Combined effect of technical, meteorological and agronomical factors on solid-set sprinkler irrigation: II. Modifications of the wind velocity and of the water interception plane by the crop canopy.

by

Sanchez I. [a1], Zapata N. [b] and Faci J.M.[a]

[a] Unidad de Suelos y Riegos (asociada a EEAD-CSIC), Centro de Investigación y Tecnología Agroalimentaria (CITA), Gobierno de Aragón. Avenida Montañana 930, 50059, Zaragoza, (Spain).

[b] Dept. Soil and Water, Estación Experimental de Aula Dei (EEAD), CSIC, Apdo. 202, 50080 Zaragoza (Spain).

Corresponding Author**:**

Sanchez Marcos I.

Unidad de Suelos y Riegos (asociada al CSIC), Centro de Investigación y Tecnología Agroalimentaria (CITA), Gobierno de Aragón. Avenida Montañana 930, 50059, Zaragoza, (Spain).

Phone: +34 976 71 6324.

Fax: + 34 976 71 6335.

Email: isanchezm@aragon.es; ingancio@gmail.com

[1] Present address: Foundation Aula Dei, Science and Technology Park. Avda. Montañana, 930. 50059 Zaragoza (Spain).

Keywords

Maize; alfalfa; uniformity, water loss; wind velocity profile; canopy architecture; pluviometer; anemometer.

Abstract

Maize (*Zea mays L.*) and alfalfa (*Medicago sativa L.*) were simultaneously irrigated in two adjoining plots with the same sprinkler solid-set system under the same operational and technical conditions. The Christiansen Uniformity Coefficient (*CUC*) and the wind drift and evaporation losses (*WDEL*) were assessed from the irrigation depth (ID_C) collected into pluviometers above each crop. A network of pluviometers was located above the maize canopy. Two networks of pluviometers were located above the alfalfa, one above the canopy and the other at the same level as that above the maize. The latter was used to analyze the effects of the water collecting plane. The wind velocity (*WV*) profile was measured above each crop using anemometers located at three levels. Both the *CUC* and the *WDEL* differed between maize and alfalfa.

The crops modified both the wind velocity above the canopy and the water interception plane. Both effects were related to the height of the crops (*h*).

When *h* increased, the water interception plane increased, and the overlap of the sprinklers decreased. The *CUC* of the ID_C increased with the overlap. Because *h* was greater for maize than for alfalfa, the *CUC* was noticeably smaller for maize.

The *WV* greatly decreased in proximity to the canopy. The *WV* at the level of the nozzles was smaller above the maize because the top of the canopy was closer to the nozzles than it was for alfalfa. However, the *CUC* of the ID_C mainly depended on the *WV* at higher levels, where the *WV* was similar above

both maize and alfalfa. The logarithmic wind profile overestimated the vertical variation of the *WV* in the space where the sprinklers distributed the water.

The *WDEL* was greater above the maize than above the alfalfa. This finding was related to the underestimation of the ID_C above maize, especially under windy conditions, because the pluviometers were located very close to the nozzles.

1. Introduction

Because irrigated agriculture is the major use of water worldwide, decreasing the amount of wind drift and evaporation losses are key factors for improving water use in sprinkler irrigation. Agronomical factors dealing with sprinkler irrigation are discussed in this paper to assist the progress of sprinkler irrigation.

Wind has been reported as the major factor decreasing irrigation uniformity and increasing water loss in sprinkler irrigation (Dechmi et al., 2003; Faci and Bercero, 1991; Kincaid, 1996; Seginer et al., 1991a, 1991b; Tarjuelo et al, 1994; Tarjuelo et al, 1999; Playán et al. 2005, 2006; Zapata et al., 2007). The wind velocity close to the Earth's surface is strongly influenced by the nature of the terrain surface (Petersen et al., 1998). The *surface layer* consists of two parts. In the upper part, called the *inertial sub-layer*, the mean flow can be described one-dimensionally using the surface-layer Monin-Obukhov similarity theory (Monin and Obukhov, 1954). In the lower part, which is close to and within the canopy itself, the mean flow is three-dimensional; this layer is called the *roughness sub-layer,* the *transition layer*, the *interfacial-layer* (Raupach and Thom, 1981) or the *canopy sub-layer* (Poggi et al., 2004). The thickness of the *roughness sub-layer* varies between two and three canopy heights above the ground (Cellier and Brunet, 1992; Dellwik, 2003; Mahrt, 2000; Mihailovic et al. 1999). The distribution of the water drops by agricultural sprinklers occurs partially or totally within the *roughness sub-layer*. Consequently, the wind surrounding the sprinkler system greatly depends on the aerodynamic characteristics of the crops.

As introduced by Mihailovic et al. (1999), under thermally neutral conditions, the steady-state air flow over horizontally bare soil can be described by the well-known logarithmic law (Monin and Yaglom, 1971):

$$WV_Z = \frac{WV^*_g}{k} \ln \frac{z}{z_{0g}} \quad (1)$$

where WV_z is the horizontal wind velocity at the height z, WV^*_g is the friction velocity for the bare soil, which, physically, represents the shear stress, k is the von Karman's constant (0.41 (Högström, 1985)) and z_{0g} is the roughness length of the bare soil. For vegetative surfaces, Eq. 1 is modified as follows:

$$WV_z = \frac{WV^*}{k} \ln \frac{z-d}{z_0} \quad (2)$$

where WV^* is the friction velocity over a vegetated surface, d is the displacement height, representing the mean height in the vegetation on which the bulk aerodynamic drag acts (Jacobs and van Boxel, 1988; Oke, 1984), and z_0 is the aerodynamic roughness length of the underlying surface.

The parameters d and z_0 have been calculated as a function of the crop height (h) as follows (Carrión et al., 2001; Dechmi et al., 2004; Stanhill, 1969; Tanner and Pelton, 1960; Vories et al. 1987):

$$[\log d = 0.9793 \log h - 0.1536] \quad (3)$$

$$[\log z_0 = 0.997 \log h - 0.883] \quad (4)$$

where d, z_0 and h are in cm.

Previous studies have found that $d = 0.75\ h$ (Cellier and Brunet, 1992; Jacobs and van Boxel, 1988).

Eqs. 3 and 4 obviate the differences that are due to canopy structure, density or stiffness, and fail to predict d and z_0 between canopies that are identical in height but different in density and in the spatial distribution of the leaves (Shaw and Pereira, 1982).

The value of WV^* is independent on h for a given adiabatic situation, so the wind velocity WV_{z1}, measured at a reference height z_1, can be related to the velocity WV_{z2} at any other height z_2 (Vories et al., 1987) by:

$$WV_{z2} = WV_{z1} \frac{\ln\left(\frac{z_2 - d}{z_0}\right)}{\ln\left(\frac{z_1 - d}{z_0}\right)} \qquad (5)$$

When Eq. 5 is used in the context of sprinkler irrigation, the following assumptions are made: thermally neutral conditions (an absence of buoyancy), steady-state flow over a horizontally homogeneous vegetated surface (no marked shifts in the wind fields during the observation period) and constancy of fluxes with height (no vertical divergence or convergence) (Oke, 1984).

The effects of the crops on sprinkler irrigation performance are not only expected in connection with their influence on the wind above them. The water interception plane is also determined by h and affects the trajectory of the drops, with consequences on the overlap of the water emitted by the sprinklers and on the time that the drops are exposed to both wind drift and evaporation. Previously, the scarce studies on this topic have only been performed indirectly, through the effects of the sprinkler riser height and of the elevation of the pluviometers.

Sprinklers located at 2 m have produce values of the *CUC* that are greater than those from sprinklers located at 0.6 m, especially under a *WV* greater than 2 m s^{-1} (Tarjuelo et al., 1999). Playán et al. (2005) reported that the *CUC* and *WDEL* should be affected by the sprinkler riser height. Some results have shown that lowering the nozzle height from 2.4 to 1.0 m had no significant effect on the *WDEL* for irrigation laterals (Faci et al., 2001; Playán et al., 2004). For a linear move sprinkler irrigation system, under no wind conditions, collectors located at 0.3 and 1.2 m above the ground resulted in differences in the ID_C and *CUC* as high as 10 mm and 6 %, respectively (Dogan et al., 2008). When the ID_C is underestimated, the *WDEL* is overestimated, though this outcome has not yet been confirmed for solid-set sprinkler systems (Tarjuelo et al. 1999).

This topic has been analyzed by testing different elevations of the sprinklers (Edling, 1985; de Wrachien and Lorenzini, 2006; Tarjuelo et al. 1999) or different elevations of the pluviometers (Clark et al., 2006; Dogan et al., 2008). However, depending on the approach, different effects will be found. The *WV* decreases and the turbulence increases in proximity to the surface. When the pluviometers are elevated above the surface, the *WV* around them will be higher and the turbulence lower. When the sprinklers are lowered, the *WV* around them will be lower and the turbulence higher.

This experiment will survey the modifications in the water interception plane and in the wind velocity above the canopy, depending on the crop and on the growing stage. These results will be connected to the values of the *CUC* and the *WDEL,* evaluated above the maize and alfalfa simultaneously.

2. Materials and Methods

2.1. Experimental layout

The experiment was performed in 2006. The sites, settings and operational conditions with regard to the 2006 season are described in the companion paper.

A cultivar 'Aragón' of alfalfa (Medicago sativa L.) and a cultivar 'Pioneer PR34N43' of maize (Zea mays L.), were farmed in two adjacent plots. Both plots were simultaneously sprinkler-irrigated under the same operational and technical conditions. The irrigation equipment was a solid-set system arranged in a rectangular layout: 18 m between sprinklers along the line and 15 m between lines (R18x15). The sprinkler nozzles were located at 2.3 m above the ground level (a.g.l.).

The experiment was performed under fetch limitations. Maize, alfalfa, young olive trees, barley and wheat were farmed around the experimental plots. Fallow land was also present. This distribution is common for many irrigation districts in the region. The Gállego River flows through a canyon between trees approximately 300 m west of the experimental plots. The topography of the farm, and the several surrounding kilometers, is flat, with an average elevation of 210 m above the mean sea level.

2.2. Wind monitoring

The wind velocity (*WV*) was monitored above the maize, alfalfa and grass (*Festuca arundinacea*) from May 24 to October 11, 2006. A meteorological station of the *SIAR* network (Figure 1 of the companion paper) measured the wind velocity at 2 m a.g.l. in the center of a 0.5 ha grassland ($WV_{grass,2}$). The station used a propeller-type anemometer (Young's wind monitor Model 05103, Campbell scientific, Inc., Shepshed, Leicestershire, UK) (accuracy ± 0.3 m s^{-1}, wind speed starting threshold 1.0 m s^{-1}). It also monitored the wind direction (accuracy ± 3º, wind speed starting threshold 1.1 m s^{-1}), which was classified in sixteen categories in clockwise rotation: from 11.25º to 33.75º was considered north-north-east (NNE), north-east (NE) from 33.75º to 56.25º, and so on up to north (N), from 348.75 to 11.25º. The wind direction was considered the same within the area. The meteorological station recorded the $WV_{grass,2}$ and wind direction, temperature and relative humidity of the air, solar radiation and precipitation every 30 min.

