclimatic and physiological changes are the consequence of the evaporation water lost during and after the irrigation and those losses depend on the application rates and irrigation duration, the microclimatic and physiological changes could be different along the different pivot arm portions and they could also be different compared to other sprinkler irrigation systems. This variability and a detailed analysis of the microclimatic changes during the irrigation events were not addressed in previous work (Steiner et al., 1983). The goal of this work was to study the variability of the magnitude and duration of the microclimatic (air temperature and VPD) and physiological (canopy temperature and plant transpiration) changes in a center pivot sprinkler system irrigating a maize crop and how they affect the water use.

2. MATERIALS AND METHODS

2.1 Experimental site

The experiment was carried out from June to September 2008 in a maize commercial plot of 32.3 ha irrigated with a center pivot sprinkler irrigation system (VXP, Irrifrance, Paulhan, France), and located at Valfarta (Huesca, Spain) (41º33’N latitude and 0º07’W longitude; 354 m altitude). The climate is Mediterranean semiarid with a yearly average precipitation of 400 mm and mean annual air temperature of 14.3º C.

Maize cultivar Pioneer PR34N44 was planted on 15 April 2008. A final plant density of 68,000 plants ha^{-1} was attained as determined by counting and averaging the number of plants within 15 sampling spots of 3.0 m^{2} each. This sampling was performed on 6 October, few days before harvest. The soil is classified as Typic Torrifluvents and the texture is silty loam. Agronomic practices (fertilization, weeds and pest control, etc.) common in the region were conducted by the owner of the commercial plot. For irrigation scheduling, the farmer obtained the maize irrigation requirements from the Spanish Irrigation Advisory System (SIAR) (MARM, 2011). The SIAR System includes a network of automated weather stations, one of them located 3 km southeast from the experimental plot. This station (thereafter the ‘nearby grass station’) is located over grass following the reference conditions defined by Allen et al. (1998). The SIAR System uses the average daily meteorological data recorded (air temperature and relative humidity, wind speed and direction, solar radiation and precipitation) to get daily estimates of ET_o, and locally adjusted maize crop coefficients to calculate the weekly crop evapotranspiration and irrigation requirements using the FAO approach (Allen et al. 1998). An irrigation efficiency of 0.85 is used to calculate the irrigation requirements.

The pivot arm was 322 m long and was divided into six portions of 49.4 m length each and a final overhang of 25.6 m length (Fig.1, Table 1). The main pipe had a diameter of 0.163 m. The number of impact sprinklers in each pivot arm portion and the general characteristics of the center pivot system are shown in Table 1. All sprinklers had a pressure regulator (Model PSR30, Senninger Irrigation Inc., Clement, FL, USA) and were located at the top of the main pipe. A complete turn of the center pivot over the whole plot lasted about 31 h. The weekly irrigation requirement was divided by the water depth applied by the pivot (≈ 13 mm) to determine the number of irrigations per week.

Irrigation pressure (P_i, kPa) was measured along the measurement period using pressure transducers (Model 2200/2600, Gems Basingstoke, Hampshire, UK) installed in the last sprinkler of pivot arm portions 2, 4 and 5 (Fig. 1). Each pressure transducer was placed between the pressure regulator and the sprinkler and connected to a logger (Model ES120, Dickson, Addison, IL, USA) which monitored and recorded pressure values every 5 min.

2.2 Microclimatic and physiological changes

Determining the microclimatic and physiological changes occurring during the irrigation events required simultaneous measurements at an irrigated and a non-irrigated area (i.e. an area under the same conditions than those of the irrigated area but irrigated at a different time). Thus three meteorological stations (thereafter, the experimental weather stations A, B and C) and sap flow measurement systems were installed at a transect AC located at northeast of the plot (Fig.1), approximately in the middle of the pivot arm portions 2, 4 and 5, respectively. A fourth meteorological station (thereafter, the experimental weather station D) and a sap flow measurement system were installed at spot D, 270 m far away from transect AC (Fig. 1). Two treatments were established in this field experiment: a) *moist* treatment, measurements taken at the stations A to C in the transect AC when the pivot arm was irrigating it; b) *dry* treatment, measurements simultaneously taken at the station D when the transect AC was being irrigated. At that time, about 8 to 10 h have passed since the pivot arm irrigated the spot D due to the duration of the rotating movement (counter clockwise) of the pivot (about 31 h), and the distance between the dry spot D and the transect AC (270 m). This time was enough to dry out all intercepted water from plants in the area surrounding that spot D by the time the pivot arm reached the transect AC. For this reason, that spot D was considered the dry treatment. The size of the pivot irrigation system, its speed and the localization of the different sensors allowed enough fetch for the different measurements.

An air temperature and relative humidity probe (HMP45C, Vaisala, Helsinki, Finland) was installed at each experimental weather station (A to D) at 2.9 m above ground. Measurement height was kept constant along the experiment. The accuracy of the probes was ± 0.3ºC for air temperature and ± 2% for relative humidity. For canopy temperature measurement, an infrared thermometer (Model IRR-P, Apogee Instruments, Inc., Roseville, CA) with an accuracy of ± 0.5ºC was also placed at three of the experimental weather stations (A, B and D) at 1.0 m above the crop canopy with an angle of 45º, oriented towards the north. In addition, a net radiometer (NR-Lite, Kipp&Zonen, Delft, The Netherlands) with an accuracy ±30 W m^{-2} at 1000 W m^{-2}, and a cup anemometer (A100R, Vector Instruments, Rhyl, UK) with an accuracy of ±0.1 m s^{-1} were installed at 2.9 m above ground at experimental weather station D. At each experimental weather station, those variables (air temperature and relative humidity, canopy temperature, and, at spot D, net radiation and windspeed) were monitored continuously every 10 s and their average values were recorded every 5 min by a datalogger (model CR10X at experimental weather stations A and B, model CR23X at experimental weather stations C and D, Campbell Scientific, Inc. Logan, UT, USA). The VPD was calculated from the recorded data of air temperature and relative humidity, following the methodology described by Allen et al. (1998). These meteorological data were also used for a direct estimation of maize evapotranspiration (ET) at each spot A, B, C and D as described in section 2.3.

The transpiration rates were determined from sap flow measurements using the heat balance method (Baker and van Bavel, 1987; Weibel and Boersma, 1995; Van Bavel 2005). This method was chosen because it had been previously used on maize in similar studies to this (Tolk et al. 1995; Martínez-Cob et al. 2008). Next to each meteorological station, a Flow4 datalogger (Dynamax, Houston, TX, USA) was installed to monitor, log and process data collected by four sap gauges SGB19 (Dynamax) each of them installed on a plant. Readings were taken every 10 min. The sap gauges were moved to a another set of four plants within the same area of the field on July 25 and 14 August of 2008 to avoid any possible damage to the plants (Van Bavel 2005). Each gauge had a soft foam collar surrounding the electronics. In addition, once installed in the plant, each gauge was surrounded by a weather shield (aluminium bubble foil) such it held a cylindrical shape. The aluminium top shield was secured using insulation tape. The shield kept out water and prevented radiation from affecting readings (Van Bavel, 2005). Following this author, the datalogger was set to apply a continuous average voltage of 4.0 V while the heater resistance of the different gauges varied between 58.9 to 64.6 Ω. Van Bavel (2005) thoroughly describes the elements of the gauges, the electronics, the recorded variables and the equations used to process them to obtain transpiration rates at each gauge. The 10-min transpiration rates at each measurement spot were determined as the average of those obtained from the four sampled plants per spot. These values were determined in g h^{-1} and transformed into mm h^{-1} using the average number of plants m^{-2} measured at each spot (6.8 plants m^{-2}). Unlike the 5-min averages of air temperature and VPD and canopy temperature that were recorded continuously along the experiment, the 10-min transpiration rates were only recorded for specific irrigation events due to limitations of the memory of the dataloggers used. For the abovementioned time scan (10 min), the datalogger's memory could only hold 24 h data so the values from 3 hours before the pivot arm passed over the transect AC until at least 6 hour after passing were recorded. Those specific irrigation events were monitored in situ, in general once per week.

We considered two set of data for the different variables (temperature and VPD of the air, canopy temperature and plant transpiration):

a) *Transpiration-measured* irrigation events: the seven irrigation events for which plant transpiration rate was measured and we were in situ to observe when the center pivot was passing over the transect AC.

b) *Remaining* irrigation events: the 27 irrigation events for which transpiration rate was not measured and we were not in situ to observe when the center pivot was passing over the transect AC.

A *transpiration-measured* irrigation event was established as the time (t_{ir}) that took the pivot to run over a distance L of 18 m, 9 m either side of the transect AC. This value of 9 m was established by visual inspection of the moistening radius of the pivot sprinklers. For each irrigation event, the value of t_{ir} was different for each monitored pivot arm portion (2, 4 and 5). For each *transpiration-measured* irrigation event the 5-min irrigation pressure values were averaged for the time t_{ir}. These average irrigation pressure values (P_i, kPa) were used to calculate the gross water depth applied (I_s, mm) at each monitored pivot arm portion. The following expression, derived from the Torricelli equation (Norman et al. 1990), was used:

$$I_s = \frac{0.00035\,\pi\, c_d\, Pi^{0.5}\left(d_L^2 + d_s^2\right) 3600\, t_g}{A_s} \qquad (1)$$

where: c_d is the discharge coefficient, 0.98 (Martínez-Cob et al., 2008); d_L is the large nozzle diameter (mm); d_s is the small nozzle diameter (mm); t_g is the time (h) to complete a turn; A_s is the surface area (m^2) irrigated by the sprinklers of pivot arm portion. The corresponding surface area for pivot arm portions 2, 4 and 5 were 23,177, 53,887 and 69,242 m^2, respectively.

The time t_g was determined for each pivot arm portion as follows:

$$t_g = \frac{2\pi \cdot r}{\omega} \qquad (2)$$

where: r is the radius at the end of the evaluated pivot arm portion (m); ω is the angular speed of the pivot (m h^{-1}) computed from the values of t_{ir}.

The *remaining* irrigation events were not identified in situ. They were defined as those periods for which differences between the two treatments (*dry* and *moist*), for each pivot arm portion and variable (temperature and VPD of the air, and canopy temperature), were higher than the accuracy of measuring instruments, and the evolution of the 5-min values of these variables was similar to that observed during the *transpiration-measured* irrigation events. Only those *remaining* irrigation events identified for daytime periods (between 8:00 and 18:00 h Greenwich Mean Time (GMT)) were selected.

The half-hour values of wind speed and direction, solar radiation, air temperature, and relative humidity recorded by the ‘nearby grass station’ were used to characterize the general standard meteorological conditions in the area during the different irrigation events.

