

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

4 by

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19 **Keywords**

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

22 **Abstract**

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

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

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

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

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

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

50 **1. Introduction**

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

56 Wind has been reported as the major factor decreasing irrigation
57 uniformity and increasing water loss in sprinkler irrigation (Dechmi et al., 2003;
58 Faci and Bercero, 1991; Kincaid, 1996; Seginer et al., 1991a, 1991b; Tarjuelo et
59 al, 1994; Tarjuelo et al, 1999; Playán et al. 2005, 2006; Zapata et al., 2007).
60 The wind velocity close to the Earth's surface is strongly influenced by the
61 nature of the terrain surface (Petersen et al., 1998). The *surface layer* consists
62 of two parts. In the upper part, called the *inertial sub-layer*, the mean flow can
63 be described one-dimensionally using the surface-layer Monin-Obukhov
64 similarity theory (Monin and Obukhov, 1954). In the lower part, which is close to
65 and within the canopy itself, the mean flow is three-dimensional; this layer is
66 called the *roughness sub-layer*, the *transition layer*, the *interfacial-layer*
67 (Raupach and Thom, 1981) or the *canopy sub-layer* (Poggi et al., 2004). The
68 thickness of the *roughness sub-layer* varies between two and three canopy

69 heights above the ground (Cellier and Brunet, 1992; Dellwik, 2003; Mahrt, 2000;
 70 Mihailovic et al. 1999). The distribution of the water drops by agricultural
 71 sprinklers occurs partially or totally within the *roughness sub-layer*.
 72 Consequently, the wind surrounding the sprinkler system greatly depends on
 73 the aerodynamic characteristics of the crops.

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

$$77 \quad WV_z = \frac{WV_g^*}{k} \ln \frac{z}{z_{0g}} \quad (1)$$

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

$$82 \quad WV_z = \frac{WV^*}{k} \ln \frac{z-d}{z_0} \quad (2)$$

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

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

$$90 \quad [\log d = 0.9793 \log h - 0.1536] \quad (3)$$

$$91 \quad [\log z_0 = 0.997 \log h - 0.883] \quad (4)$$

92 where d , z_0 and h are in cm.

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

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

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

$$102 \quad WV_{z_2} = WV_{z_1} \frac{\ln\left(\frac{z_2 - d}{z_0}\right)}{\ln\left(\frac{z_1 - d}{z_0}\right)} \quad (5)$$

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

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

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

128 This topic has been analyzed by testing different elevations of the
129 sprinklers (Edling, 1985; de Wrachien and Lorenzini, 2006; Tarjuelo et al. 1999)
130 or different elevations of the pluviometers (Clark et al., 2006; Dogan et al.,
131 2008). However, depending on the approach, different effects will be found. The
132 *WV* decreases and the turbulence increases in proximity to the surface. When
133 the pluviometers are elevated above the surface, the *WV* around them will be
134 higher and the turbulence lower. When the sprinklers are lowered, the *WV*
135 around them will be lower and the turbulence higher.

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

140 **2. Materials and Methods**

141 **2.1. Experimental layout**

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

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

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

159 **2.2. Wind monitoring**

160 The wind velocity (WV) was monitored above the maize, alfalfa and
161 grass (*Festuca arundinacea*) from May 24 to October 11, 2006. A
162 meteorological station of the *SIAR* network (Figure 1 of the companion paper)
163 measured the wind velocity at 2 m a.g.l. in the center of a 0.5 ha grassland
164 ($WV_{grass,2}$). The station used a propeller-type anemometer (Young's wind

165 monitor Model 05103, Campbell scientific, Inc., Shepshed, Leicestershire, UK)
166 (accuracy $\pm 0.3 \text{ m s}^{-1}$, wind speed starting threshold 1.0 m s^{-1}). It also monitored
167 the wind direction (accuracy $\pm 3^\circ$, wind speed starting threshold 1.1 m s^{-1}),
168 which was classified in sixteen categories in clockwise rotation: from 11.25° to
169 33.75° was considered north-north-east (NNE), north-east (NE) from 33.75° to
170 56.25° , and so on up to north (N), from 348.75 to 11.25° . The wind direction was
171 considered the same within the area. The meteorological station recorded the
172 $WV_{grass,2}$ and wind direction, temperature and relative humidity of the air, solar
173 radiation and precipitation every 30 min.

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

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

189 2.2.1. Measurement limitations of the anemometers

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

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

198
$$MAE_{Com} (j = 1, 2, \dots, 6) = \frac{1}{n} \sum_{i=1}^n \left| WV_{ij} - \frac{1}{6} \sum_{j=1}^6 WV_{ij} \right| \quad (6)$$

199 where n is the number of 5 min periods during the testing time, WV_{ij} the average
200 wind velocity recorded by an anemometer j in each 5 min period i , and
201 $\frac{1}{6} \sum_{j=1}^6 WV_{ij}$ the average of the wind velocity for the six anemometers during each
202 period i .