The wind velocity above the crops (WV_{crop}) was monitored with A-100R series anemometers (Vector Instruments, Rhyl, UK) (accuracy 0.1 m s^{-1}, start speed threshold 0.25 m s^{-1}) and recorded every 5 min with data loggers of the model CR10X (Campbell Scientific, Logan, Utah). Three anemometers were assembled to a mast by horizontal rods (one meter long) facing the prevailing wind direction (north-westward) within each experimental area. The anemometers were initially positioned at 1.2, 2.3 and 3.5 m a.g.l. above the alfalfa (WV_a) and at 1.05, 2.3 and 3.5 m a.g.l. above the maize (WV_m). The anemometers remained at the same positions above the alfalfa throughout the season. For the maize, the bottom and medium anemometers were elevated as the crop grew (Figure 1). $WV_{crop,z}$ symbolizes the *WV* monitored at the elevation *z*. The measurements of $WV_{crop,z}$ were averaged every 30 min so that their format matched the measurements of WV_{grass}.

A least square means test was used to compare $WV_{grass,2}$ *and* $WV_{crop,2.3}$ (*Proc Glm* procedure and *lsmeans* statement, SAS institute, 2000).

2.2.1. Measurement limitations of the anemometers

From May 11 to May 22, the six anemometers were mounted on tripods spaced 2 m apart to measure the *WV* at 2 m above the bare soil. The mean absolute error (MAE_{Com}) and the root mean square error ($RMSE_{Com}$) were used to establish the thresholds up to which the differences in *WV* were considered to be measurement limitations of the anemometers. As the *RMSE* will be applied in a subsequent section, the subscript '*Com*' (as an abbreviation of “comparison”) will now be used to avoid confusion.

For each anemometer *j*, the MAE_{Com} was calculated as follows:

$$MAE_{Com}\ (j = 1,2...6) = \frac{1}{n}\sum_{i=1}^{n}\left|WV_{ij} - \frac{1}{6}\sum_{j=1}^{6}WV_{ij}\right| \qquad (6)$$

where n is the number of 5 min periods during the testing time, WV_{ij} the average wind velocity recorded by an anemometer j in each 5 min period i, and $\frac{1}{6}\sum_{j=1}^{6}WV_{ij}$ the average of the wind velocity for the six anemometers during each period i.

For each 5 min period i, $RMSE_{Com}$ was calculated as follows:

$$RMSE_{Com}\ (i = 1,2...n) = \sqrt{\frac{1}{6}\sum_{j=1}^{6}\left(WV_{ij} - \frac{1}{6}\sum_{j=1}^{6}WV_{ij}\right)^2} \qquad (7)$$

The minimum wind speed at which a cup anemometer starts rotation is not necessarily the same at which it stops. Records below 1 m s^{-1} were discarded in this section because this is the threshold below which this complication is important for most cup anemometers (Kristensen, 1998).

2.2.2. *Accuracy in the estimation of the wind profile*

The wind velocity profile (*MWP*) was calculated from $WV_{crop,z}$ above the maize (MWP_m) and above the alfalfa (MWP_a).

Two approaches were used to estimate the wind profile (*EWP)*:

EWP_{grass}: substituting WV_{z1} for $WV_{grass,2}$ into Eq. 5.

EWP_{crop}: substituting WV_{z1} for $WV_{crop,2.3}$ into Eq. 5.

From July 10 to 18, $WV_{crop,2}$ was used instead of $WV_{crop,2.3}$ under the EWP_{crop} approach. The parameters d and z_0 in Eq. 5 were calculated as a function of h according to Eqs. 3 and 4.

Estimates were evaluated using the Mean Error (ME_{WP}) and the root mean square error ($RMSE_{WP}$):

$$ME_{WP} = WV_{2.3}^{EWP_{grass}} - WV_{crop,2.3} \quad (8)$$

where $WV_{2.3}^{EWPgrass}$ is the WV estimated at 2.3 m a.g.l. according to the EWP_{grass} approach. ME_{WP} is zero using the EWP_{crop} approach. The subscript '*WP*' denotes 'wind profile'.

$$RMSE_{WP} = \sqrt{\frac{1}{3}((WV_{z_1}^{EWP} - WV_{crop,z1})^2 + (WV_{z2}^{EWP} - WV_{crop,z2})^2 + (WV_{z3}^{EWP} - WV_{crop,z3})^2)} \quad (9)$$

where z_1, z_2 and z_3 are the positions of the anemometers above the crop. $RMSE_{WP}$ was calculated for both the EWP_{grass} and the EWP_{crop} approaches.

2.3. Evaluation of the irrigation performance

The irrigation water depth (ID_C) was collected into pluviometers just above the canopy. The pluviometers are described in the companion paper. The pluviometers were elevated as the crops grew: up to 2.25 m a.g.l. above the maize and up to 0.9 m a.g.l. above the alfalfa (Figure 1). In addition, the ID_C was collected at the same level above the alfalfa and the maize for ten irrigation events (Table 1). For this collection, a second network of pluviometers was located above the alfalfa at 2.25 m a.g.l. (Figure 1).

The wind drift and evaporation losses (*WDEL*) and the Christiansen Uniformity Coefficient (*CUC*) (Christiansen, 1942) were assessed to evaluate the sprinkler irrigation performance above each crop. The *WDEL* represents the percentage of water emitted by the sprinklers (ID_D, mm) but not collected inside the pluviometers (ID_C) according to:

$$WDEL = \frac{ID_D - ID_C}{ID_D} \times 100 \qquad (10)$$

$$ID_D = \frac{Q \times t}{15 \times 18} \qquad (11)$$

where Q (l s^{-1}) is the sprinkler flow rate, calculated using the Orifice Equation, t (s) the operating time, and *15* and 18 (m) the spacing between laterals and between sprinklers along the lateral, respectively, in this experiment.

Numeric subscripts, such as in $ID_{Ca,2.25}$, $CUC_{a,0.9}$ or $WDEL_{m,2.25}$, denote the height of pluviometers (z). The subscripts 'm' and 'a' denote maize and alfalfa, respectively.

The differences in the ID_C, *CUC* and *WDEL* between crops were analyzed by observing WV_{grass}, WV_{crop} and h. Using regression analysis, a *CUC* explanatory model including WV_{grass} and h was achieved.

3. Results and Discussions

3.1. Measurement limitations of the anemometers

Systematic or large, random errors in one or more of the anemometers have been reported to be one of the main causes of the differences found between positions (Schaudt, 1998). The threshold below which differences between the anemometer measurements were considered to be measurement limitations of the anemometers, and therefore discarded as differences among heights or sites, was 0.3 m s^{-1} for comparisons based on records averaged every 5 min (maximum $RMSE_{Com}$, Eq. 7, Table 2) and 0.1 m s^{-1} for comparisons based on records averaged every 30 min (maximum MAE_{Com}, Eq. 6, Table 2).

3.2. Modifications of the wind velocity by the crop canopy

The wind direction fitted the Ebro Valley 40 % of the time during the 2006 irrigation season. This percentage greatly increased in windy conditions: it was 76 % for *WV* greater than 3.5 m s^{-1}. *Cierzo*, wind from the *WNW-NW* direction, was the most frequent (26 %) and the highest velocities were recorded in this direction. *Bochorno*, wind from the *ESE-SE* direction, was also frequent (14 %).

The values of *h* increased up to 1.75 m for maize and up to 0.75 m for alfalfa just before the cuttings (Figure 1). The differences in the *WV* between the crops increased as the differences in *h* increased. $WV_{m,2.3}$ was smaller than $WV_{grass,2}$ and $WV_{a,2.3}$ after early July. In contrast, $WV_{a,2.3}$ and $WV_{grass,2}$ were similar throughout the season (Figure 2).

$WV_{m,2.3}$ and $WV_{a,2.3}$ were compared with $WV_{grass,2}$ using a *least square means test* with the values of *WV* averaged every 30 min. Three wind ranges were considered: $WV_{grass,2}$ up to 3.5 m s^{-1}, from 3.5 m s^{-1} to 5 m s^{-1} and greater than 5 m s^{-1}. $WV_{m,2.3}$ was significantly different (α = 0.05) from $WV_{grass,2}$ when h_m was between 0.2 and 0.4 m: $WV_{m,2.3}$ was between 0.1 m s^{-1} and 0.6 m s^{-1} greater than $WV_{grass,2}$ (the differences increased with the *WV*). $WV_{m,2.3}$ and $WV_{grass,2}$ were not significantly different when h_m was between 0.4 and 0.6 m. When h_m was 0.6 m and greater, $WV_{m,2.3}$ was smaller than $WV_{grass,2}$. For $h >$ 1.75 m, $WV_{m,2.3}$ was, depending on the wind range, between 0.8 and 1.6 m s^{-1} smaller than $WV_{grass,2}$, or about 60 % of the $WV_{grass,2}$ *value*. Similar results have been previously reported (Dechmi et al., 2004). This percentage depended on the wind direction and range, and decreased when maize defoliated. The differences between $WV_{a,2.3}$ and $WV_{grass,2}$ were less than 0.5 m s^{-1}. For h_a up to 0.45 m, $WV_{a,2.3}$ was greater than $WV_{grass,2}$; the opposite was true for h_a greater than 0.45 m. The differences were not statistically significant when $WV_{grass,2}$ was less than 3.5 m s^{-1}.

The differences in the monitoring level (2 m a.g.l. above the grass, 2.3 m a.g.l. above the maize and alfalfa) introduced noise into the comparison. However, the trend was valid when using the same level for the comparison. On May 31, $WV_{grass,2}$ (4.5 m s^{-1}) almost matched $WV_{a,2}$ (4.4 m s^{-1}) but was less than $WV_{m,2}$ (4.8 m s^{-1}); on July 6, $WV_{grass,2}$ (4.8 m s^{-1}) was greater than $WV_{a,2}$ (4.5 m s^{-1}) and $WV_{m,2}$ (4.0 m s^{-1}); the same trend was found on October 3 (Figure 3).

3.2.1. Comparison of the wind velocity profiles

Figure 3 shows, for three irrigation events corresponding to different growing stages, a comparison between crops with regard to the *MWP*, and between the *MWP* and *EWP*. Table 3 complements Figure 3. The prevailing wind direction on the three dates was *Cierzo.*

The *MWP* differed between maize and alfalfa according to the differences in *h* (stiffness, density, leaf arrangement, etc., should have been involved as well). The shear stress exerted by the plants and the surface resulted in the *WV* rapidly decreasing in proximity to the canopy. The influence of the surface decreased at the upper layers and the *WV* gradually increased.