2.3. Estimation of maize evapotranspiration

It is expected that the maize evapotranspiration is also affected by the microclimatic and plant physiological changes occurring before, during and after the irrigation events. The FAO Penman-Monteith equation (Allen et al., 1998) only describes a particular application of the Penman-Monteith equation, that for calculation of reference evapotranspiration (ET for an hypothetical, grass-like crop, 0.12 m high and with a fixed surface resistance of 70 s m^{-1}). However, the Penman-Monteith equation can be used for the direct calculation (i.e. without using crop coefficients and reference ET) of any crop evapotranspiration as the surface and aerodynamic resistance values required in these computations are crop specific (Allen et al., 1996, 1998). Therefore, this equation was chosen for estimation of maize evapotranspiration for each *transpiration-measured* irrigation event at the four spots A to D using the corresponding 5-min averages air temperature and relative humidity recorded at the experimental weather stations during the different phases identified for transpiration changes. Thus three sets of moist maize ET (for pivot arm portions 2, 4 and 5) and one set of dry maize ET were computed following Allen et al. (1996):

$$ET_{corn} = \frac{300}{10^6\,\lambda}\,\frac{\Delta\left(R_n - G\right) + \rho_a\, c_p\, VPD / r_a}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \qquad (3)$$

where: λ, latent heat of vaporization (MJ Kg^{-1}); R_n, net radiation (W m^{-2}); G, soil heat flux (W m^{-2}); Δ, slope of the saturation vapour pressure curve versus the temperature (kPa

$^{o}C^{-1}$); ρ_a, air density (Kg m^{-3}); c_p, specific heat of the air (J Kg^{-1} $^{o}C^{-1}$); VPD, vapour pressure deficit (kPa); r_a, aerodynamic resistance of maize (s m^{-1}); r_c, bulk stomatal (canopy) resistance of maize (s m^{-1}); γ, psychrometric constant (kPa $^{o}C^{-1}$).

The variables λ, Δ, ρ_a, γ, and c_p were estimated from the measured air temperature and relative humidity following standard procedures described by Allen et al. (1998). Note that the estimated values of these parameters were different at the four spots A to D as the corresponding values of air temperature and relative humidity were used. G was estimated from net radiation following Allen et al. (1996):

$$G = 0.4\, e^{-0.5 LAI}\, R_n \qquad (4)$$

where LAI is the daily leaf area index estimated from measured crop height as suggested by Allen et al. (1996). As the crop height at the four spots A to D was quite similar, only a single set of LAI values was estimated and used.

The aerodynamic resistance r_a (s m^{-1}) to vapour transfer was estimated following Allen et al. (1996):

$$r_a = \frac{\left[\ln\left(\frac{z_u - d}{z_{0m}}\right)\right]\left[\ln\left(\frac{z_h - d}{z_{0h}}\right)\right]}{k^2\, u_{zu}} \qquad (5)$$

where: u_{zu} is the wind speed (m s^{-1}) measured at a height z_u at spot D, it was assumed that wind speed was not affected by irrigation at the transect A-C; k is the von Karman's constant (0.41); z_u and z_h are the measurement heights (m) above ground of wind speed, and air temperature and relative humidity, respectively; and d, z_{0m}, and z_{0h} (all three in m) are the zero-plane displacement and the roughness lengths for momentum and heat transfer, respectively, estimated (daily) as a function of crop height (h_c) and LAI following Farahani and Bausch (1995) and Kjelgaard et al. (1994):

$$d = 1.1 h_c \ln\left[1 + (c_d\, LAI)^{1/4}\right] \quad (6)$$

$$z_{om} = 0.3\, h_c \left(1 - d / h_c\right) \quad (7)$$

and,

$$z_{0h} = 0.2\, z_{0m} \quad (8)$$

where c_d is the mean drag coefficient for individual leaves (0.07). Eq. (6) was chosen as the product (c_d LAI) was above 0.2 (Farahani and Bausch 1995) due to the LAI values around 4.0 estimated during the monitoring period as crop height was about 2.5 m. The same roughness parameters, d, z_{0m} and z_{0h}, were used at the four spots A to D as the average crop height was similar.

The bulk canopy resistance (s m^{-1}), r_c, was estimated following Farahani and Bausch (1995):

$$r_c = \left\{ c_0\, LAI + \frac{c_1}{c_2\, C} \ln\left[\frac{1 + c_2\, C\ R_s}{1 + c_2\, C\ R_s \exp(-C\ LAI)} \right] \right\}^{-1} \quad (9)$$

where: R_s is the incoming solar radiation (W m^{-2}); c_0 is the minimum stomatal conductance (0.0005 m s^{-1}); c_1 and c_2 are constants defined as c_1 = 3.2E-5 m s^{-1} and c_2 = 5.7E-5 m s^{-1}; and C is the light extinction coefficient, assumed to be 0.50 as suggested by Cavero et al. (1999, 2000) for similar crop and climatic conditions to those in this work. R_s was that measured at the ‘nearby grass station’ and it was assumed to be the same along the pivot surface area.

Net radiation was only measured at spot D. Though net short-wave radiation should not be affected by irrigated, net long-wave radiation could be. Therefore, the net radiation (in W m^{-2}) at the four spots A to D was estimated as described in Allen et al. (1996, 1998):

$$R_n \quad = \quad (1-\alpha) R_s - \sigma\, T_{mK}^4 \left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35 \frac{Rs}{Rsol} - 0.35\right) \qquad (10)$$

where: α is albedo (assumed to be equal to 0.23); σ is the Stefan-Boltzmann constant (2.04E-10 MJ K^{-4} m^{-2} h^{-1}); T_{mK} is the mean air temperature at the corresponding 5-min period and spot A to D (°K); e_a is actual vapour pressure (kPa) estimated from air temperature and relative humidity at each spot A to D; and R_{Sol} is the clear-sky solar radiation (W m^{-2}) estimated at clear-sky days following Allen el al. (1996, 1998).

2.4. Statistical analysis

The 5-min averages of air temperature, air VPD and canopy temperature, and the 10-min values of transpiration rates recorded for the *moist* treatment were compared to those simultaneously recorded for the dry treatment for each *transpiration-measured* irrigation event. Three phases were identified: 1) phase *before*: time period that started when the differences between the *dry* and *moist* treatments were higher than the accuracy of measuring instruments and finished when the pivot arm portion was 9 m ahead of the transect AC; 2) phase *during*: time period corresponding to t_{ir}; and 3) phase *after*: time period that started when the arm portion had surpassed the transect AC by 9 m and finished when the differences between treatments were lower than the accuracy of measuring instruments. For a given irrigation event and pivot arm portion, the duration of the phases *before* and *after* was independently established for each monitored variable. Once identified the different phases for each irrigation event, the 5-min values (or 10-min values) of each variable and pivot arm portion were averaged over the time of duration of each phase. These average values obtained in the *moist* and *dry* treatments in the different irrigation events for each pivot arm portion and phase were compared with a paired t-test and a level of significance of *P*= 0.05.

For the *remaining* irrigation events, it was established a single phase integrating the phases *before*, *during* and *after* established for the *transpiration-measured* irrigated events. The 5-min values of air temperature and VPD and canopy temperature were averaged for the overall duration of each *remaining* irrigation event. The values obtained in the *moist* and *dry* treatments in the different irrigation events for each pivot arm portion were compared with a paired t-test and a level of significance of *P*= 0.05.

The values of ET obtained in the *moist* and *dry* treatments in the different irrigation events for each pivot arm portion and phase (before, during and after) were compared using a paired t-test and a level of significance of *P*= 0.05.

Linear regression analysis was used to determine the relationships between the microclimatic and physiological changes due to sprinkler irrigation and the climatic conditions.

The Statgraphics software was used for the analysis.

3. RESULTS AND DISCUSSION

3.1 Characteristics of the irrigation events

The average duration of the *transpiration-measured* irrigation events decreased with the distance to the center of the pivot ranging from 1.6 h for pivot arm portion 2 to 0.5 h for pivot arm portion 5 (Table 2). All these irrigation events started between 8:25 and 10:55 GMT. The average irrigation pressure in the three pivot arm portions was 197 kPa with a coefficient of variation (CV) of 3% (Table 2). This low CV value indicated a quite constant irrigation pressure during the *transpiration-measured* irrigation events. On average, the irrigation pressure in the pivot arm portion 2 was slightly higher (209 kPa) than that in the portions 4 (190 kPa) and 5 (192 kPa) (Table 2). The average applied water in the three monitored pivot arm portions was similar, 14.2 (pivot arm portion 2), 13.1 (pivot arm portion 4), and 13.9 mm (pivot arm portion 5).

There were some differences between the average meteorological conditions recorded during the *transpiration-measured* irrigations events (Table 3). The overall mean air temperature was 27.2ºC, but the individual mean temperatures ranged between 22.8 °C (13 August) and 32.5 ºC (31 July). The cooler irrigation event (13 August) was also the windiest, while the hottest irrigation event (31 July) showed the highest VPD. No precipitation was recorded during the *transpiration-measured* irrigation events.

3.2 Microclimatic changes

The time evolution of air temperature and VPD recorded from 2 h before until 6 h after the *transpiration-measured* irrigation event on 6 August 2008 is shown in Fig. 2. Before the irrigation event, there was a period for which there were no differences between treatments; but as the center pivot was approaching transect AC, the values recorded at the *moist* treatment started to decrease compared to the dry treatment (phase *before*). For the phase *during*, that decrease became much higher. Finally, for the phase *after*, the observed reductions at the *moist* treatment, although gradually diminishing, lasted for some time until finally the values became again similar to those recorded at the *dry* treatment. In general, this time evolution was similar to that observed for all *transpiration-measured* irrigation events.

In general terms, the evolution of the monitored variables studied in this work during and after the *transpiration-measured* irrigation events was similar to that described in previous works (Steiner et al. 1983; Thompson et al. 1993; Tolk et al. 1995; Saadia et al. 1996; Liu and Kang 2006a; Cavero et al. 2009). However, a reduction of the air temperature and VPD before the pivot irrigated the AC transect has not been previously observed. Monteith and Unsworth (2008) indicated that the values recorded by a meteorological station are affected by the vegetation type and characteristics and the plant-atmosphere interchange within the fetch distance surrounding the station, particularly upwind the measurement spot. Roughly, the fetch distance is estimated as 100 times the measurement height; thus, in this work, the fetch distance was about 290 m around the station skewed to the upwind direction. Due to the rotating movement of the pivot, the nearby areas were already being moistened by irrigation as the pivot was approaching the transect AC, leading to microclimatic changes at those nearby areas, within the fetch distance of the station at that transect. Then those microclimatic changes at the nearby areas were likely causing the differences among treatments observed at the phase *before*. This effect was somewhat larger when the wind was blowing from the east as the pivot rotation was counter-clockwise. Thus, the average decrease in air temperature and VPD were about 0.7 °C and 0.21 kPa, respectively, with a duration of about 0.9-1.0 h for those events for which predominant wind direction was east (with average windspeed of about 1.9 m s^{-1}), while the average decrease in air temperature and VPD were about 0.5 ºC and 0.15 kPa, respectively, with a duration of about 0.5-0.7 h for those events for which wind was blowing from other directions (with average windspeed of about 3.0 m s^{-1}).