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

204
$$RMSE_{Com} (i = 1, 2, \dots, n) = \sqrt{\frac{1}{6} \sum_{j=1}^6 \left(WV_{ij} - \frac{1}{6} \sum_{j=1}^6 WV_{ij} \right)^2} \quad (7)$$

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

209 2.2.2. Accuracy in the estimation of the wind profile

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

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

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

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

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

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

$$220 \quad ME_{WP} = WV_{2.3}^{EWP_{grass}} - WV_{crop,2.3} \quad (8)$$

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

$$224 \quad RMSE_{WP} = \sqrt{\frac{1}{3}((WV_{z_1}^{EWP} - WV_{crop,z_1})^2 + (WV_{z_2}^{EWP} - WV_{crop,z_2})^2 + (WV_{z_3}^{EWP} - WV_{crop,z_3})^2)} \quad (9)$$

225 where z_1 , z_2 and z_3 are the positions of the anemometers above the crop.

226 $RMSE_{WP}$ was calculated for both the EWP_{grass} and the EWP_{crop} approaches.

227 2.3. Evaluation of the irrigation performance

228 The irrigation water depth (ID_C) was collected into pluviometers just
229 above the canopy. The pluviometers are described in the companion paper.

230 The pluviometers were elevated as the crops grew: up to 2.25 m a.g.l. above

231 the maize and up to 0.9 m a.g.l. above the alfalfa (Figure 1). In addition, the ID_C

232 was collected at the same level above the alfalfa and the maize for ten irrigation

233 events (Table 1). For this collection, a second network of pluviometers was
234 located above the alfalfa at 2.25 m a.g.l. (Figure 1).

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

$$240 \quad WDEL = \frac{ID_D - ID_C}{ID_D} \times 100 \quad (10)$$

$$241 \quad ID_D = \frac{Q \times t}{15 \times 18} \quad (11)$$

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

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

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

251 **3. Results and Discussions**

252 **3.1. Measurement limitations of the anemometers**

253 Systematic or large, random errors in one or more of the anemometers
254 have been reported to be one of the main causes of the differences found
255 between positions (Schaudt, 1998). The threshold below which differences
256 between the anemometer measurements were considered to be measurement

257 limitations of the anemometers, and therefore discarded as differences among
258 heights or sites, was 0.3 m s^{-1} for comparisons based on records averaged
259 every 5 min (maximum $RMSE_{Com}$, Eq. 7, Table 2) and 0.1 m s^{-1} for comparisons
260 based on records averaged every 30 min (maximum MAE_{Com} , Eq. 6, Table 2).

261 **3.2. Modifications of the wind velocity by the crop canopy**

262 The wind direction fitted the Ebro Valley 40 % of the time during the 2006
263 irrigation season. This percentage greatly increased in windy conditions: it was
264 76 % for WV greater than 3.5 m s^{-1} . *Cierzo*, wind from the *WNW-NW* direction,
265 was the most frequent (26 %) and the highest velocities were recorded in this
266 direction. *Bochorno*, wind from the *ESE-SE* direction, was also frequent (14 %).

267 The values of h increased up to 1.75 m for maize and up to 0.75 m for
268 alfalfa just before the cuttings (Figure 1). The differences in the WV between the
269 crops increased as the differences in h increased. $WV_{m,2.3}$ was smaller than
270 $WV_{grass,2}$ and $WV_{a,2.3}$ after early July. In contrast, $WV_{a,2.3}$ and $WV_{grass,2}$ were
271 similar throughout the season (Figure 2).

272 $WV_{m,2.3}$ and $WV_{a,2.3}$ were compared with $WV_{grass,2}$ using a *least square*
273 *means test* with the values of WV averaged every 30 min. Three wind ranges
274 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
275 than 5 m s^{-1} . $WV_{m,2.3}$ was significantly different ($\alpha = 0.05$) from $WV_{grass,2}$ when
276 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}
277 greater than $WV_{grass,2}$ (the differences increased with the WV). $WV_{m,2.3}$ and
278 $WV_{grass,2}$ were not significantly different when h_m was between 0.4 and 0.6 m.
279 When h_m was 0.6 m and greater, $WV_{m,2.3}$ was smaller than $WV_{grass,2}$. For $h >$
280 1.75 m, $WV_{m,2.3}$ was, depending on the wind range, between 0.8 and 1.6 m s^{-1}
281 smaller than $WV_{grass,2}$, or about 60 % of the $WV_{grass,2}$ value. Similar results have

282 been previously reported (Dechmi et al., 2004). This percentage depended on
283 the wind direction and range, and decreased when maize defoliated. The
284 differences between $WV_{a,2.3}$ and $WV_{grass,2}$ were less than 0.5 m s^{-1} . For h_a up to
285 0.45 m , $WV_{a,2.3}$ was greater than $WV_{grass,2}$; the opposite was true for h_a greater
286 than 0.45 m . The differences were not statistically significant when $WV_{grass,2}$
287 was less than 3.5 m s^{-1} .