Eq. 5 led to the overestimation of the wind velocity profile, as illustrated by the comparison between *MWP* and EWP_{crop} (Figure 3). The comparison between EWP_{crop} and EWP_{grass} illustrates that the miscalculation was significant when the wind profile was calculated from WV_{grass}.

Table 3 shows that, for maize, h_m above 0.60 m resulted in ME_{WP} equal to 0.3 m s^{-1} or greater (up to 4 m s^{-1} under very windy conditions). When h_m was 1.75 m, ME_{WP} resulted 48 % of $WV_{grass,2}$ (coefficient of determination R^2 of 0.92) and $RMSE_{WP}$ was 63 % of $WV_{grass,2}$ (R^2 of 0.95) according to the EWP_{grass} approach. For alfalfa, the ME_{WP} was visibly less than it was for maize (values up to 0.4 m s^{-1}), and the $RMSE_{WP}$ was 8 % of $WV_{grass,2}$ (R^2 of 0.59) according to the EWP_{grass} approach.

The results show that the assumption of a logarithmic wind profile under neutral stability conditions departs from reality just above the canopy. Above tall and rough crops like maize, it seems to be inadequate even up to a height of several times the canopy height (Cellier and Brunet, 1992; De Bruin and Moore, 1985; Haenel, 1993; Haman and Finnigan, 2007; Finnigan, 2000; Mahrt, 2000; Mihailovic et al., 1999; Poggi et al., 2004; Schaudt, 1998). The velocity profile in the *roughness sub-layer* is inflected (De Bruin and Moore, 1985), and measured values are lesser than predicted (Shaw and Pereira, 1982; Wilson; 1982), because the single-point statistics of turbulence in the *roughness sub-layer* change significantly from those in the *surface layer* (Finnigan; 2000). The errors ensuing from this assumption are not gross as long as the reference wind velocity input in Eq. 5 is measured above the crop. When the latter is not available, approaches such as that applied by Dechmi et al. (2004) to transform WV_{grass} into WV_{crop} will considerably improve the results.

These results must be set in context, as they stem from specific surrounding conditions and fetch limitations. Nonetheless, the crop distribution for this experiment was not far from others in many irrigation districts in the Ebro Valley and in other irrigated areas. Valuable results from other experiments were also obtained under fetch limitations (Jacobs and van Boxel, 1988; Kustas et al., 1989; Todd et al., 2000).

3.3. Differences in the solid set sprinkler performance above maize and alfalfa

3.3.1. Effect of the canopy on the sprinkler irrigation performance through its influence on the wind velocity

The strong interaction between the *WV* and the uniformity of the sprinkler irrigation system has been extensively reported in the literature (Carrión et al., 2001; Christiansen, 1942; Dechmi et al., 2003; Seginer et al., 1991a, 1991b; Vories et al., 1987). Despite many technical, operational and meteorologic factors affecting sprinkler irrigation (Keller and Bliesner, 1990; Playán et al., 2006; Tarjuelo et al., 1999), linear relationships are commonly established between the *CUC* and the *WV*. As shown in Figures 2 and 3, *h* was included to study the relationship between the *CUC* and the *WV*. Two series were considered for maize: h_m up to 1.20 m (before July 6) and higher (subsequently referred to as tall maize).

The *CUC* greatly decreased with the *WV*, down to a threshold under which the *CUC* decreased insignificantly (Figure 4). For alfalfa and maize shorter than 1.20 m, a threshold was found in $WV_{grass,2}$ at about 4 m s^{-1} (the minimum *CUC* was about 75 % for alfalfa and about 65 % for maize). For tall maize, the threshold for $WV_{grass,2}$ was about 5 m s^{-1}, and the minimum *CUC* was 50 %. Similar trends have been found previously (Dechmi et al., 2003; Playán et al., 2006; Seginer et al., 1991a; Tarjuelo et al., 1999). Some authors found this relationship to be parabolic (Dechmi et al., 2003; Tarjuelo et al., 1999). However, we decided to fit linear regression models up to the values of *WV* that were defined as thresholds because this agrees with our understanding of the trend, and it emphasizes the change in the decrease of the *CUC* with the *WV*. In addition, this decision avoids leverage effects from the windiest event on August 3; the analysis revealed that the results for this date were not outliers, but a confirmation of the asymptotic trend.

Considering that the *WV* is the main factor decreasing the *CUC*, because $WV_{m,2.3}$ was less than $WV_{a,2.3}$ (Table 3, Figures 2 and 3), it was expected that the *CUC* would be greater for tall maize. Nevertheless, the opposite was true. The reason for this outcome is that increases in *h* caused the drop in the *CUC* with the *WV* to be more pronounced. The decrease in the *CUC* (%) was on the scale of five times the average $WV_{grass,2}$ (m s^{-1}) for alfalfa but almost double this value for tall maize. Considering $WV_{crop,2.3}$ instead of $WV_{grass,2}$, the differences were greater and the threshold after which the *CUC* insignificantly decreased was 3 m s^{-1} for tall maize.

Unfortunately, for the irrigation events evaluated during the period for which h_m was below 1.20 m, the $WV_{grass,2}$ values were less than 1.4 m s^{-1} or greater than 3.6 m s^{-1} (Table 3). Thus, our conclusions must be confirmed for growing maize under moderate winds.

The *WDEL* increased with the *WV* in both crops but was significantly greater for maize (18 % on average above the maize, 16 % above the alfalfa). This topic is introduced in the companion paper. Because WV_a was greater than WV_m, the *WDEL* was expected to be greater above the alfalfa. However, the opposite was true. The linear regression models between the *WDEL* and the

WV (both using $WV_{crop,2.3}$ or $WV_{grass,2}$) showed an important scattering pattern (coefficients of determination R^2 lower than 0.70).

Satisfactory explanations for the differences in the irrigation performance between maize and alfalfa, both for the *CUC* and the *WDEL*, were found by observing their influence on the crops via the water interception plane.

3.3.2. Effect of the canopy on the sprinkler irrigation performance through its influence on the water interception plane

Both the *WV* (Dechmi et al., 2003; Playán et al., 2005; Tarjuelo et al., 2000; Yazar, 1984) and the time of exposure (Burt, 2005; Lorenzini and De Wrachien, 2005) have been shown to increase the *WDEL*. The canopy was shorter for alfalfa than for maize; therefore the time of exposure was greater for alfalfa. In addition, WV_a was greater than WV_m. Therefore, the *WDEL was* expected to be greater above the alfalfa. However, it was found to be less because of the influence of the water interception plane. The *WDEL* evaluated at 2.25 m a.g.l was similar above the maize and alfalfa: $WDEL_{m,2.25}$ was 13 % and $WDEL_{a,2.25}$ 12 %, while $WDEL_{a,0.9}$ was 10 % (values were averaged among the ten irrigation events in Table 1).

The *WDEL* comprises evaporation and wind drift losses. For a detailed analysis, results were divided between mild ($WV_{grass,2}$ < 2.5 m s^{-1}) and windy ($WV_{grass,2}$ > 2.5 m s^{-1}) conditions (Figure 5). In mild conditions, $WDEL_{m,2.25}$ was 9 %, $WDEL_{a,0.9}$ was 7 % and $WDEL_{a,2.25}$ 5 % (the values were significantly different; paired t-test, two tails, $\alpha = 0.05$).

In mild conditions, we can assume that evaporation losses predominated over drift losses. Concerning the comparison of the *WDEL* at two different levels above the alfalfa, $WDEL_{a,0.9}$ was greater than $WDEL_{a,2.25}$ because the time of exposure was greater at 0.9 m. Because $WDEL_{m,2.25}$ was greater than $WDEL_{a,2.25}$ despite the supposedly equal time of exposure, we inferred that the heat transfer was greater above the maize. This explanation will also explain why $WDEL_{m,2.25}$ was greater than $WDEL_{a,0.9}$. This explanation should be confirmed because heat transfer was not evaluated in this experiment.

In windy conditions (WV_{grass} > 2.5 m s^{-1}), the values of *WDEL* greatly increased and were notably greater at 2.25 m, irrespective of the crop irrigated: $WDEL_{m,2.25}$, $WDEL_{a,0.9}$ and $WDEL_{a,2.25}$ were, respectively, 22, 17 and 28 % (Figure 5). On the assumption that drift losses predominated over evaporation in windy conditions, $WDEL_{a,2.25}$ exceeded $WDEL_{m,2.25}$ because WV_a exceeded WV_m. However, the finding that $WDEL_{a,2.25}$ exceeded $WDEL_{a,0.9}$ contradicted this explanation. The explanation we provide is that in windy conditions, the errors in the estimation of *WDEL* increase with the elevation of the pluviometers. $WDEL_{2.25}$ was overestimated, as we subsequently explain.

When the drops are wind-drifted, their trajectories tend to be horizontal with the major wind component. Because of the small difference between the height of the nozzles (2.3 m a.g.l.) and the top of the pluviometers being located at 2.25 m a.g.l., some drops might have flown directly below the opening of the pluviometers. However, those drops might have entered the pluviometers located at 0.9 m a.g.l. above the alfalfa canopy. This phenomenon would have particularly affected the smallest drops and the secondary nozzle (for which the insertion angle with the vertical is lower than for the main nozzle). It must also be considered that the *WV* increases with the elevation. In addition, a geometric issue has been found to be related. The plane containing the openings of the pluviometers is horizontal and parallel to the surface. When the drops' trajectories are vertical, the effective orifice section approaches its maximum. In contrast, the effective orifice section decreases when the trajectory of the drops departs from vertical, as when they are wind-drifted. Both assumptions explain why, under windy conditions, $ID_{Ca,2.25}$ was lower than $ID_{Ca,0.9}$ (Table 1), and why the $WDEL_{2.25}$ was overestimated with respect to the $WDEL_{0.9}$. Further research is needed to confirm these explanations.

In conclusion, the elevation of the nozzles and of the pluviometers, the difference in elevation between them, and the crop height affect the estimation of the *WDEL*. Other studies have reported that the accuracy of the water depth estimation increased with the distance between the sprinkler nozzles and the collectors (Dogan et al., 2008). The ASAE methodology (ASAE, 2001) for the evaluation of the technical performance of irrigation systems over bare soil states that the height of the collectors should not be more than 300 mm from the surface when the *WV* exceeds 2 m s^{-1}. However, when trials are conducted to evaluate real situations in fields that include agronomic factors, such as in our experiment, these standards cannot be followed for the evaluation of the irrigation above tall crops such as maize. The topics we are dealing with are related to the usefulness of the information distributed by the manufacturers and the feasibility of the indoor testing facilities to predict the sprinkler irrigation performance under the real conditions where irrigation is naturally fulfilled, i.e., above the crops.