The differences between treatments for the air temperature and VPD during the *transpiration-measured* irrigation events were significant (P=0.05) for the three phases, *before*, *during* and *after*, and the three pivot arm portions (Tables 4 and 5). For the phase *before*, the average decreases for the *moist* treatment were 0.5 to 0.7 °C (2.1 to 2.8 %) for air temperature, and 0.16 to 0.25 kPa (14.2 to 20.6 %) for VPD of the air. The average duration of phase *before* was 0.6 to 0.8 h for air temperature and 0.6 to 0.7 h for VPD of the air. For the phase *during*, the average decreases for the *moist* treatment were much higher than those for the phase *before* and amounted 1.8 to 2.1 ºC (7.1 to 8.2%) for air temperature and 0.53 to 0.61 kPa (37.8 to 45.9%) for VPD of the air. Finally, for the phase *after*, the decreases for the *moist* treatment were lower than those for the phase *during* amounting 0.8 to 1.3 ºC (2.8 to 4.9%) for air temperature and 0.30 to 0.41 KPa (14.8 to 26.6%) for VPD of the air.

The observed decreases in air temperature and VPD in this study were similar to the reductions in the long-term daily averages of air temperature and VPD due to center pivot sprinkler irrigation reported by Steiner et al. (1983). The decreases in air temperature and VPD listed on Tables 4 and 5 for the phases *during* and *after* were within the ranges reported by previous works on sprinkler irrigation with other irrigation systems (Thompson et al., 1993; Tolk et al., 1995; Saadia et al., 1996; Liu and Kang 2006a; Cavero et al., 2009). The decrease in air temperature and VPD lasted about 1.3

h after the irrigation event finished (Tables 4 and 5), which is similar to durations reported in other works (Thompson et al., 1993; Tolk et al., 1995; Saadia et al., 1996; Cavero et al., 2009).

For the *remaining* irrigation events, the air temperature for the *moist* treatment significantly decreased 1.4 to 1.6 °C (5.3 to 6.0 %) on average, while the VPD of the air significantly decreased 0.46 to 0.48 kPa (24.2 to 26.2 %) on average (Table 6). These decreases were slightly higher than those observed for the *transpiration-measured* irrigation events when the phases *before*, *during* and *after* were integrated into a single period (Table 6). This slight difference between the microclimatic changes observed for the *transpiration-measured* and those for the *remaining* irrigation events was probably due to the climatic conditions during both measurement periods. As discussed later, the observed decreases in air temperature and VPD for the *moist* treatment were higher as the air temperature and VPD at the 'nearby grass station' were higher (Figs.3 and 4). Given that the *transpiration-measured* irrigation events were monitored early in the morning while the *remaining* irrigation events covered the whole daytime period, air temperature and VPD at the 'nearby grass station' were lower during the *transpiration-measured* irrigation events. Thus, changes were slightly lower in the *transpiration-measured* irrigation events.

The magnitude of the decreases in air temperature and VPD for the *moist* treatment was, in general terms, relatively similar between the three pivot arm portions for both *transpiration-measured* and *remaining* irrigation events (Table 6); nevertheless the decreases in VPD of the air for the phase *after* at the former irrigation events slightly increased from the center to the end of the pivot (Table 5). The main difference between the three pivot arm portions was the duration of those decreases in air temperature and

VPD. That duration was highly variable as indicated by the high coefficients of variation obtained (Tables 4 to 6), but, on average, the total durations of the microclimatic changes observed for the *transpiration-measured* irrigation events (when integrating the three phases *before*, *during* and *after*) were much higher at pivot arm portion 2 (the closest to the center of the pivot) than the duration at the pivot arm portion 5, the furthest from the center of the pivot. Relatively similar results were observed for the *remaining* irrigation events; the duration of the microclimatic changes at pivot arm portion 2 was about 0.6 h longer than the duration at pivot arm portion 5 (Table 6). There were no differences in the duration of the microclimatic changes between the pivot arm portions 4 and 5. This difference in the duration of the microclimatic changes was mainly due to the longer duration of the irrigation at pivot arm portion 2 (Table 5) and at a lesser extent to the longer presence of the pivot irrigating nearby areas within the fetch distance to experimental weather station A such that the microclimatic changes in those areas were also affecting to the readings of that station.

The average decrease in air temperature and VPD observed both in the 7 *transpiration-measured* irrigation events and the 27 *remaining* irrigation events was higher as the air temperature and VPD measured over grass at the ‘nearby grass station’ were also higher (Figs. 3 and 4). The linear regressions between the decreases in air temperature for the *moist* treatment and the air temperature at the ‘nearby grass station’, and between the decreases in VPD of the air for the *moist* treatment and the VPD of the air at the ‘nearby grass station’ were significant for the three pivot arm portions for the phase *during* at the *transpiration-measured* irrigation events (Figs. 3A and 4A) and for the whole period of microclimatic changes at the *remaining* irrigation events (Figs. 3B and 4B). The corresponding coefficients of determination ranged from 0.50 to 0.85. The

12 regression slopes shown in Figs. 3 and 4 were significant at P < 0.01 (except one significant at P=0.07). In general, the relationships between the microclimatic changes and the mean meteorological conditions at the ‘nearby grass station’ increased from pivot arm portion 2 to pivot arm portion 5. During the irrigation phase, the reduction of air temperature and VPD as the value of these variables increased in the ‘nearby grass station’ was greater in the outer pivot arm portion, probably due to the higher instantaneous water application rate. The relationships were stronger for the *transpiration-monitored* irrigation events (Figs. 3A and 4A) as they are calculated only for the phase *during*, while these relationships for the *remaining* irrigation events (Figs. 3B and 4B) were calculated for the whole period of microclimatic changes. These weaker relationships found at the *remaining* irrigation events were due to the integration of the three phases identified for the *transpiration-measured* irrigation events. In other words, including the microclimatic changes for the phases *before* and *after* smoothes the relationship between the general climatic conditions and the microclimatic changes observed for the phase *during*.

3.3 Physiological changes

Both physiological variables studied in this work (maize canopy temperature and transpiration) showed a similar behaviour for the monitored irrigation events. The time evolution recorded from 2 h before until 6 h after the *transpiration-measured* irrigation event on 6 August 2008 is shown in Fig. 2. Before the irrigation event, there was a period for which there were no differences between treatments. As the center pivot was approaching to transect AC, the canopy temperature and maize transpiration recorded at the *moist* treatment started to decrease compared to the dry treatment (phase *before*). For the phase *during*, that decrease became much higher. Finally, for the phase *after*, the observed reductions at the *moist* treatment, although gradually diminishing, lasted for some time until finally the values became again similar to those recorded at the *dry* treatment. Thus, for the *transpiration-measured* irrigation events phase *before* the canopy temperature and the transpiration rates for the *moist* treatment decreased 1.0 to 1.2 ºC (4.3 to 5.2%) and 0.15 to 0.19 mm h^{-1} (23.8 to 31.7 %), respectively (Tables 7 and 8). For the phase *during*, these decreases were higher and ranged from 3.1 to 3.8 ºC (11.7 to 14.5 %) for canopy temperature and from 0.22 to 0.28 mm h^{-1} (30.1 to 36.4 %) for transpiration rates. For the phase *after*, the physiological changes were smaller; thus the decreases for the *moist* treatment ranged from 1.1 to 1.4 ºC (4.0 to 5.2 %) for canopy temperature and 0.14 to 0.24 mm h^{-1} (17.1 to 27.9 %) for transpiration rates (Tables 7 and 8).

The magnitude and duration of the canopy temperature decreases for the *moist* treatment for the *remaining* irrigation events were similar to those observed for the *transpiration-measured* irrigation events when integrating the three phases, *before*, *during* and *after* (Table 6). Again, integrating the phases *before* and *after* smoothes the canopy temperature changes observed for the phase *during*. On average, the decrease of canopy temperature for the *remaining* irrigation events was 1.8 °C, which was similar in the *transpiration-measured* irrigation events.

Transpiration reduction due to irrigation in the *moist* treatment ranged from 0.75 mm (22%) to 1.03 mm (30%) (Table 8), with a higher reduction as closer to the center of the pivot. This represents between 5 to 7% of the applied water. Tolk et al. (1995) working with a lateral move sprinkler irrigation system found 1.59 mm (32%) transpiration reduction, which represented 10% of applied water. Considering the time period when transpiration changes occurred, the estimated crop evapotranspiration (ET_c) was also reduced in the *moist* treatment (Table 9). However, the reduction of ET_c (8 to 10%) in the *moist* treatment was less than the reduction of transpiration (22 to 30%) and was similar in the different pivot arm portions. In general, ET_c reduction *before* and *after* irrigation was less than 8%, and was around 15% *during* the irrigation. The ET_c reduction due to irrigation in the *moist* treatment ranged from 0.22 mm (8%) to 0.26 mm (10%) (Table 9), which represents 1.5 to 1.8% of the applied water. This reduction must be taken into account when calculating the irrigation requirements. Frost and Schwallen (1960) reported a 18% decrease of crop evapotranspiration due to sprinkler irrigation, which was greater than the 8 to 10% estimated in our work.

Transpiration reduction *during* irrigation was related to the decrease of air temperature and VPD, but not to the decrease of canopy temperature (Fig. 5). The strongest relationship was with the decrease of air VPD as found by others (Tolk et al. 1995; Ray et al. 2002; Yu et al. 2003). A stepwise regression analysis of the transpiration reduction versus the decrease of air temperature, of air VPD and of canopy temperature showed that the reduction of air VPD was the only variable that explained the transpiration reduction. However, for the phases *before* and *after* the smaller changes in all these variables did not allow to establish a clear relationship with the slight reduction of transpiration rate (Fig. 5).