The values of the *CUC* of the ID_C above the maize and alfalfa canopies were statistically different, but the opposite was true when the *CUC* was evaluated at the same level above both crops (two tailed paired t-test, $\alpha = 0.05$):

$CUC_{m,2.25}$ was 77 %, $CUC_{a,0.9}$ 87 % and $CUC_{a,2.25}$ 78 % (values averaged among the ten irrigation events on Table 1).

Figure 6 complements Figure 4 by including the influence of the water interception plane. The water collecting level has been found to be a major factor explaining the differences in the *CUC* between maize and alfalfa. Given the close relationship between the *CUC* and the *WV*, it was surprising that $CUC_{2.25}$ was nearly equal between maize and alfalfa (Figure 6a and Figure 6c) despite the difference between $WV_{m,2.3}$ and $WV_{a,2.3}$ (Figure 6b).

The differences between WV_a and WV_m at the level of the nozzles did not satisfactorily explain the differences in the *CUC* between maize and alfalfa. In contrast, the relationship between the *CUC* and the *WV* mainly depended on the values of the *WV* above the plane of the nozzles, where the differences between WV_a and WV_m diminished (Figure 3). For the events from August 24 to October 10 (Table 1), the average difference between WV_a and WV_m decreased from 0.5 m s^{-1} to 0.1 m s^{-1} when measured at 3.5 m instead of at 2.3 m a.g.l.

The maps in Figure 7 show the experimental area (Figure 1 of the companion paper). The selected dates are representative of mild conditions (September 19 and October 10) and windy conditions (August 24 and August 30) (Table 1). The ID_C decreased from the sprinklers toward the center. The least irrigated areas were displaced according to the wind direction because the wind drift. The irrigation uniformity decreased with the *WV*. The uniformity decreased when the water collecting level increased. The distribution pattern of $ID_{C,2.25}$ was similar above maize and alfalfa. The differences between WV_a and WV_m might have caused the slight differences between the patterns of $ID_{Ca,2.25}$

and $ID_{Cm,2.25}$. Nonetheless, some variability always exists, even when restricting to the same plot, the same conditions and the same crop.

3.4. Prediction of the uniformity of the sprinkler irrigation above different crops in windy conditions

A model for the prediction of the *CUC* of the ID_C in windy conditions was developed using $WV_{grass,2}$ and *h* as the explanatory variables (the latter was input as the pluviometer elevation). The thresholds of $WV_{grass,2}$ beyond which the *CUC* decreased insignificantly were considered as well (section 3.3.1).

A multiple linear regression analysis was performed to assess the parameters of the model: *CUC* in %, $WV_{grass,2}$ in m s^{-1} and *h* in m:

$$CUC = 107.4 - 8.2927\, WV_{grass,2} - 5.9314\, h \qquad (R^2 = 0.91) \qquad (12)$$

It was compared to a model based only on $WV_{grass,2}$:

$$CUC = 98.6 - 7.8801\, WV_{grass,2} \qquad (R^2 = 0.79) \qquad (13)$$

which included *h* as an explanatory variable (Eq. 12). The dispersion noticeably decreased; the R^2 was 0.91 *vs.* 0.79, and the standard error of the estimates was 3 vs. 6 %.

Figure 8 shows that the predicted *CUC* almost matched the 1:1 line with respect to the evaluated *CUC* for both models (Eqs. 12 and 13). However, the dispersion noticeably decreased for Eq. 12.

4. Conclusions

Future efforts to improve sprinkler irrigation should pay attention to the importance of agronomic factors. This experiment illustrates the effect of the crops on the water distribution of a solid-set sprinkler system through a comparison between maize and alfalfa simultaneously irrigated with the same technical and operational conditions.

The crops significantly influence the irrigation performance through their influence on the wind velocity (*WV*) above the canopy and on the water collecting plane, both depending on the canopy height (*h*). The sprinkler irrigation uniformity (*CUC*) resulted greater, and the wind drift and evaporation losses (*WDEL*) lesser, above alfalfa than above maize.

The horizontal wind velocity (*WV*) decreases the *CUC* and increases the *WDEL*. The *WV* greatly decreases in proximity to the canopy. Consequently, at the level of the nozzles, the *WV* was noticeably smaller above the maize than above the alfalfa. However, the difference in the *WV* between the crops at the nozzle level was not significant on the *CUC* of the ID_C because it was mainly influenced by the *WV* above the nozzles, levels for which the *WV* was similar above both crops. The assumption of the logarithmic wind profile under neutral conditions, as considered in several sprinkler irrigation models to calculate the vertical variation of the *WV*, overestimates the wind profile above the canopies.

The *CUC* of the ID_C mainly differed between maize and alfalfa because the differences in the water interception plane. The water interception plane depends on *h* and it is connected with the *CUC* because the elevation of this plane affects the overlap of the drop trajectories. When *h* increases, the landing plane of the drops raises and the overlap and the *CUC* of the ID_C decrease.

The influence of *h* on *WDEL* varies between mild and windy conditions. In mild conditions, for which evaporation predominates over drift losses, lower values of *h* imply greater time of exposure of the drops and increases in *WDEL*. As a consequence, *WDEL was* greater above the alfalfa canopy than above maize. On the contrary, in windy conditions, *WDEL* above the maize canopy resulted greater than above alfalfa, despite the time of exposure was greater for the latter. The results suggest that the ID_C was underestimated, thus the *WDEL* was overestimated, when the distance between the nozzles and the pluviometers is small as for maize. The underestimation increases under windy conditions as a consequence of the wind drift which provokes that the trajectory of the drops tends to be horizontal.

With respect to a model based on the *WV* disregarding the crop irrigated, as many presented before, the results of this experiment show a great improvement in the prediction of *CUC* including both the *WV* and *h*.

Acknowledgements

We applied the sequence-determines-credit approach for the sequence of authors. This research was funded by the CICYT of the Government of Spain through grants AGL2004-06675-C03-03/AGR and AGL2007- 66716-C03, and by the Government of Aragón through grant 13 PIP090/2005 and by the INIA and CITA through the PhD grants program. We are very grateful to the colleagues and friends of the Dept. of Soils and Irrigations (CITA-DGA) and of the Dept. of Soil and Water (EEAD-CSIC), for their support and co-operation in the field work and weather monitoring and retrieval. Thanks are particularly due to Antonio Martínez-Cob, Miguel Izquierdo, Jesus Gaudo, Daniel Mayoral and Juan Manuel Acin.

5. References

American Society of Agricultural Engineers (ASAE), 2001. Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles. ANSI/ASAE S436.1. ASAE Standards, St. Joseph.

Burt, C.M., Mutziger, A.J., Allen, R.G., Howell, T.A., 2005. Evaporation research: Review and interpretation. J. Irrig. Drain. E-ASCE 131 (1): 37-58.

Carrión, P., Tarjuelo, J.M., Montero, J., 2001. SIRIAS: a simulation model for sprinkler irrigation - I. Description of model. Irrigation Sci. 20 (2): 73-84.

Cellier, P., Brunet, Y., 1992. Flux-Gradient relationships above tall plant canopies. Agr. Forest Meteorol. 58: 93–117.

Christiansen, J.E., 1942. Irrigation by sprinkling. California Ag. Expt. Sta. Bulletin 670, University of California, Berkeley.

Clark, G.A., Dogan, E., Rogers, D.H., Martin, V.L., 2006. Evaluation of irrigage collectors to measure irrigation depths from low pressure sprinklers. Appl. Eng. Agric. 22 (1): 63-72.

De Bruin, H.A.R., Moore, C.J., 1985. Zero-plane displacement and Roughness length for tall vegetation, derived from a simple mass conservation hypothesis. Boundary-Layer Meteorol. 42: 53-62.

De Lima, J.L.M.P., Torfs, P.J.J.F., Singh, V.P., 2002. A mathematical model for evaluating the effect of wind on downward-spraying rainfall simulators. Catena 46: 221–241.

De Wrachien, D., Lorenzini, G., 2006. Modelling jet flow and losses in sprinkler irrigation: overview and perspective of a new approach. Biosys. Eng. 94 (2): 297–309.

Dechmi, F., Playán, E., Cavero, J., Faci, J.M., Martínez-Cob, A., 2003. Wind effects on solid set sprinkler irrigation depth and yield of maize (Zea mays). Irrigation Sci. 22: 67–77.

Dechmi, F., Playán, E., Cavero, J., Martínez-Cob, A., Faci, J.M., 2004. Coupled crop and solid set sprinkler simulation model. I: Model development., J. Irrig. Drain. E-ASCE 130 (6): 499-510.

Dellwik, E., 2003. Surface layer characteristics and SVAT modelling of a fetch-limited forest. PhD. Thesis, Risoe National Laboratory, Roskilde.

Dogan, E., Kirnak, H., Doyan, Z., 2008. Effect of varying the distance of collectors below a sprinkler head and travel speed on measurements of mean water depth and uniformity for a linear move irrigation sprinkler system. Biosyst. Eng. 99 (2): 190-195.

Edling, R.J., 1985. Kinetic energy, evaporation and wind drift of droplets from low pressure irrigation nozzles. Trans. ASAE 28 (5): 1543-1550.

Faci, J.M., Bercero, A., 1991. Efecto del viento en la uniformidad y en las pérdidas por evaporación y arrastre en el riego por aspersión. Investigación Agraria, Producción y Protección Vegetal. 6 (2): 171-182.

Faci, J.M., Salvador, R., Playán, E., Sourell, H., 2001. Comparison of fixed and rotating spray plate sprinklers. J. Irrig. Drain. E-ASCE 127 (4): 224-233

Finnigan, J.J., 2000. Turbulence in plant canopies. Ann. Rev. Fluid. Mech. 32: 519-571.

Fukui, Y., Nakanishi, K., Okamura, S., 1980. Computer evaluation of sprinkler irrigation uniformity. Irrigation Sci. 2: 23–32.

Haenel, H.D., 1993. Surface-layer profile evaluation using a generalization of Robinson method for the determination of d and z_0. Boundary-Layer Meteorol. 65 (1-2): 55-67.

Haman, I.N., Finnigan, J.J., 2007. A simple unified theory for flow in the canopy and roughness sublayer. Boundary-Layer Meteorol. 123 (2): 339-363.

Högström, U., 1985. Von Karman's constant in atmospheric boundary-layer flow: reevaluated. J. Atmos. Sci. 42: 263–270.

Jacobs, A.F.G., van Boxel, J.H., 1988. Changes of the displacement height and roughness length of maize during a growing-season. Agr. Forest Meteorol. 42 (1): 53-62.

Keller, J., Bliesner, R.D., 1990. Sprinkler and trickle irrigation. Van Nostrand Reinhold, New York.

Kincaid, D.C., 1996. Spraydrop kinetic energy from irrigation sprinklers. Trans. ASAE 39 (3): 847-853.

Kristensen, L., 1998. Cup anemometer behavior in turbulent environments. J. Atmos. Ocean. Tech. 15 (1): 5-17.

Kustas, W.P., Choudhury, B.J., Kunkel, K.E., Gay, L.W., 1989. Estimate of the aerodynamic roughness parameters over an incomplete canopy cover of cotton. Agr. Forest Meteorol. 46 (1-2): 91-105.

Lorenzini, G., De Wrachien, D., 2005. Performance assessment of sprinkler irrigation systems: a new indicator for spray evaporation losses. Irrig. Drain. 54: 295-305.

Mahrt, L., 2000. Surface heterogeneity and vertical structure of the boundary layer. Boundary-Layer Meteorol. 96: 33-62.

Mateos, L., 1998. Assessing whole-field uniformity of stationary sprinkler irrigation systems. Irrigation Sci. 18: 73-81.

Mihailovic, D.T. Lalic, B., Rajkovic, B. Arsenic, I., 1999. A roughness sub-layer wind profile above a non-uniform surface. Boundary-Layer Meteorol. 93 (3): 425-451.

Monin, A.S., Obukhov, A.M., 1954. Basic regularity in turbulent mixing in the surface layer in the atmosphere. Trudy geofiz. inst. AN SSSR 24 (151): 163-187.

Monin, A.S., Yaglom, A.M., 1971. Statistical fluid mechanics: mechanics of turbulence. Vol.1, The MIT Press, Cambridge.

Oke, T.R., 1984. Boundary layer climates, second Edn. Methuen, London and New York.

Petersen, E.L., Mortensen, N.G. Landberg, L., Hojstrup, J., Frank, H.P., 1998. Wind power meteorology. Part II: Sitting and models. Wind Energy 1 (2): 55-72.

Playán, E., Garrido, S., Faci, J.M., Galán, A., 2004. Characterizing pivot sprinklers using an experimental irrigation machine. Agric. Water Manage. 70 (3): 177-193.

Playán, E., Salvador, R., Faci, J.M., Zapata, N., Martínez-Cob, A., Sanchez, I., 2005. Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. Agric. Water Manage. 76 (3): 139-159.

Playán, E., Zapata, N., Faci, J.M., Tolosa, D., Lacueva, J.L., Pelegrin, J., Salvador, R. Sanchez, I., Lafita, A., 2006. Assessing sprinkler irrigation uniformity using a ballistic simulation model. Agric Water Manage. 84 (1-2): 89-100.

Poggi, D., Porporato, A., Ridolfi, L., Katul, G., Albertson J. 2004. The effect of vegetation density on canopy sub-layer turbulence. Boundary-Layer Meteorol. 111 (3): 565–587.

Raupach, M.R., Thom, A.S., 1981. Turbulence in and above plant canopies. Ann. Rev. Fluid. Mech. 13: 97-129.

Schaudt, K.J., 1998. A new method for estimating roughness parameters and evaluating the quality of observations. J Appl. Meteorol. Clim. 37 (5): 470-476.

Seginer, I., Kantz, D., Nir, D., 1991a. The Distortion by wind of the distribution patterns of single sprinklers. Agric. Water Manage. 19 (4): 341-359.

Seginer, I., Nir, D., von Bernuth, R.D., 1991b. Simulation of wind-distorted sprinkler patterns. J. Irrig. Dr. Eng. 117: 285-305.

Shaw, R.H., Pereira, A.R., 1982. Aerodynamic roughness of a plant canopy: a numerical experiment. Agric. Meteorol. 26: 51–65.

Stanhill, G., 1969. A simple instrument for the field measurement of turbulent diffusion flux. J. Applied Meteorol. 8 (4): 509-513.

Tanner, C.B., Pelton, W.L., 1960. Potential evapotranspiration estimates by the approximate energy balance method of Penman. J. Geophys. Res. 65: 3391-3413.

Tarjuelo, J.M., Carrión, P., Valiente, M., 1994. Simulación de la distribución del riego por aspersión en condiciones de viento. Investigación Agraria, Producción y Protección Vegetal. 9: 255-271.

Tarjuelo, J.M., Montero, J., Carrión, P.A., Honrubia, F.T., Calvo, A., 1999. Irrigation uniformity with medium size sprinklers part II: Influence of wind and other factors on water distribution. Trans. ASAE 42 (3): 677-690.

Tarjuelo, J.M., Ortega, J.F., Montero, J., de Juan, J.A., 2000. Modelling evaporation and drift losses in irrigation with medium size impact sprinklers under semi-arid conditions. Agric. Water Manage. 43 (3): 263-284.

Todd, R.W., Evett, S.R., Howell, T.A., 2000. The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment. Agr. Forest Meteorol. 103 (4): 335-348.

Vories, E.D. von Bernuth, R.D., Mickelson, R.H., 1987. Simulating sprinkler performance in wind. J. Irrig. Drain. E-ASCE 113 (1): 119-130.

Wilson, J.D., Ward, D.P., Thurtell, G.W., Kidd, G.E., 1982. Statistics of atmospheric turbulence within and above a corn canopy. Boundary-Layer Meteorol. 24: 495–519.

Yazar, A., 1984. Evaporation and drift losses from sprinkler irrigation systems under various operating conditions. Agric. Water Manage. 8: 439-449.

Zapata, N., Playán, E., Martínez-Cob, A. Sanchez, I., Faci, J.M., Lecina, S., 2007. From on-farm solid-set sprinkler irrigation design to collective irrigation network design in windy areas. Agric. Water Manage. 87 (2): 187-199.

Nomenclature.

τ	= *Shear stress*
ρ	= *Air density*
A	= *Area of the nozzles orifices* (mm^2)
a.g.l.	= *Above the ground level*
C_D	= *Discharge coefficient*
CUC	= *Christiansen's Uniformity Coefficient (%)*
$CUC_{a,z}$	= *CUC above alfalfa evaluated at the height z (%)*
$CUC_{m,z}$	= *CUC above maize evaluated at the height z (%)*
CUC_z	= *CUC evaluated at the height z (%)*
d	= *Displacement height (cm)*
EWP	= *Estimated wind velocity profile*
EWP_{crop}	= *Wind velocity profile estimated from* $WV_{crop,2.3}$
EWP_{grass}	= *Wind velocity profile estimated from* $WV_{grass,2}$
g	= *Gravity acceleration* ($m\ s^{-2}$)
h	= *Crop height (m)*
h_a	= *Height of the alfalfa crop (m)*
h_m	= *Height of the maize crop (m)*
ID_C	= *Irrigation depth averaged for the experimental area (mm)*
$ID_{Ca,z}$	= ID_C *collected above alfalfa at the height z (mm)*
$ID_{Cm,z}$	= ID_C *collected above maize at the height z (mm)*
$ID_{C,z}$	= ID_C *collected at the height z (mm)*
ID_D	= *Irrigation depth emitted by the sprinklers (mm)*
k	= *von Karman's constant (0.41)*
l	= *Spacing among laterals (m)*

MAE_{Com} = *Mean Absolute Error for the anemometers comparison (m s*$^{-1}$*)*

ME_{WP} = *Mean Error for the estimation of the wind profile (m s*$^{-1}$*)*

MWP = *Measured wind velocity profile*

p = *Pressure in nozzle (kPa)*

Q = *Sprinkler flow rate (l s*$^{-1}$*)*

r = *Sample linear correlation coefficient*

R^2 = *Coefficient of determination*

RH = *Air relative humidity (%)*

$RMSE_{Com}$ = *Root mean square error for the anemometers comparison (m s*$^{-1}$*)*

$RMSE_{WP}$ = *Root Mean Square Error for the estimation of the wind profile (m s*$^{-1}$*)*

s = *Spacing among sprinklers along the lateral (m)*

SD = *Standard deviation*

T = *Air temperature (ºC)*

t = *Operating time of the irrigation event (s)*

$WDEL$ = *Wind drift and evaporation losses (%)*

$WDEL_{a,z}$ = *WDEL above alfalfa estimated at the height z (%)*

$WDEL_{m,z}$ = *WDEL above maize estimated at the height z. (%)*

$WDEL_z$ = *WDEL estimated at the height z (%)*

WV = *Wind velocity (m s*$^{-1}$*)*

WV_a = *WV above alfalfa (m s*$^{-1}$*)*

$WV_{crop,\,z}$ = WV_z *above the crops at the height z (m s*$^{-1}$*)*

WV_{grass} = *WV above grass (m s*$^{-1}$*)*

WV_m = *WV above maize (m s*$^{-1}$*)*

WV_z = *WV at the height z (m s*$^{-1}$*)*

WV^* = *Friction velocity over a vegetated surface*

WV^*_g = *Friction velocity for a bare soil*

z = *Height above the ground level (m)*

z_0 = *Roughness length of a vegetated surface (cm)*

z_{0g} = *Roughness length of a bare soil (cm)*

List of Tables

Table 1. Irrigation date, temperature (T) and relative humidity (RH) of the air, wind velocity above grass at 2 m ($WV_{grass,2}$), operating pressure at the nozzles (p), average irrigation depth (ID_C), Christiansen uniformity coefficient (CUC) of ID_C and wind drift and evaporation losses (WDEL) for ten irrigation events during the 2006 season.

Date	T (º)	HR (%)	$WV_{grass,2}$ (m s^{-1})	p (kPa)		ID_C (mm)			CUC (%)			WDEL (%)		
				m^b	a^b	m^b	a^b	$a_{2.25}{}^b$	m^b	a^b	$a_{2.25}{}^b$	m^b	a^b	$a_{2.25}{}^b$
Ag 24	22	55	4.2	355	330	13.9	14.9	12.5	55	76	58	21	13	27
Ag 30	24	53	5.6	330	340	12.7	13.3	11.7	56	78	56	26	23	33
Sp 1	26	60	0.8	321	352	16.2	17.7	17.9	90	93	91	8	4	3
Sp 4	27	51	0.9	326	348	15.3	16.0	16.4	84	93	89	10	9	6
Sp 8	25	49	0.9	343	341	15.4	15.8	16.2	90	94	90	11	9	6
Sp 19	24	45	1.5	336	341	15.5	15.7	15.6	84	90	85	13	12	12
Sp 27	23	44	0.8	290	342	19.5	21.5	21.9	89	92	89	9	7	5
Oc 3	21	50	4.6	330	327	13.7	14.3	13.1	51	75	58	19	16	23
Oc 6	19	56	0.9	333	327	15.9	16.6	17.0	91	94	90	7	3	0
Oc 10	22	68	2.2	350	323	18.7	19.1	19.2	75	83	75	9	4	4

Table 2: Mean Absolute Error (MAE_{Com}) for each anemometer and maximum value of the Root Mean Square Error ($RMSE_{Com}$).