Similar to the microclimatic change of air VPD due to irrigation, the transpiration rate reduction was also greater when the VPD of the air at the ‘nearby grass station’ was higher (drier days). Thus, Fig. 6 shows the strong relationship between the transpiration reduction due to irrigation and the VPD of the air at the ‘nearby grass station’. This result agrees with previous works (Tolk et al. 1995; Martínez-Cob et al. 2008; Cavero et al. 2009). However, the reduction of canopy temperature was not related to the VPD of the air but for the pivot arm portion 4 was greater when the temperature of the air at the 'nearby grass station' was higher (warmer days) (Fig. 7). The strength of the relationship between transpiration reduction and the VPD of the air was higher for the pivot arm portions 4 and 5 (Fig. 6). These results suggests that physiological changes due to sprinkler irrigation in the areas furthest from the centre of the pivot were more affected by the general climatic conditions outside the plot. Likewise, the results of Figs. 3A, 4A, 6 and 7 indicate that the microclimatic and physiological changes are more relevant under high evaporative demand conditions as those changes are the result of the evaporation of a portion of the applied water during the irrigation.

The existence of microclimatic and physiological changes before the plants receive the irrigation water had not been previously reported in detail for sprinkler irrigation systems and it was likely due to the effect of the changes occurring in the nearby areas as the pivot arm was moving towards the monitored transect. This specific behaviour of the pivot irrigation systems before the irrigation events deserves to be modelled by sprinkler irrigation efficiency models that also include the microclimatic and physiological changes due to the irrigation (Zhao et al., 2012). Thus, the results reported here can be helpful for the improvement and application of those models under different conditions and scenarios.

The relative decrease of the canopy temperature due to irrigation was somewhat higher than that of the air temperature, while the relative decrease of the transpiration due to irrigation was higher than that of the VPD of the air. Also, the physiological changes for the phases *before* and *after* lasted, in general, longer than the microclimatic changes (Tables 4, 5, 7 and 8). There was a slight tendency for this duration being longer for the pivot arm portions 4 and 5 with respect to pivot arm portion 2. In general terms, the decreases in canopy temperature and transpiration rates for the phase *during* observed in this work were lower than those reported for solid-set sprinkler irrigation systems (Cavero et al. 2009) and lateral-move sprinkler irrigation systems (Tolk et al. 1995) irrigating also a maize crop. Cavero et al. (2009) argued that higher application rates of irrigation water increase the cooling effect on plants and thus enhance the canopy temperature decreases at the *moist* treatment. In this study, application rates for the pivot arm portion 4 (21.8 mm h^{-1}) were much higher than those of the studies by Tolk et al. (1995) and Cavero et al. (2009), which were much closer to the application rates for the pivot arm portion 2 (8.9 mm h^{-1}) in this study. The duration of the irrigation event was much shorter in our study than at the two abovementioned works. This shorter irrigation duration could explain why the cooling effect of the irrigation water on canopy temperature was less than in the works of Tolk et al. (1995) and Cavero et al. (2009). Fig. 2 shows that the decrease in canopy temperature progresses as the irrigation is occurring. Thus shorter irrigation durations would lead to smaller canopy temperature decreases for the *moist* treatment. In addition to the shorter duration of the irrigation event (phase *during*), the lower decreases in air temperature, VPD of the air and transpiration rates (Tables 4, 5, 7 and 8) at the *moist* treatment obtained in this work compared with those reported by Tolk et al. (1995) and Cavero et al. (2009) were also probably due to the climatic conditions during those events, which in this work were performed before solar noon when the evaporative demand and the VPD of the air are, in general, lower than those for afternoon periods when the irrigations reported by those authors were performed. Despite the shorter duration of the *transpiration-measured* irrigation events in this study, the average canopy temperature decrease for pivot arm portion 4 was higher than that of pivot arm portion 2 which agrees with the influence of the application rates as suggested by Cavero et al. (2009).

These microclimatic and physiological changes are the consequence of the evaporation of irrigation applied water while travelling through the air and the evaporation of intercepted water by stem and leaves of the plants. The amount of intercepted water depends mainly on the architecture of the crop and in the case of maize values of 0.4 to 2.7 mm have been reported (Norman and Campbell 1983; Steiner et al. 1983). Thus, the volume of water evaporated during the irrigation is usually higher than that evaporated after the irrigation. Subsequently, the microclimatic and physiological changes are usually higher for the phase *during* than those for the phase *after*.

The temperature and VPD of the air were measured at 0.5 m above the crop canopy while canopy temperature is measured at the crop canopy height and transpiration of the plant with the sap flow integrates the transpiration along all the plant height. Cavero et al. (2009) found that the microclimatic changes due to sprinkler irrigation (decrease of air temperature and VPD) were smaller and lasted for less time after the irrigation as the measurement height was higher. Thus, the lower height of measurement of physiological changes (canopy temperature and plant transpiration) could explain that these changes lasted longer and were greater than the microclimatic changes.

4. CONCLUSIONS

- Center pivot sprinkler irrigation significantly reduced air temperature and VPD (microclimatic changes) and canopy temperature and maize transpiration rates (physiological changes). These changes occurred for some time before (about 0.6 to 2.1 h), during and some time after (about 0.8 to 2.4 h) the irrigation events.

- Physiological changes lasted longer than microclimatic changes, particularly after the irrigation events, likely due to the effect of the evaporation of the intercepted water and to the higher measurement height of microclimatic changes.
- Center pivot sprinkler irrigation decreased the air temperature by 1.8 to 2.1 °C, the air VPD by 0.53 to 0.61 kPa, the canopy temperature by 3.1 to 3.8 °C and the transpiration rate by 0.22 to 0.28 mm h^{-1}. These decreases were lower for the phases *before* and *after* and were greater in drier and warmer days.
- The duration of the microclimatic changes decreased as the distance from the centre of the pivot increased, but the duration of the physiological changes was similar in the different pivot arm portions.
- Transpiration reduction due to irrigation was higher as closer to the center of the pivot and represented between 5 to 7% of the applied water. However, the reduction of ET was similar in the different pivot arm portions and represented 1.5 to 1.8% of the applied water.
- The decrease in maize canopy temperature could be positive or negative, depending on its effect on photosynthesis. The reduction of transpiration and ET must be considered positive because it represents a reduction of irrigation requirements. Whether the physiological changes will result in increased plant production should be further studied.

REFERENCES

Allen, R.G., Pruitt, W.O., Businger, J.A., Fritschen, L.J., Jensen, M.E., and Quinn, F.H. 1996. Evaporation and Transpiration. Hydrology Handbook (Manuals and Reports on Engineering Practice No. 28). American Society of Civil Engineers (ASCE), Nueva York, EE.UU. 768 pp.

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome, Italy.

Allen, R.G., Keller, J., and Martin, D. 2000. Center Pivot System Design. The Irrigation Association VA, USA. 300 p.

Baker, J.M., and Van Bavel, C.H.M. 1987. Measurement of mass flow of water in the stems of herbaceous plants. Plant Cell & Environment, 10: 777-782.

Cavero, J., Zaragoza, C., Suso, M.L., and Pardo, A. 1999. Competition between maize and Datura stramonium in an irrigated field under semi-arid conditions. Weed Research, 39: 225-240.

Cavero, J., Zaragoza, C., Bastiaans, L., Suso, M.L., and Pardo, A. 2000. The relevance of morphological plasticity in the simulation of competition between maize and Datura stramonium. Weed Research, 40: 163-180.

Cavero, J., Medina, E.T., Puig, M., and Martinez-Cob, A. 2009. Sprinkler Irrigation Changes Maize Canopy Microclimate and Crop Water Status, Transpiration, and Temperature. Agronomy Journal, 101: 854-864.

Evans, R.G. 2001. Center Pivot Irrigation; Research Report; USDA-Agricultural Research Service: Sidney, MT, USA.

Farahani, H.J., and Bausch, W.C.1995. Performance of evapotranspiration models for maize-bare soil to closed canopy. Transactions of the ASAE, 38: 1049-1059.

Frost, K.R., and Schwalen, H.C. 1960. Evapotranspiration during sprinkler irrigation. Transactions of the ASAE, 3: 18-20, 24.

Howell, T.A., Hiler, E.A., and Van Bavel, C.H.M. 1971. Crop response to mist irrigation. Transactions of the ASAE, 14: 906-910.

Kjelgaard, J.F., Stockle, C.O., Villar, J.M., Evans, R.G., and Campbell, G.S. 1994. Evaluating methods to estimate corn evapotranspiration from short-time interval weather data. Transactions of the ASAE, 37: 1825-1833.

Liu, H.J., and Kang, Y.H. 2006a. Effect of sprinkler irrigation on microclimate in the winter wheat field in the North China Plain. Agricultural Water Management, 84: 3-19.

Liu, H.J., and Kang, Y.H. 2006b. Regulating field microclimate using sprinkler misting under hot-dry windy conditions. Biosystems Engineering, 95: 349-358.

MAGRAMA 2011. Encuesta de superficies y rendimientos de cultivos en España (ESYRCE). Ministerio de Agricultura, Alimentación y Medio Ambiente.

MARM 2011. Sistema de Información Agroclimática para el Regadío (SIAR). http://www.marm.es/es/agua/temas/observatorio-del-regadio-espanol/sistema-de-informacion-agroclimatica-para-el-regadio/. Spanish Ministry of Natural, Rural and Marine Environment (MARM). Data were downloaded on January 2011.

Martinez-Cob, A., Playan, E., Zapata, N., Cavero, J., Medina, E.T., and Puig, M. 2008. Contribution of evapotranspiration reduction during sprinkler irrigation to application efficiency. Journal of Irrigation and Drainage Engineering, 134: 745-756.

Monteith, J.L., and Unsworth, M.H. 2008. Principles of environmental physics, 3rd edn. Burlington, MA, USA.

Norman, J. M., and Campbell, G. 1983. Application of a plant-environment model to problems in irrigation. In: D. Hillel, (Ed.), Advances in Irrigation. Academic Press, New York, vol. 2, pp. 155-188.

Norman, E., Joyce, R., and Whittaker, M. 1990. Advanced design and technology. 3rd ed. Longman, Harlow, Essex.

Ray, J.D., Gesch, R.W., Sinclair, T.R., and Allen, L.H. 2002. The effect of vapour pressure deficit on maize transpiration response to a drying soil. Plant Soil, 238: 113–121.

Robinson, F.E. 1970. Modifying an arid microclimate with sprinklers. Agricultural Engineering, 51: 465.

Saadia, R., Huber, L., and Lacroix , B. 1996. Using evaporative cooling to fight heat stress in corn. The potential of sprinkler irrigation to reduce air and reproductive organ temperature. Agronomie, 16: 465-477.

Steiner, J.L., Kanemasu, E.T., and Hasza, D. 1983. Microclimatic and crop responses to center pivot sprinkler and to surface irrigation. Irrigation Science, 4: 201-214.

Thompson, A.L., Gilley, J.R., and Norman, J.M. 1993. A sprinkler water droplet evaporation and plant canopy model: II. Model application. Transactions of the ASAE, 36: 743-750.