WV range ($m\ s^{-1}$)	*$MAE_{Com}{}^{a}$ ($m\ s^{-1}$)*						*$RMSE_{Com}{}^{a}$ ($m\ s^{-1}$) (Max.)*
	1	2	3	4	5	6	
< 2	0.03	0.07	0.03	0.03	0.04	0.03	0.27
2 – 4	0.03	0.06	0.04	0.04	0.05	0.03	0.30
4 – 6	0.04	0.08	0.05	0.05	0.07	0.05	0.20
> 6	0.08	0.09	0.08	0.08	0.09	0.07	0.17

[a] Values calculated according to the equations 6 and 7, respectively.

Table 3: Irrigation date, wind velocity averaged during the irrigation event at 2 m above grass ($WV_{grass,2}$); height of the crop (h); mean error (ME_{WP}) and root mean square error ($RMSE_{WP}$) in the estimation of the wind velocity profile according to the logarithmic profile using $WV_{grass,2}$ (EWP_{grass}), or WV over the crop at 2.3 m ($WV_{crop,2.3}$) as reference velocity (EWP_{crop}). In columns, A refers to alfalfa and M to maize.

Date	$WV_{grass,2}$ ($m\ s^{-1}$)	*h (m)*		ME_{WP} ($m\ s^{-1}$)		$RMSE_{WP}$ ($m\ s^{-1}$)			
						EWP_{crop}		EWP_{grass}	
		A	*M*	*A*	*M*	*A*	*M*	*A*	*M*
May 31	4.5	0.50	0.20	0.1	-0.2	0.3	0.2	0.3	0.3
Jun 1	4.4	0.50	0.25	0.1	-0.3	0.2	0.2	0.3	0.4
Jun 6	1.1	0.75	0.30	-0.1	-0.1	0.1	0.0	0.1	0.1
Jun 8	3.7	0.75	0.30	0.3	0.1	0.2	0.2	0.5	0.3
Jun 12	5.3	0.75	0.40	0.0	0.1	0.4	0.2	0.4	0.2
Jun 16	1.1	0.10	0.60	0.2	0.3	0.0	0.1	0.2	0.2
Jun 20	4.3	0.25	0.60	-0.2	0.4	0.3	0.1	0.4	0.4
Jun 22	3.9	0.25	0.65	0.1	0.3	0.2	0.1	0.1	0.3
Jun 30	0.9	0.50	0.94	0.2	0.3	0.0	0.1	0.2	0.2
Jul 3	1.3	0.75	1.20	0.3	0.6	0.0	0.1	0.3	0.5
Jul 6	4.8	0.75	1.22	0.4	0.9	0.2	0.1	0.5	0.9
Jul 10[a]	1.5	0.10	1.50	0.2	0.5	0.1	0.1	0.2	0.5
Jul 13[a]	2.7	0.25	1.60	0.0	0.6	0.2	0.1	0.2	0.9
Jul 17[a]	1.4	0.25	1.75	0.1	0.6	0.0	0.1	0.1	0.8
Jul 24	1.1	0.50	1.75	0.3	0.7	0.0	0.1	0.3	0.9
Jul 27	0.7	0.50	1.75	-0.1	0.1	0.0	0.1	0.1	0.2
Jul 31	2.2	0.75	1.75	-0.1	1.0	0.2	0.1	0.2	1.3
Aug 3	7.8	0.10	1.75	-0.8	4.0	0.2	0.3	0.8	5.1
Aug 8	2.2	0.10	1.75	0.0	1.2	0.1	0.1	0.1	1.5
Aug 10	3.2	0.25	1.75	0.0	1.8	0.1	0.1	0.1	2.3
Aug 18	1.5	0.50	1.75	0.2	0.9	0.1	0.1	0.2	1.2
Aug 21	2.4	0.50	1.75	0.1	0.9	0.1	0.0	0.2	1.2
Aug 24	4.2	0.50	1.75	0.2	2.2	0.0	0.1	0.2	2.8
Aug 27	3.5	0.50	1.75	0.4	1.7	0.0	0.1	0.4	2.2
Aug 30	5.6	0.50	1.75	0.4	3.1	0.1	0.1	0.4	3.8
Sep 1	0.8	0.50	1.75	0.2	0.4	0.1	0.0	0.1	0.5
Sep 4	0.9	0.50	1.75	-0.1	0.2	0.0	0.0	0.1	0.3
Sep 8	0.9	0.50	1.75	0.0	0.5	0.1	0.1	0.1	0.7
Sep 19	1.5	0.25	1.75	-0.1	0.7	0.0	0.1	0.1	0.9
Sep 27	0.8	0.50	1.75	0.1	0.2	0.1	0.1	0.1	0.4
Oct 3	4.6	0.50	1.75	0.2	1.3	0.1	0.5	0.3	2.1
Oct 6	0.9	0.50	1.75	0.1	0.4	0.0	0.3	0.1	0.8
Oct 10	2.2	0.50	1.75	0.0	0.8	0.1	0.2	0.1	1.2

[a] Above maize, the *WV* was monitored at 2.0 m instead of at 2.3 m.

List of Figures

Figure 1. Crop height and elevation of the anemometers and pluviometers during the 2006 irrigation season for maize and alfalfa. Above alfalfa, two collections of pluviometers were used: one above the canopy and the other at the same elevation than those above the maize canopy after August 23.

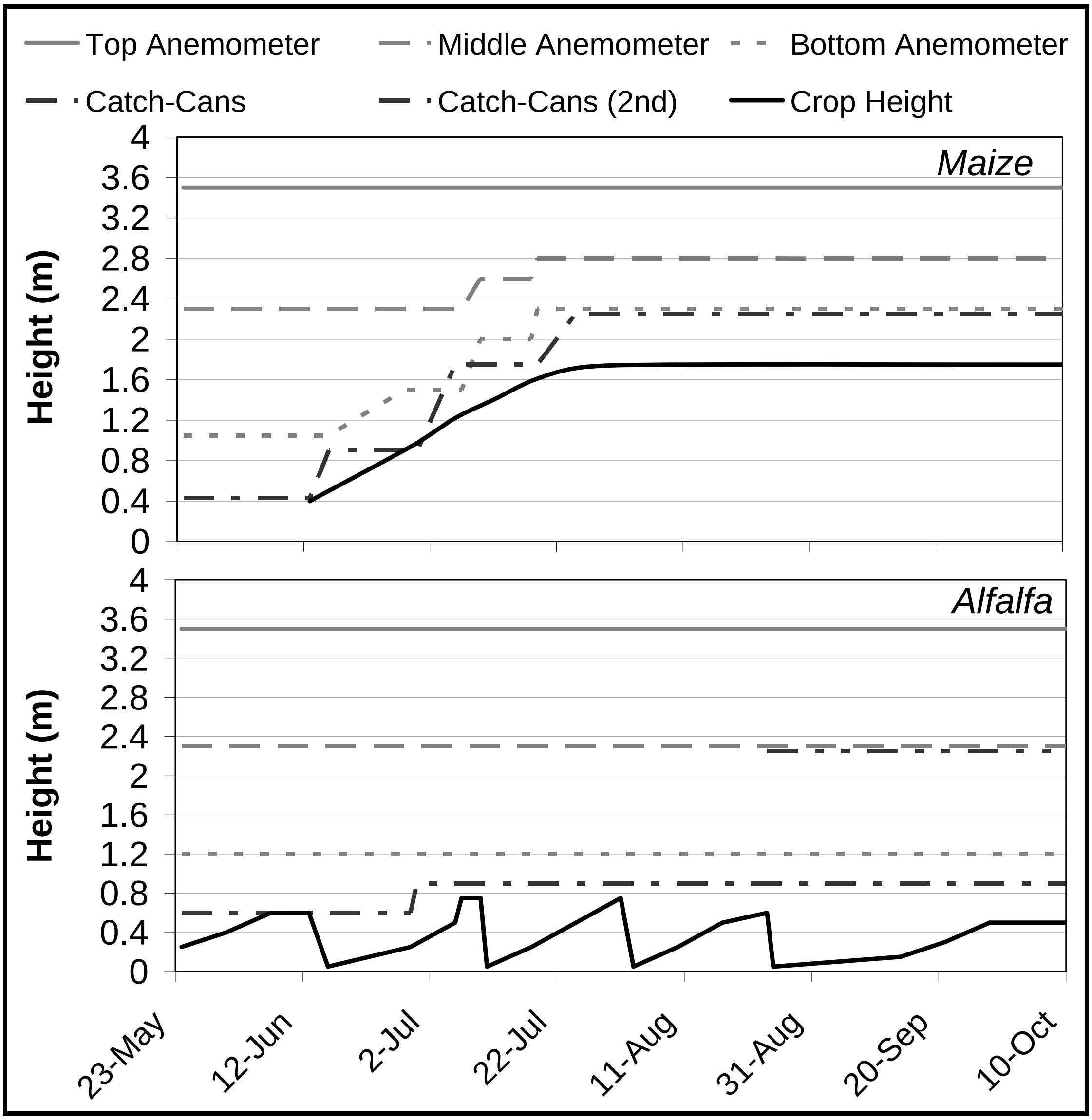
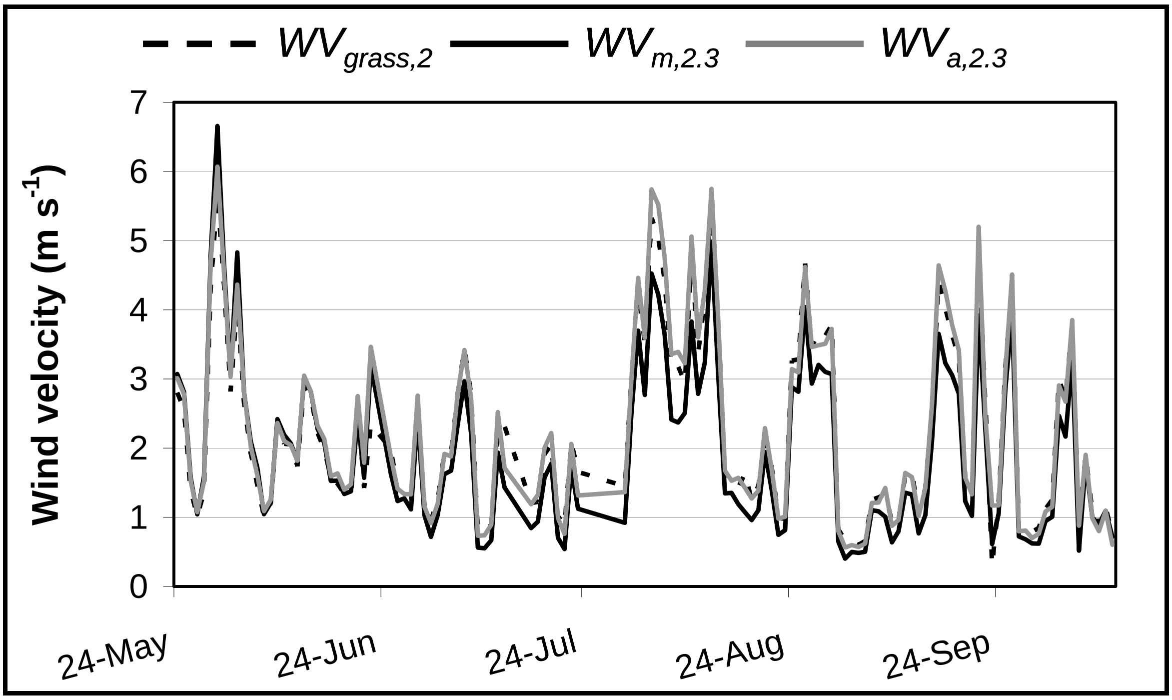


Figure 2. Evolution of the daily average wind velocity measured at 2 m above the ground level (a.g.l.) above grass ($WV_{grass,2}$) and at 2.3 m a.g.l. above maize (WV_m) and alfalfa (WV_a).