Tolk, J.A., Howell, T.A., Steiner, J.L., Krieg, D.R., and Schneider, A.D. 1995. Role of transpiration suppression by evaporation of intercepted water in improving irrigation efficiency. Irrigation Science, 16: 89-95.

USDA 2008. Farm and Ranch Irrigation Survey (2008), Vol. 3, Special Studies-Part 1 of the 2007 Census of Agriculture, AC-07-SS-1, National Agricultural Statistics Service, (Updated July 2010).

Van Bavel, M.G. 2005. Flow4 Installation and Operation Manual, Dynamax Inc., Houston, Texas, 191 pp.

Wanjura, D.F., and Upchurch, D.R. 2000. Canopy temperature characterizations of corn and cotton water status. Transactions of the ASAE, 43:867-875.

Weibel, F.P., and Boersma, K. 1995. An improved stem heat-balance method using analog heat control. Agricultural and Forest Meteorology, 75: 191-208.

Yu, G.R., Kobayashi, T., Zhuang, J., Wang, Q.F., and Qu, L.Q. 2003. A coupled model of photosynthesis-transpiration based on the stomatal behaviour for maize (Zea mays L.) grown in the field. Plant Soil, 249: 401–416.

Zhao, W., Li, J., and Li, Y. 2012. Modeling sprinkler efficiency with consideration of microclimate modification effects. Agricultural Water Management, 161: 116-122.

Table 1. Main characteristics of the center pivot system.

Pivot arm portion	Distance from centre pivot	Number of sprinklers	Nozzle diameters	Spacing between sprinklers
	m		mm	m
1	0 – 48	5	2.8 - 4.8	9.3
2	48 – 98	7	4.8 - 5.4	7.0
3	98 – 147	8	4.2 - 5.8	6.2
4	147 – 197	8	4.8 - 6.0	6.2
5	197 – 246	16	4.2 - 6.0	3.1
6	246 – 295	16	4.4 - 5.6	3.1
Overhang	295 – 321	8	4.6 - 5.4	2.9

Table 2. Mean characteristics of the *transpiration-measured* irrigations events.

Pivot arm section	Date	Starting time[a]	Duration	Pressure		Applied water depth
				Mean	CV[b]	
		-------- h --------		KPa	%	mm
2	24 July	0825	1.70	208		14.6
	31 July	0935	1.62	218	0.8	14.9
	6 August	0900	1.62	214	0.5	14.8
	13 August	0905	1.55	216	0.6	14.2
	21 August	0920	1.55	198	1.0	13.6
	28 August	0945	1.62	207	1.0	14.5
	10 September	1015	1.62	208	3.3	14.6
4	24 July	0840	0.62	193	2.2	13.6
	31 July	0955	0.60	197	1.6	13.8
	6 August	0915	0.60	194	1.9	13.6
	13 August	0920	0.57	197	1.0	13.1
	21 August	0935	0.57	177	2.4	12.4
	28 August	1000	0.60	181	1.9	13.2
	10 September	1030	0.60	194	1.6	13.7
5	24 July	0840	0.50	195	0.3	14.4
	31 July	0955	0.48	199	1.3	14.5
	6 August	0920	0.48	197	1.5	14.5
	13 August	0920	0.45	200	0.7	13.9
	21 August	0940	0.45	174	0.8	13.0
	28 August	1000	0.48	179	0.9	13.8
	10 September	1030	0.48	202	0.6	14.7

[a] Greenwich Mean Time.

[b] CV, coefficient of variation.

Table 3. Meteorological conditions during each *transpiration-measured* irrigation event, recorded at the ‘nearby grass station’ of Valfarta[a].

Date	Air temperature	Air vapor pressure deficit	Wind speed	Solar radiation
	ºC	kPa	$m\ s^{-1}$	$W\ m^{-2}$
24 July	28.0	1.9	2.0	742
31 July	32.5	3.6	1.5	880
6 August	29.9	2.6	1.8	772
13 August	22.8	1.7	3.5	723
21 August	27.4	1.7	2.0	780
28 August	26.6	1.6	0.9	768
10 September	27.3	1.8	1.6	651

[a] Station included in the network SIAR (Spanish Irrigation Advisory System) (MARM 2011).

Table 4. Average values of air temperature recorded in the *moist* (T_{MT}) and *dry* (T_{DT}) treatments before, during and after the *transpiration-measured* irrigation events at the pivot arm portions 2, 4 and 5.

Phase	Pivot arm portion	N[a]	Air Temperature				Duration	
			Mean T_{MT}	SD[b]	Mean T_{DT}	SD	Mean	CV[c]
			-----------------(ºC)			-----------------	h	%
Before	2	6	23.8 b[d]	± 1.7	24.4 a	± 1.9	0.8	20
	4	4	23.4 b	± 2.4	23.9 a	± 2.5	0.6	54
	5	4	24.4 b	± 2.0	25.1 a	± 2.1	0.7	43
During	2	7	23.5 b	± 1.9	25.6 a	± 2.4	1.6	3
	4	7	23.4 b	± 1.9	25.2 a	± 2.3	0.6	11
	5	7	23.2 b	± 1.6	25.2 a	± 2.3	0.5	10
After	2	7	27.9 b	± 2.5	28.7 a	± 2.3	1.5	21
	4	7	26.3 b	± 3.2	27.4 a	± 2.8	1.3	31
	5	7	25.1 b	± 2.5	26.4 a	± 2.3	1.0	29

[a] Number of *transpiration-measured* irrigation events.

[b] Standard deviation.

[c] Coefficient of variation.

[d] For each phase and pivot arm portion the air temperature values marked with different letters indicate that they were significantly different after a paired *t*-test (P = 0.05).

Table 5. Average values of air vapor pressure deficit recorded in the *moist* (T_{MT}) and *dry* (T_{DT}) treatments before, during and after the *transpiration-measured* irrigation events at the pivot arm portions 2, 4 and 5.

Phase	Pivot arm portion	N[a]	Vapor pressure deficit				Duration	
			Mean T_{MT}	SD[b]	Mean T_{DT}	SD	Mean	CV[c]
			-----------------(KPa) -----------------				h	%
Before	2	6	0.92 b[d]	± 0.37	1.11 a	± 0.45	0.7	43
	4	4	0.97 b	± 0.46	1.13 a	± 0.51	0.6	54
	5	4	1.01 b	± 0.40	1.26 a	± 0.48	0.7	43
During	2	7	0.87 b	± 0.25	1.40 a	± 0.44	1.6	3
	4	7	0.80 b	± 0.30	1.33 a	± 0.43	0.6	11
	5	7	0.72 b	± 0.20	1.33 a	± 0.44	0.5	10
After	2	7	1.72 b	± 0.51	2.02 a	± 0.51	1.4	21
	4	7	1.39 b	± 0.62	1.76 a	± 0.54	1.3	31
	5	7	1.13 b	± 0.37	1.54 a	± 0.41	1.1	30

[a] Number of *transpiration-measured* irrigation events.

[b] Standard deviation.

[c] Coefficient of variation.

[d] For each phase and pivot arm portion the air temperature values marked with different letters indicate that they were significantly different after a paired *t*-test (P = 0.05).

Table 6. Average values of air temperature, air vapor pressure deficit (VPD) and canopy temperature recorded in the *moist* (T_{MT}) and *dry* (T_{DT}) treatments along the different pivot arm portions (PAP) for the 7 *transpiration-measured* irrigation events and the 27 *remaining* irrigation events.

		Transpiration-measured irrigation events				*Remaining* irrigation events			
				Duration				Duration	
Variable	PAP	T_{MT}	T_{DT}	Mean[a]	CV[b]	T_{MT}	T_{DT}	Mean	CV
		------- ºC -------		h	%	------- ºC ------		h	%
Air temperature	2	25.4 b[c]	26.7 a	3.8	9	25.0 b	26.6 a	3.0	30
	4	25.1 b	26.2 a	2.3	28	25.2 b	26.8 a	2.4	29
	5	24.5 b	25.7 a	2.0	26	25.1 b	26.5 a	2.4	33
		------- kPa ------				------ kPa ------			
Air VPD	2	1.21 b	1.58 a	3.6	14	1.38 b	1.84 a	3.0	30
	4	1.20 b	1.56 a	2.3	28	1.44 b	1.90 a	2.4	29
	5	1.03 b	1.43 a	2.1	23	1.35 b	1.83 a	2.4	33
		------- ºC -------				------- ºC -------			
Canopy temperature	2	23.1 b	24.9 a	4.1	30	24.2 b	26.0 a	4.0	22
	4	23.0 b	24.7 a	4.5	36	24.3 b	26.1 a	3.6	21

[a], Mean duration.

[b], Coefficient of variation.

[c] For each variable, pivot arm portion and irrigation type event the values marked with different letters were significantly different after a paired *t*-test (P = 0.05).

Table 7. Average values of canopy temperature recorded in the *moist* (T_{MT}) and *dry* (T_{DT}) treatments before, during and after the *transpiration-measured* irrigation events at the pivot arm portions 2 and 4.

Phase	Pivot arm portion	N[a]	Canopy Temperature				Duration	
			Mean T_{MT}	SD[b]	Mean T_{DT}	SD	Mean	CV[c]
			-----------------(°C) -----------------				h	%
Before	2	7	22.3 b[d]	± 2.7	23.3 a	± 2.8	1.8	64
	4	7	22.0 b	± 2.6	23.2 a	± 2.8	2.1	56
During	2	7	23.3 b	± 2.1	26.4 a	± 2.0	1.6	3
	4	7	22.4 b	± 1.9	26.2 a	± 2.0	0.6	11
After	2	7	26.2 b	± 2.2	27.3 a	± 1.9	0.8	84
	4	7	25.5 b	± 1.9	26.9 a	± 1.7	1.7	44

[a] Number of *transpiration-measured* irrigation events.

[b] Standard deviation.

[c] Coefficient of variation.

[d] For each phase and pivot arm portion the canopy temperature values marked with different letters indicate that they were significantly different after a paired *t*-test (P = 0.05).

Table 8. Average values of transpiration rate recorded in the *moist* (T_{MT}) and *dry* (T_{DT}) treatments before, during and after the *transpiration-measured* irrigation events at the pivot arm portions (PAP) 2, 4 and 5. The transpiration reduction duration and magnitude is also shown.

Phase	PAP	N[a]	Transpiration rate				Duration		Transpiration reduction	
			T_{MT}	SD[b]	T_{DT}	SD	Mean	CV[c]	Mean	
			----------------- mm h^{-1} -----------------				h	%	mm	%
Before	2	3	0.48 b[d]	± 0.15	0.63 a	± 0.14	1.0	76	0.15	24
	4	7	0.41 b	± 0.07	0.60 a	± 0.15	0.9	67	0.17	31
	5	3	0.53 b	± 0.17	0.69 a	± 0.18	1.7	60	0.27	24
During	2	7	0.48 b	± 0.08	0.75 a	± 0.15	1.6	3	0.45	36
	4	7	0.51 b	± 0.06	0.73 a	± 0.15	0.6	11	0.15	30
	5	7	0.49 b	± 0.07	0.77 a	± 0.14	0.5	10	0.14	36
After	2	7	0.62 b	± 0.16	0.86 a	± 0.11	1.8	73	0.43	28
	4	7	0.58 b	± 0.15	0.80 a	± 0.14	2.4	48	0.54	28
	5	7	0.68 b	± 0.11	0.82 a	± 0.13	2.4	63	0.34	17
All	2						3.9	43	1.03	30
	4						4.0	35	0.86	29
	5						3.6	67	0.75	22

[a] Number of *transpiration-measured* irrigation events.

[b] Standard deviation.

[c] Coefficient of variation.

[d] For each phase and pivot arm portion the transpiration rate values marked with different letters indicate that they were significantly different after a paired *t*-test (P = 0.05).

Table 9. Average values of evapotranspiration (ET) rate estimated in the *moist* (T_{MT}) and *dry* (T_{DT}) treatments before, during and after the *transpiration-measured* irrigation events at the pivot arm portions (PAP) 2, 4 and 5. The duration of periods was the same as for transpiration. The ET reduction magnitude is also shown.

Phase	PAP	N[a]	ET rate				ET reduction	
			T_{MT}	SD[b]	T_{DT}	SD	Mean	
			---------------- mm h^{-1} ----------------				mm	%
Before	2	3	0.56 b[c]	± 0.09	0.60 a	± 0.08	0.04	7.7
	4	7	0.57 b	± 0.07	0.59 a	± 0.07	0.02	3.5
	5	3	0.58 b	± 0.11	0.63 a	± 0.09	0.06	8.0
During	2	7	0.62 b	± 0.11	0.72 a	± 0.12	0.16	13.8
	4	7	0.60 b	± 0.11	0.70 a	± 0.12	0.07	14.9
	5	7	0.58 b	± 0.10	0.70 a	± 0.12	0.06	16.8
After	2	7	0.84 b	± 0.16	0.89 a	± 0.15	0.08	6.2
	4	7	0.76 b	± 0.16	0.82 a	± 0.13	0.14	8.2
	5	7	0.73 b	± 0.14	0.79 a	± 0.13	0.13	7.6
All	2						0.26	9.6
	4						0.22	7.8
	5						0.22	9.3

[a] Number of *transpiration-measured* irrigation events.

[b] Standard deviation.

[c] For each phase and pivot arm portion the ET rate values marked with different letters indicate that they were significantly different after a paired *t*-test (P = 0.05).

Figure_1

Click here to download high resolution image

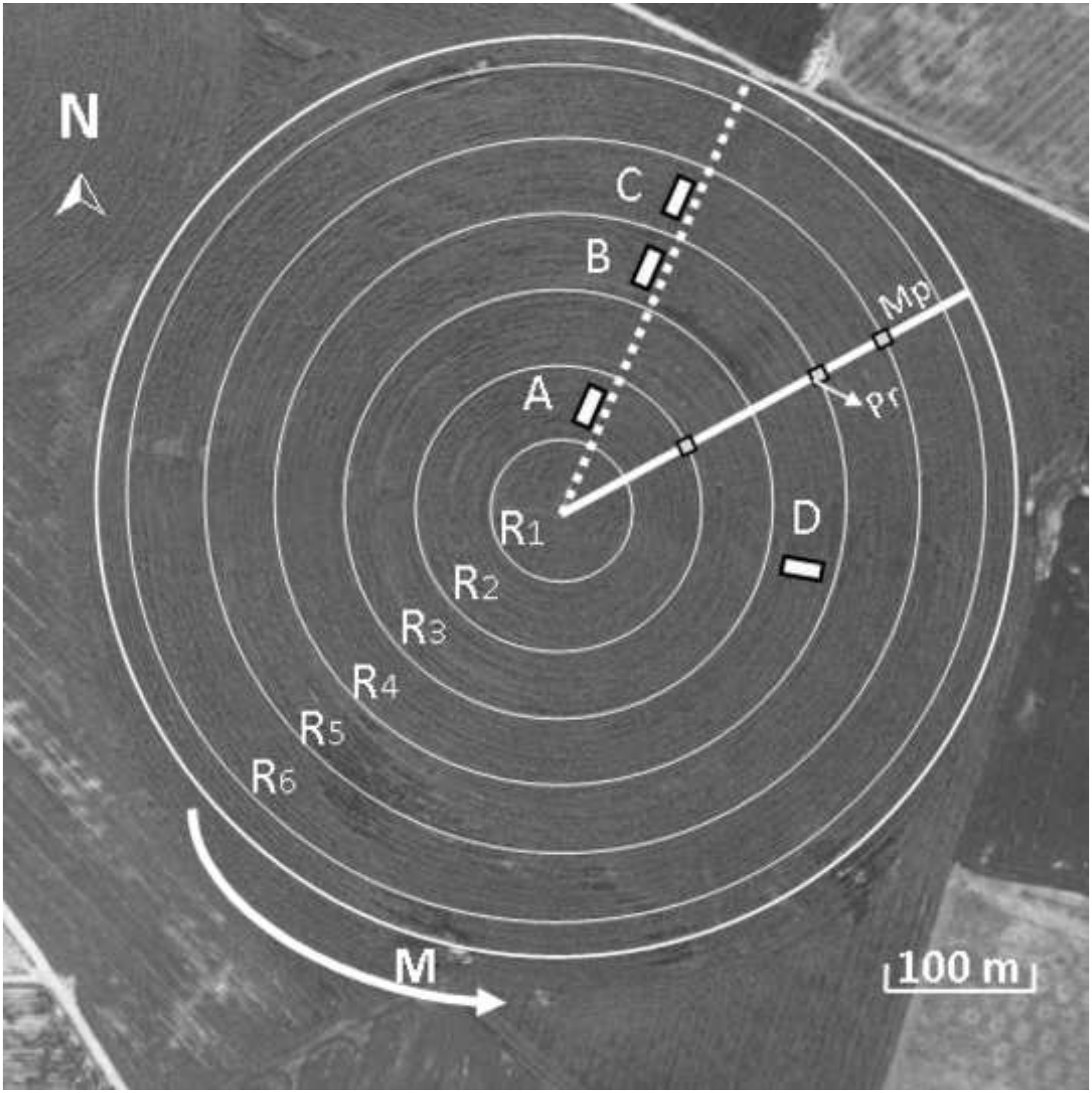

Figure_2

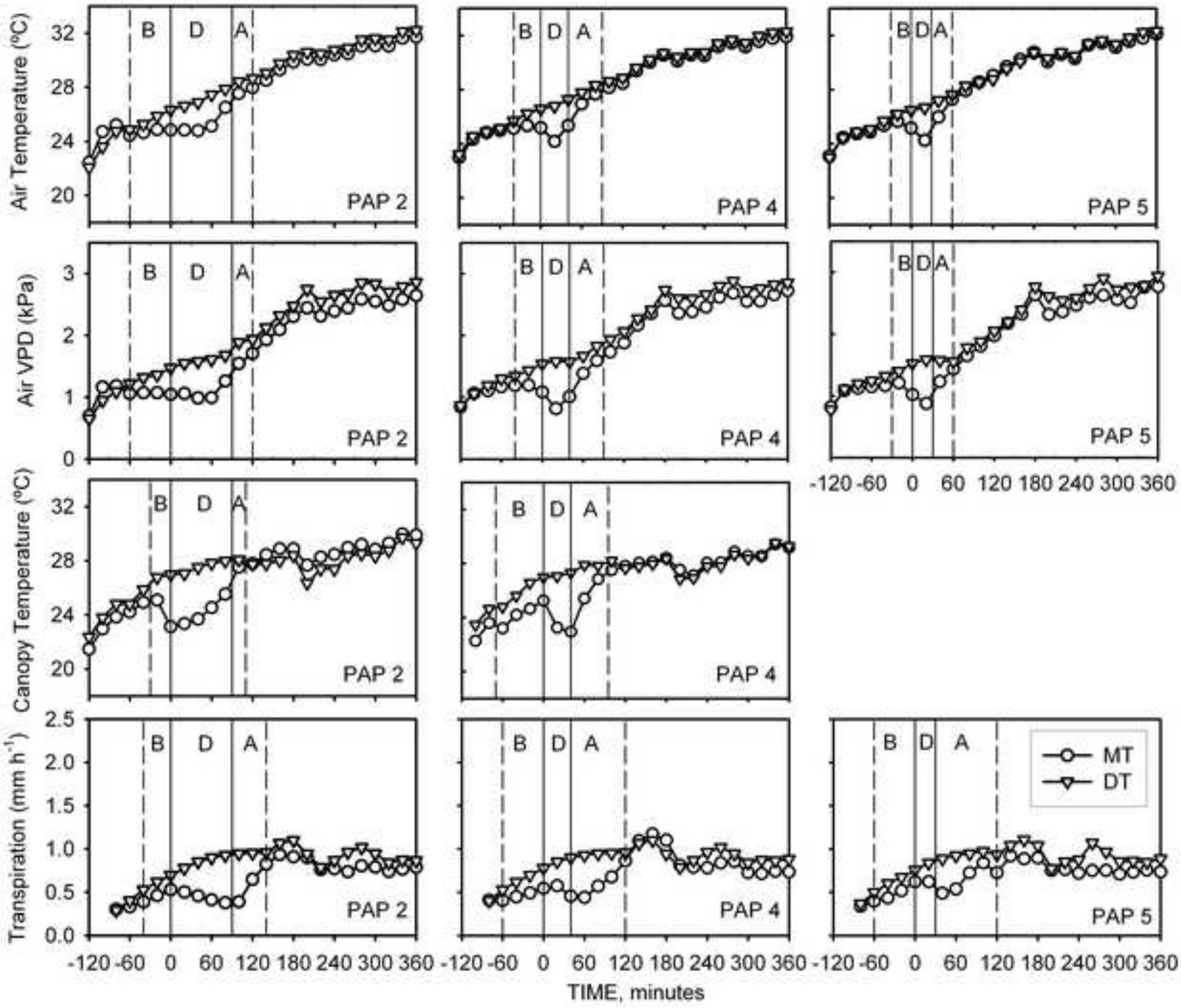
Air Temperature (ºC)
32
28
24
20
Air VPD (kPa)
3
2
1
0
Canopy Temperature (ºC)
32
28
24
20
Transpiration (mm h-1)
2.5
2.0
1.5
1.0
0.5
0.0
B
D
A
PAP 2
PAP 4
PAP 5
MT
DT
-120
-60
0
60
120
180
240
300
360
TIME, minutes