754 *Figure 3. Measured wind velocity profiles (MWP) from the recordings at three levels above the canopy for three irrigation events. Wind profiles estimated according to the logarithmic profile under neutral stability conditions from the wind velocity monitored at 2.3 m a.g.l. above the crop (EWP_{crop}). The same estimated from the wind velocity monitored simultaneously at 2 m a.g.l. above grass ($WV_{grass,2}$) (EWP_{grass}). The horizontal black line represents the height of the crop. The plane of displacement (d) and the roughness length (z_0) are calculated from h via the Eqs. 3 and 4.*

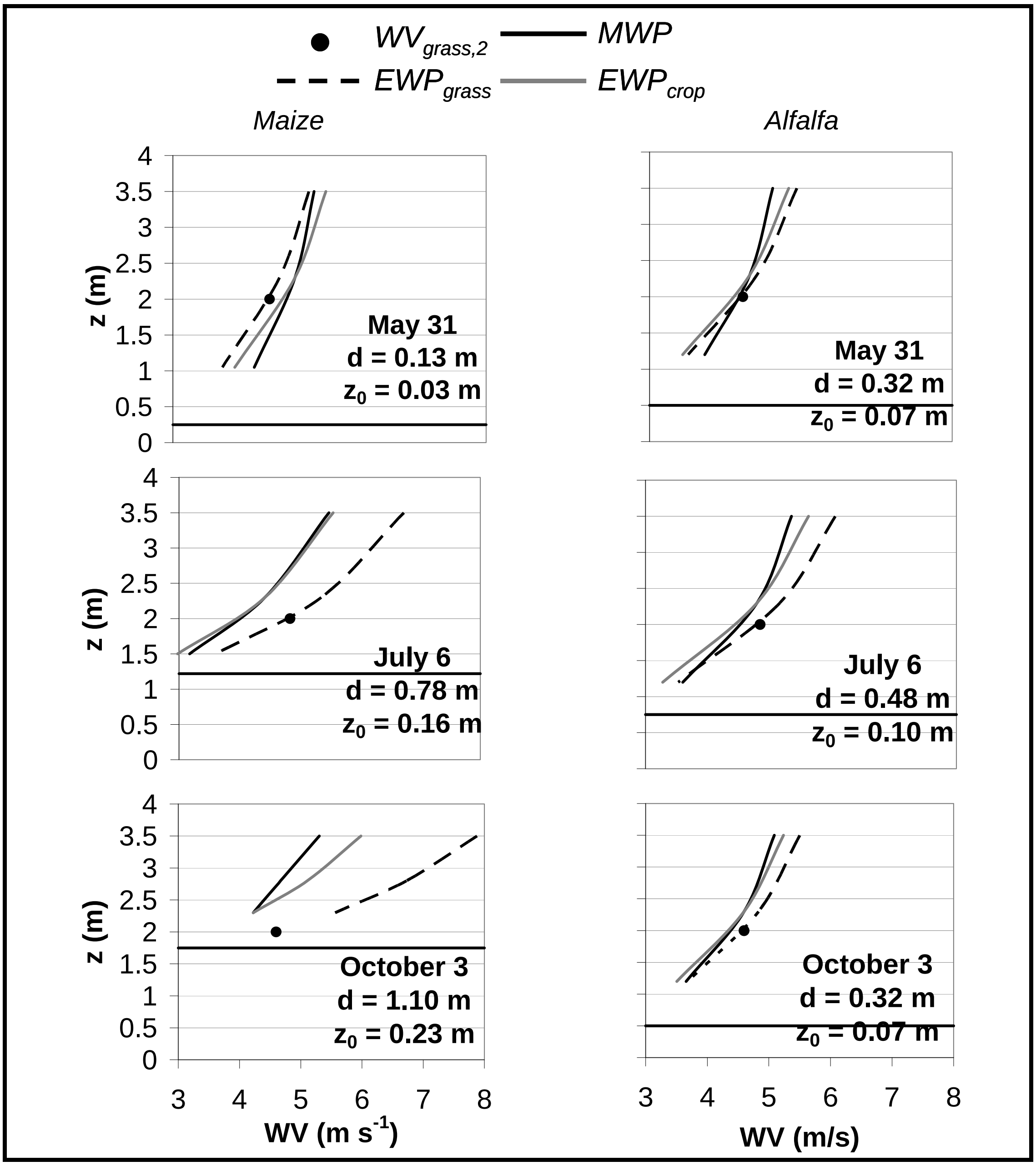


Figure 4. Influence of the crop height (h) on the relationship between the Christiansen's Uniformity Coefficient (CUC) of the irrigation depth collected above the canopy and the wind velocity measured above grass at 2 m ($WV_{grass,2}$) (a); the same for the wind velocity measured above the crops at 2.3 m ($WV_{crop,2.3}$) (b). For maize, the results are analyzed for h smaller than 1.2 m and greater. For alfalfa, maximum h was 0.75 m.

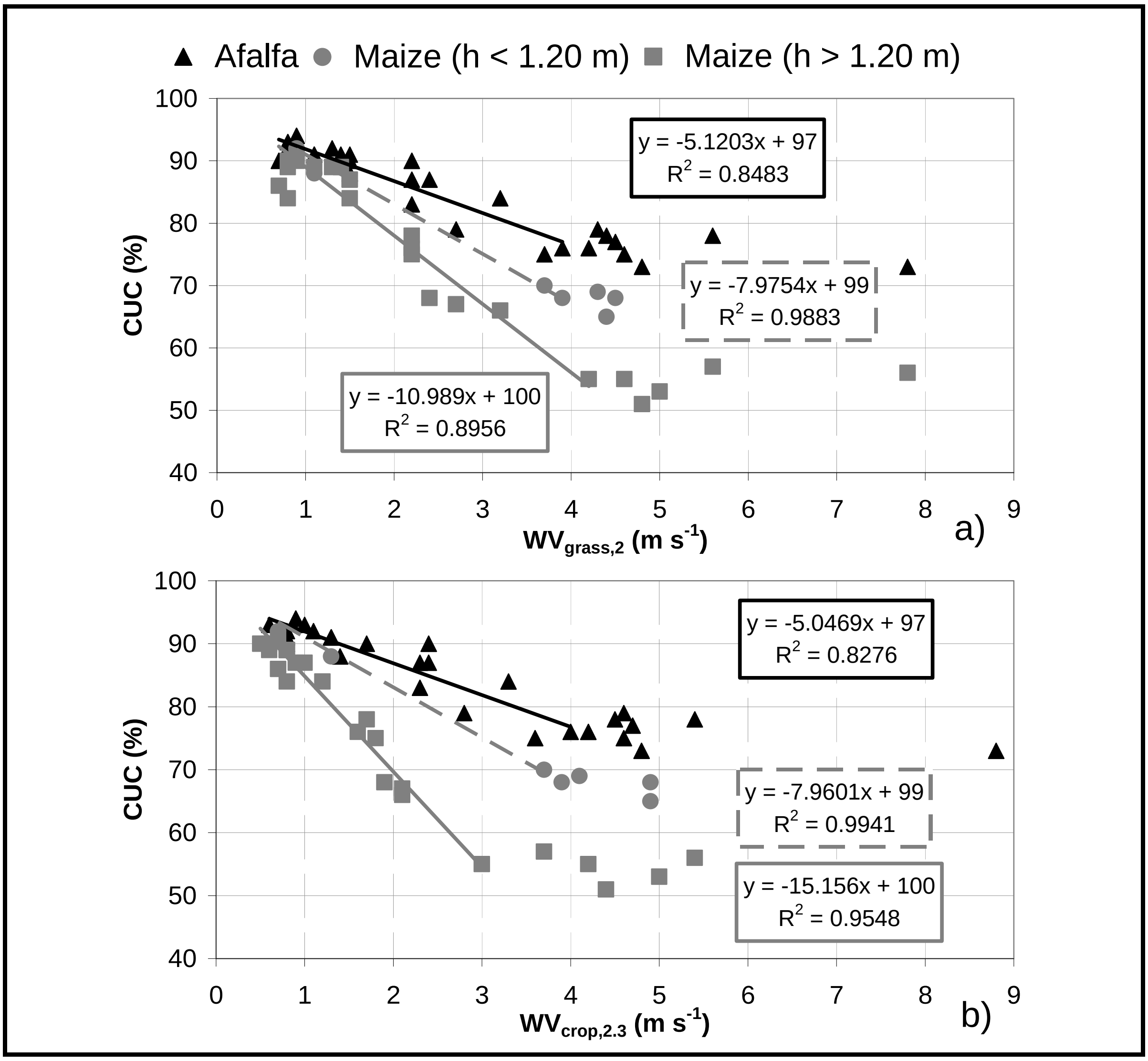


Figure 5. Influence of the water interception plane and of the wind velocity (measured above grass at 2 m, $WV_{grass,2}$) on the wind drift and evaporation losses (WDEL). The water interception plane was 2.25 and 0.9 m a.g.l. above the maize and alfalfa canopies, respectively, and also 2.25 m a.g.l. above the alfalfa (as for maize), for mild (WV_{grass} < 2 m s^{-1}) and windy (WV_{grass} > 2 m s^{-1}) conditions. Bars show the standard deviation.