Figure_3

Click here to download high resolution image

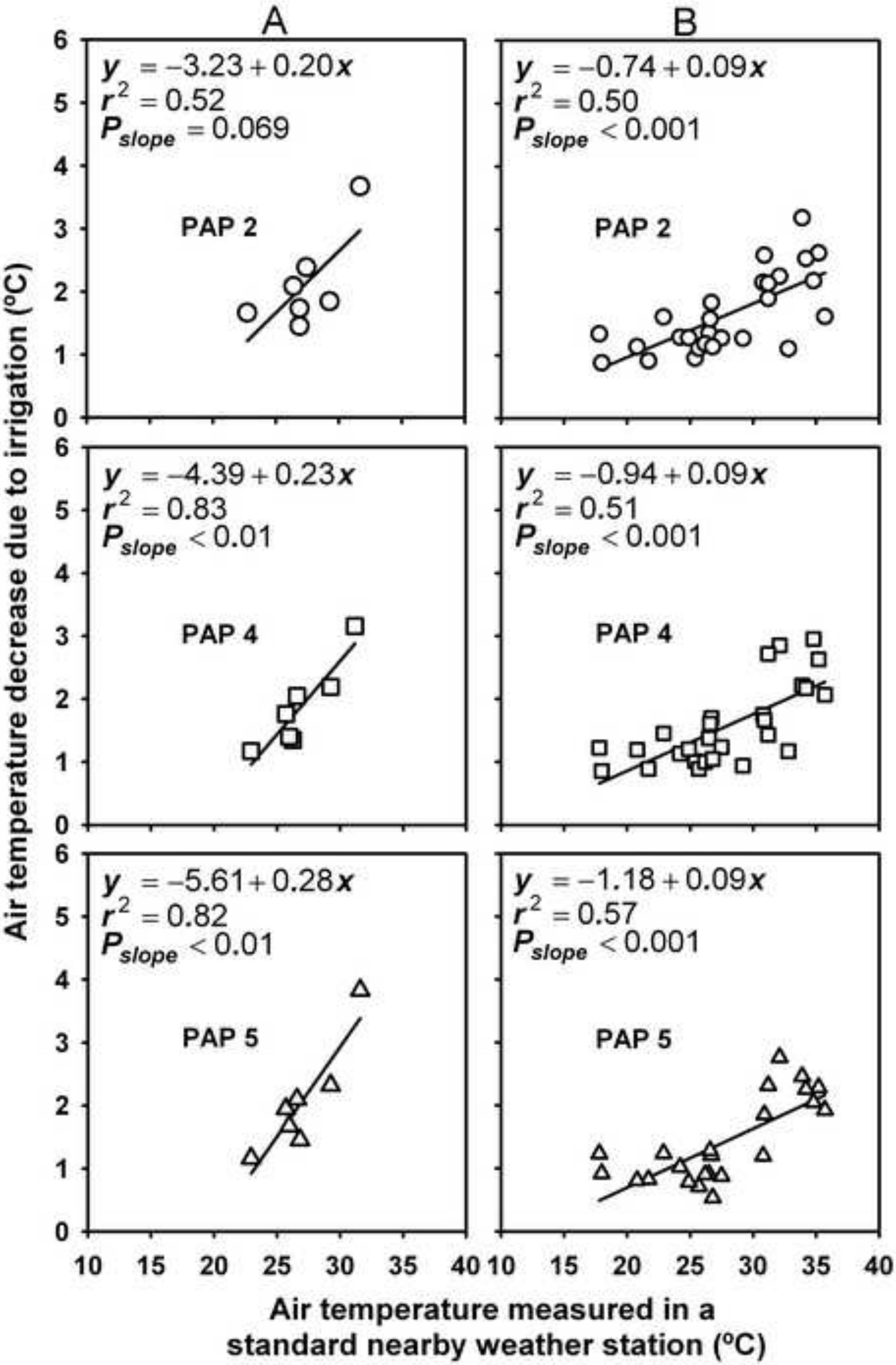

Figure_4

Click here to download high resolution image

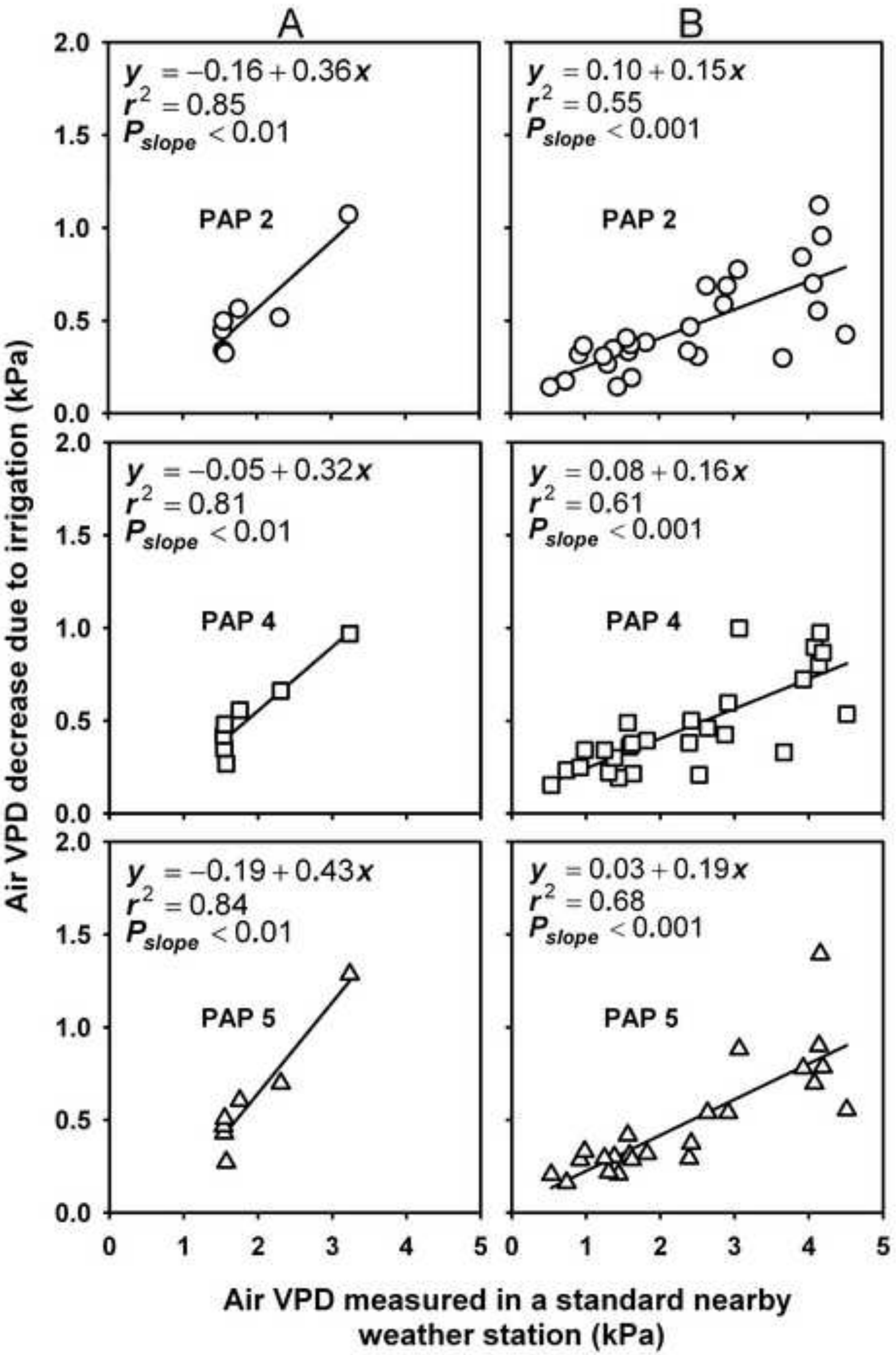

Figure_5

Click here to download high resolution image

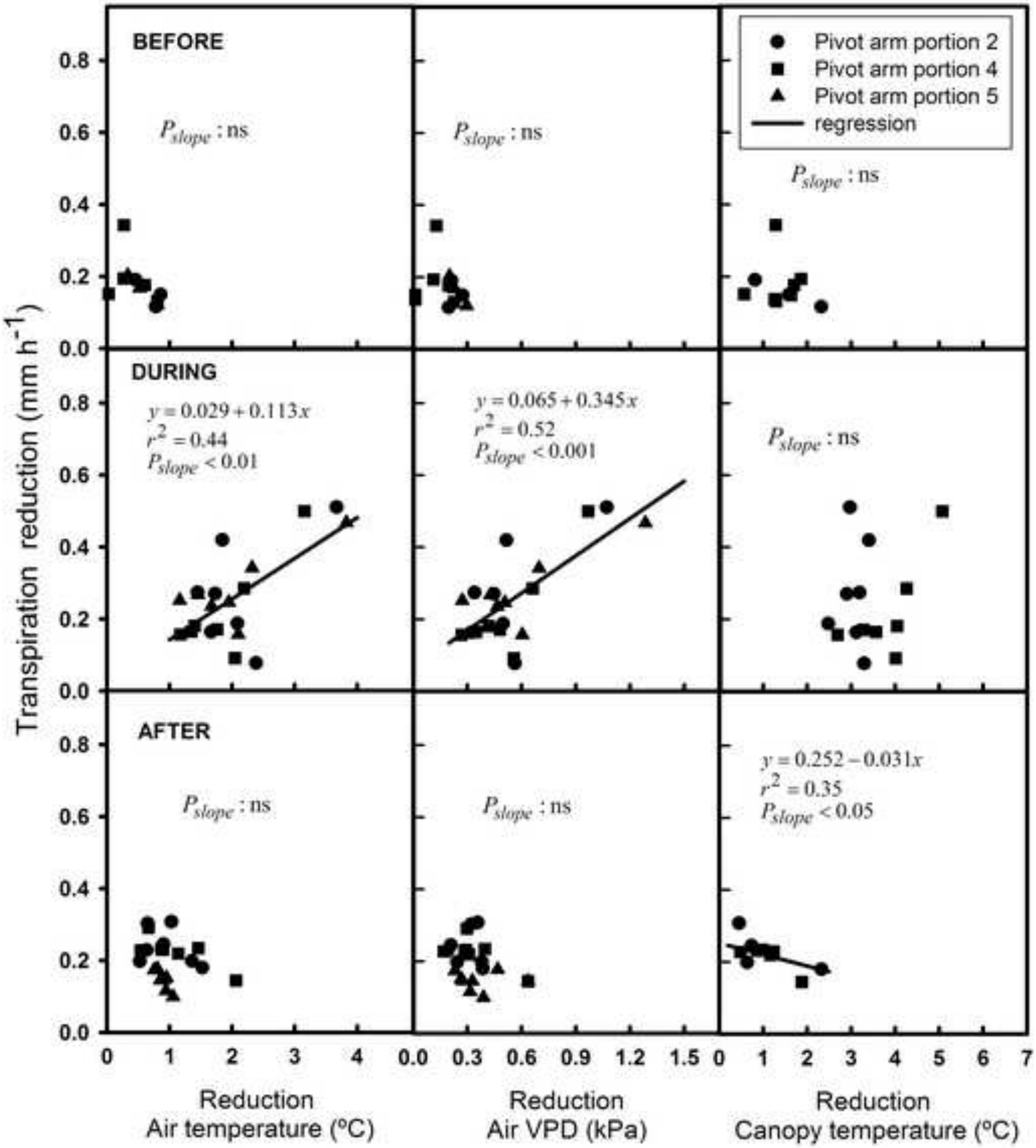

Figure_6

Click here to download high resolution image

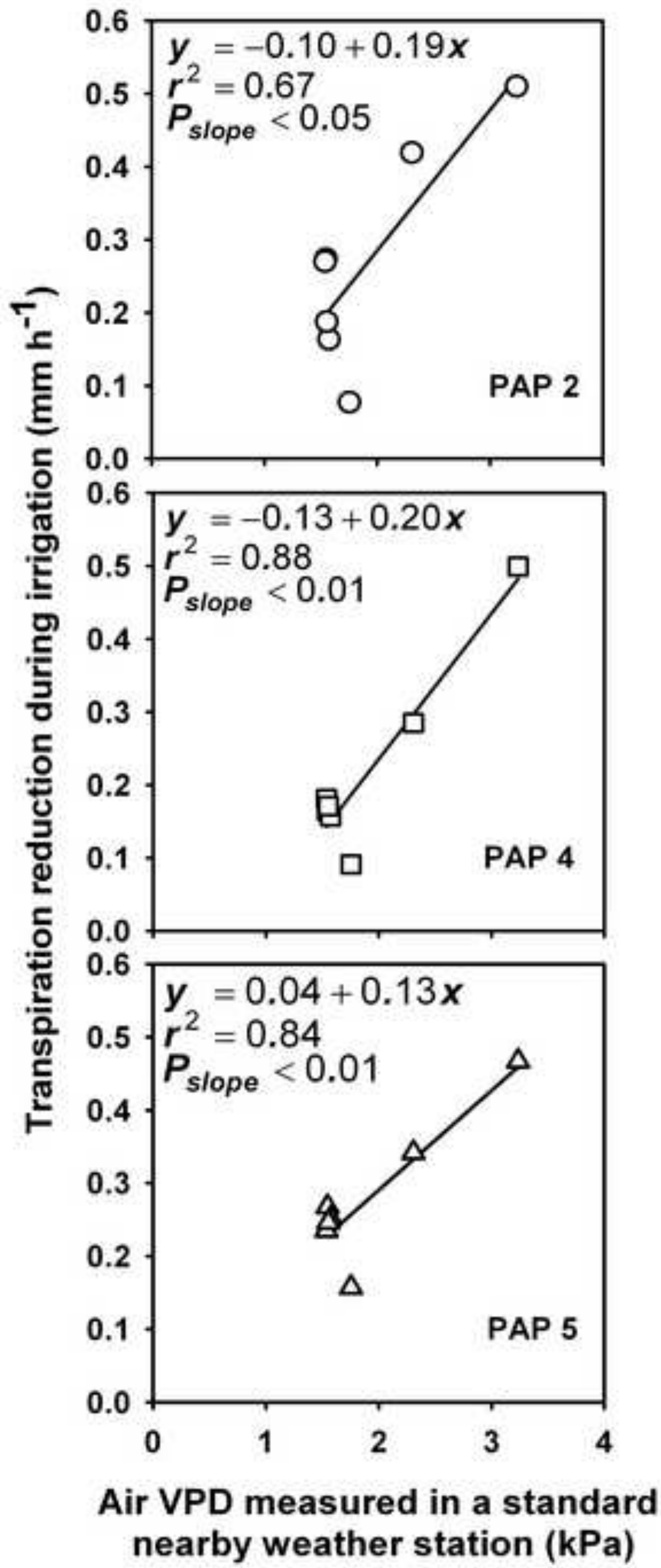

Figure_7

Click here to download high resolution image

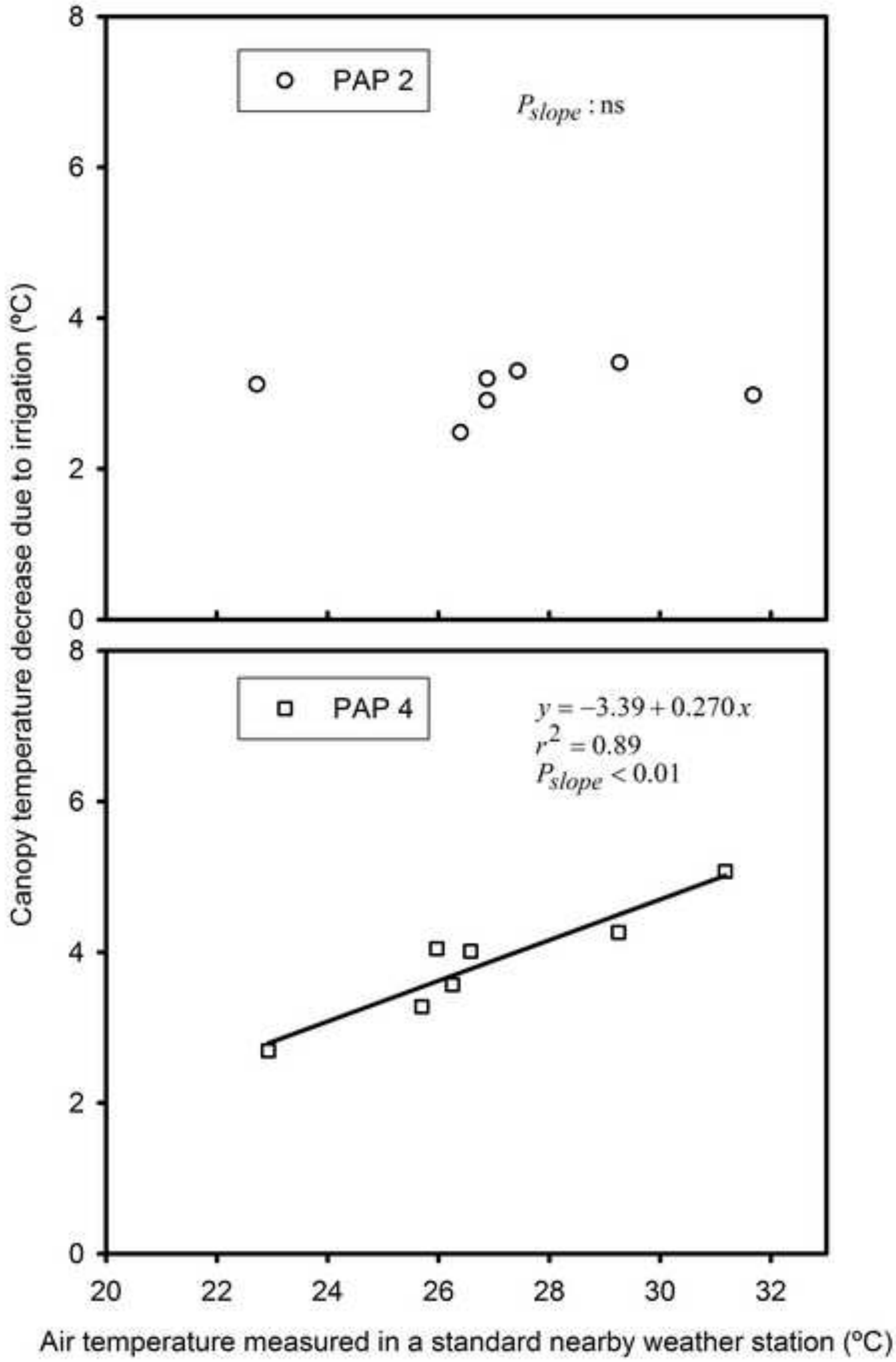

FIGURE CAPTIONS

Fig. 1. Overview of the center pivot sprinkler irrigation system at the commercial plot. A to C, meteorological stations and sap flow measurement systems for *moist* treatment. D, meteorological station and sap flow measurement system for *dry* treatment. Ap, pivot arm. Pr, irrigation pressure transducers. R1-6, radius at the end of each pivot arm portion. M, direction of center pivot movement.

Fig. 2. 5-min averages of microclimatic variables (temperature and vapour pressure deficit of the air) and physiological variables (canopy temperature and transpiration rate) monitored at the different pivot arm portions on 6 August, 2008 since 2 h before until 6 h after the irrigation event. MT, *moist* treatment. DT, *dry* treatment. The vertical solid lines indicate the start and the end of the irrigation event over the transect AC. The vertical dashed lines indicate the period during which the monitored variables were different between the two treatments *before* (B), *during* (D) and *after* (A) irrigation event.

Fig. 3. Relationship between the decrease in air temperature due to sprinkler irrigation and the air temperature measured over grass at a nearby weather station. PAP, Pivot Arm Portions. A, the Y axis represents the decrease in air temperature for the phase *during* at the 7 *transpiration-measured* irrigation events. B, the Y axis represents the decrease in air temperature observed for the whole duration of the 27 *remaining* irrigation events.

Fig. 4. Relationship between the decrease in vapour pressure deficit (VPD) due to sprinkler irrigation and the VPD measured over grass at a nearby

standard weather station. PAP, Pivot Arm Portions. A, the Y axis represents the decrease in VPD for the phase *during* at the 7 *transpiration-measured* irrigation events. B, the Y axis represents the decrease in VPD observed for the whole duration of the 27 *remaining* irrigation events.

Fig. 5. Relationship between the maize transpiration reduction for the different phases (before, during and after) and the reduction of air temperature, air VPD and canopy temperature at the 7 *transpiration-measured* center pivot irrigation events.

Fig. 6. Relationship between the maize transpiration reduction for the phase *during* at the 7 *transpiration-measured* irrigation events at the different pivot arm portions (PAP), and the vapor pressure deficit (VPD) of the air measured at a nearby standard weather station.

Fig. 7. Relationship between the maize canopy temperature reduction for the phase *during* at the 7 *transpiration-measured* irrigation events at the different pivot arm portions (PAP), and the air temperature measured at a nearby standard weather station.