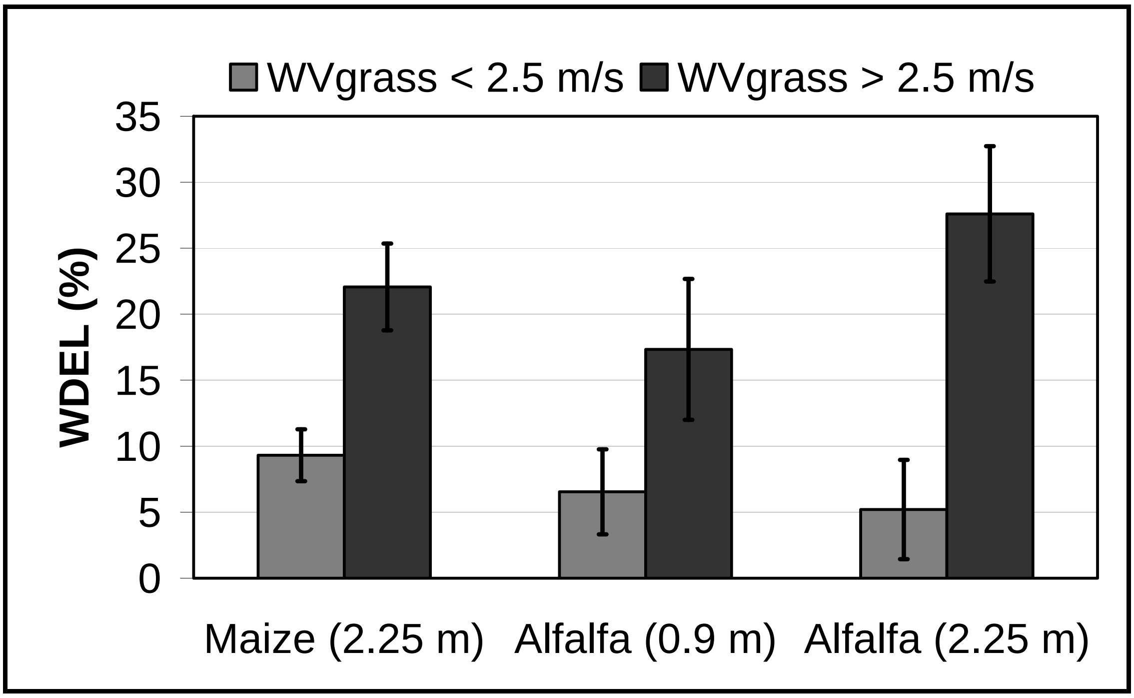


Figure 6. Influence of the water interception plane and of the wind velocity (WV) monitoring position on the Christiansen's Uniformity Coefficient (CUC) of the irrigation depth (ID_C): at 2.25 m ($CUC_{2.25}$) above maize and alfalfa and at 0.9 m ($CUC_{0.9}$) above alfalfa. WV monitored at 2 m above grass ($WV_{grass,2}$) (a) at 2.3 m above the crops ($WV_{crops,2.3}$) (b) and at 3.5 m a.g.l. above the crops ($WV_{crops,3.5}$) (c).

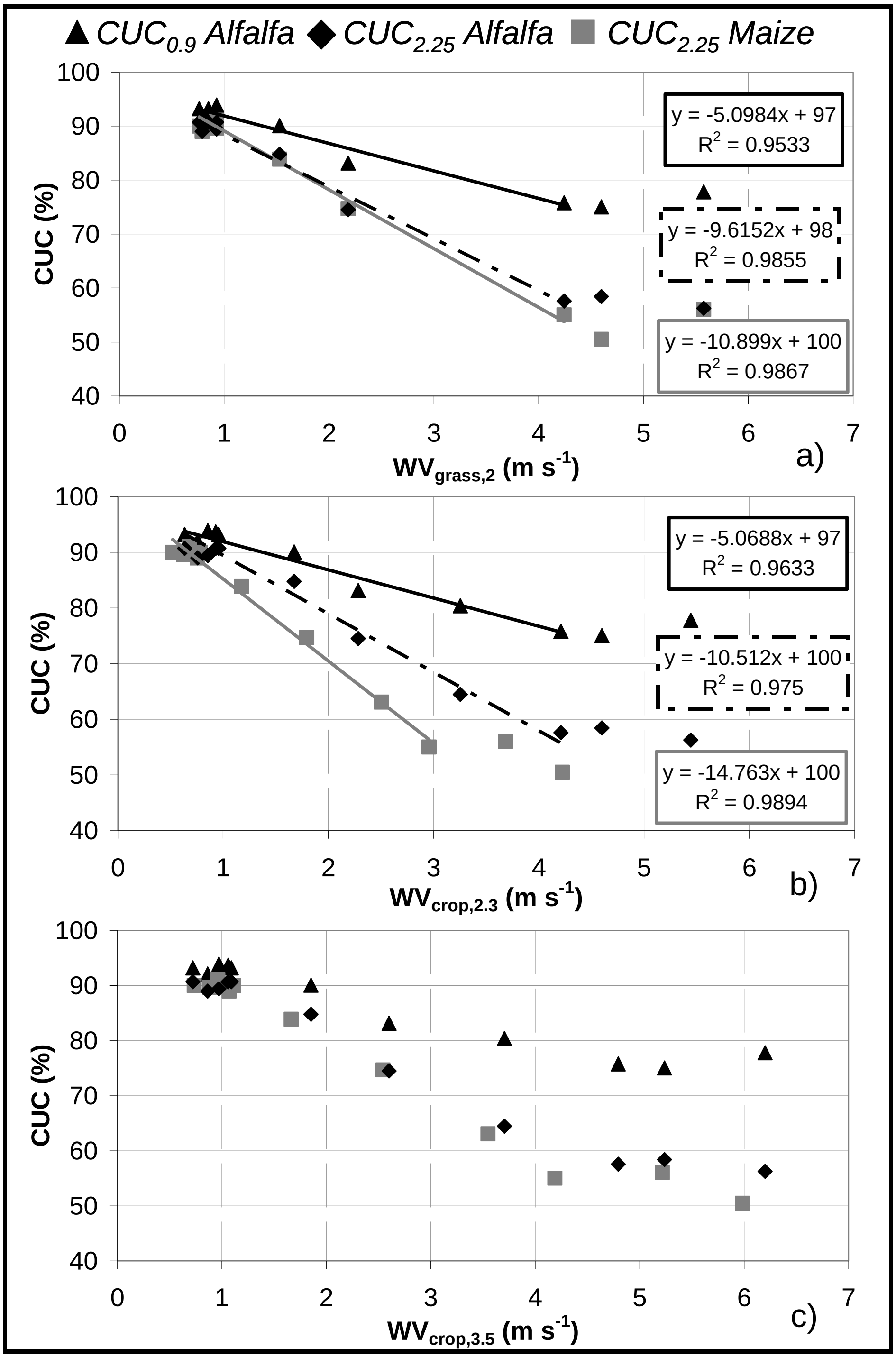


Figure 7. Contour lines maps within the experimental plot between four sprinklers (in the corners) estimated from the irrigation depth (ID_C) collected into pluviometers (crosses) located at 2.25 m ($ID_{C,2.25}$) above maize and alfalfa, and at 0.9 m ($ID_{C,0.9}$) above alfalfa. The arrows indicate the prevailing wind direction during the irrigation event.

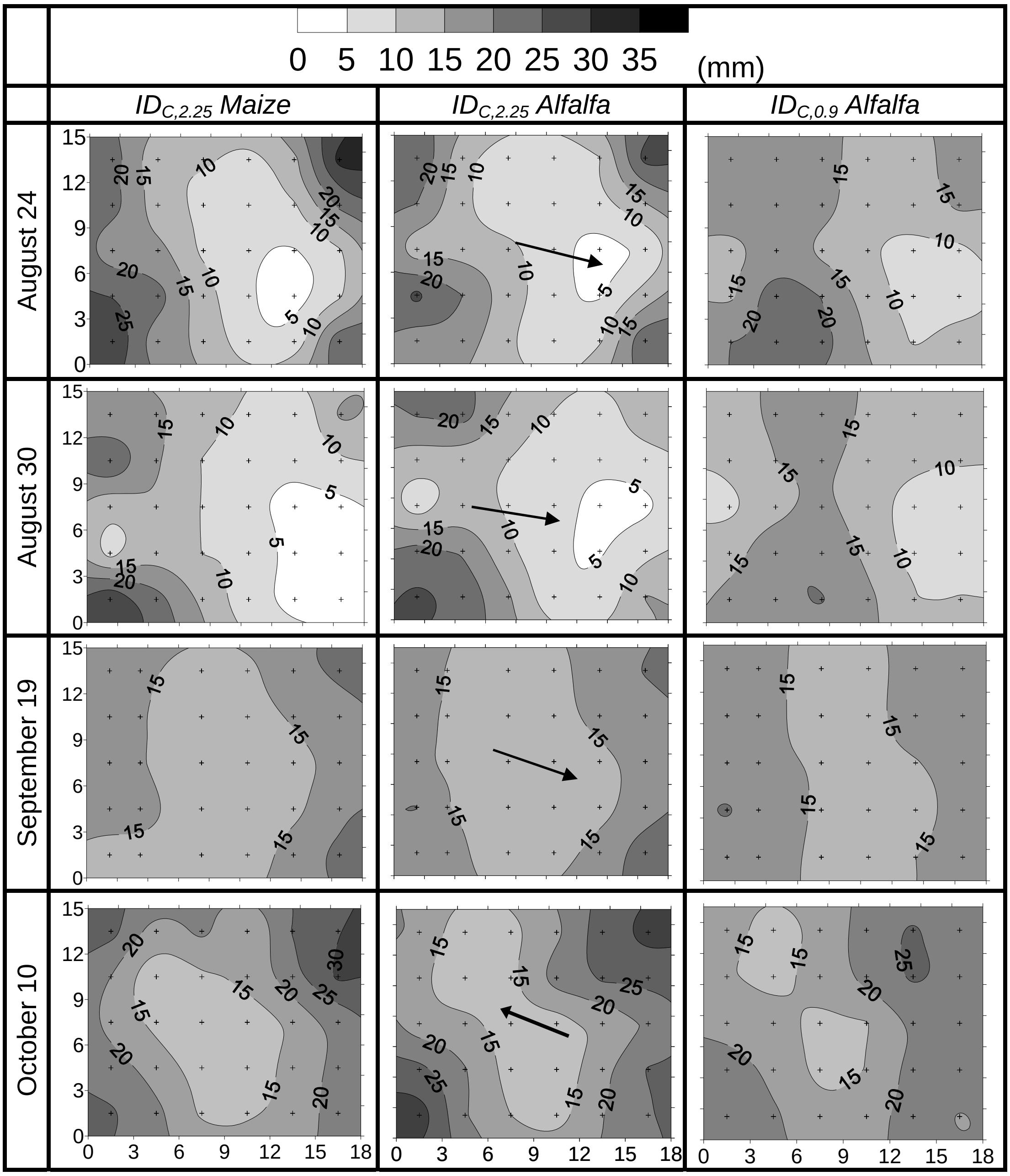


Figure 8. Comparison of the modelled and evaluated values of the Christiansen's Uniformity coefficient (CUC) of the irrigation depth above the maize and alfalfa canopies during the 2006 season. The CUC is calculated as a function of the wind velocity at 2 m above grass [F ($WV_{grass,2}$)] or as a function of the $WV_{grass,2}$ and of the water interception plane [f ($WV_{grass,2}$, h)].