288 The differences in the monitoring level (2 m a.g.l. above the grass, 2.3 m
289 a.g.l. above the maize and alfalfa) introduced noise into the comparison.
290 However, the trend was valid when using the same level for the comparison. On
291 May 31, $WV_{grass,2}$ (4.5 m s^{-1}) almost matched $WV_{a,2}$ (4.4 m s^{-1}) but was less than
292 $WV_{m,2}$ (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
293 s^{-1}) and $WV_{m,2}$ (4.0 m s^{-1}); the same trend was found on October 3 (Figure 3).

294 3.2.1. Comparison of the wind velocity profiles

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

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

304 Eq. 5 led to the overestimation of the wind velocity profile, as illustrated
305 by the comparison between *MWP* and EWP_{crop} (Figure 3). The comparison

306 between EWP_{crop} and EWP_{grass} illustrates that the miscalculation was significant
307 when the wind profile was calculated from WV_{grass} .

308 Table 3 shows that, for maize, h_m above 0.60 m resulted in ME_{WP} equal
309 to 0.3 m s^{-1} or greater (up to 4 m s^{-1} under very windy conditions). When h_m was
310 1.75 m, ME_{WP} resulted 48 % of $WV_{grass,2}$ (coefficient of determination R^2 of 0.92)
311 and $RMSE_{WP}$ was 63 % of $WV_{grass,2}$ (R^2 of 0.95) according to the EWP_{grass}
312 approach. For alfalfa, the ME_{WP} was visibly less than it was for maize (values up
313 to 0.4 m s^{-1}), and the $RMSE_{WP}$ was 8 % of $WV_{grass,2}$ (R^2 of 0.59) according to
314 the EWP_{grass} approach.

315 The results show that the assumption of a logarithmic wind profile under
316 neutral stability conditions departs from reality just above the canopy. Above tall
317 and rough crops like maize, it seems to be inadequate even up to a height of
318 several times the canopy height (Cellier and Brunet, 1992; De Bruin and Moore,
319 1985; Haenel, 1993; Haman and Finnigan, 2007; Finnigan, 2000; Mahrt, 2000;
320 Mihailovic et al., 1999; Poggi et al., 2004; Schaudt, 1998). The velocity profile in
321 the *roughness sub-layer* is inflected (De Bruin and Moore, 1985), and measured
322 values are lesser than predicted (Shaw and Pereira, 1982; Wilson, 1982),
323 because the single-point statistics of turbulence in the *roughness sub-layer*
324 change significantly from those in the *surface layer* (Finnigan, 2000). The errors
325 ensuing from this assumption are not gross as long as the reference wind
326 velocity input in Eq. 5 is measured above the crop. When the latter is not
327 available, approaches such as that applied by Dechmi et al. (2004) to transform
328 WV_{grass} into WV_{crop} will considerably improve the results.

329 These results must be set in context, as they stem from specific
330 surrounding conditions and fetch limitations. Nonetheless, the crop distribution

331 for this experiment was not far from others in many irrigation districts in the Ebro
332 Valley and in other irrigated areas. Valuable results from other experiments
333 were also obtained under fetch limitations (Jacobs and van Boxel, 1988; Kustas
334 et al., 1989; Todd et al., 2000).

335 **3.3. Differences in the solid set sprinkler performance above maize and** 336 **alfalfa**

337 *3.3.1. Effect of the canopy on the sprinkler irrigation performance* 338 *through its influence on the wind velocity*

339 The strong interaction between the *WV* and the uniformity of the sprinkler
340 irrigation system has been extensively reported in the literature (Carrión et al.,
341 2001; Christiansen, 1942; Dechmi et al., 2003; Seginer et al., 1991a, 1991b;
342 Vories et al., 1987). Despite many technical, operational and meteorologic
343 factors affecting sprinkler irrigation (Keller and Bliesner, 1990; Playán et al.,
344 2006; Tarjuelo et al., 1999), linear relationships are commonly established
345 between the *CUC* and the *WV*. As shown in Figures 2 and 3, *h* was included to
346 study the relationship between the *CUC* and the *WV*. Two series were
347 considered for maize: h_m up to 1.20 m (before July 6) and higher (subsequently
348 referred to as tall maize).

349 The *CUC* greatly decreased with the *WV*, down to a threshold under
350 which the *CUC* decreased insignificantly (Figure 4). For alfalfa and maize
351 shorter than 1.20 m, a threshold was found in $WV_{grass,2}$ at about 4 m s^{-1} (the
352 minimum *CUC* was about 75 % for alfalfa and about 65 % for maize). For tall
353 maize, the threshold for $WV_{grass,2}$ was about 5 m s^{-1} , and the minimum *CUC* was
354 50 %. Similar trends have been found previously (Dechmi et al., 2003; Playán et
355 al., 2006; Seginer et al., 1991a; Tarjuelo et al., 1999). Some authors found this

356 relationship to be parabolic (Dechmi et al., 2003; Tarjuelo et al., 1999).
357 However, we decided to fit linear regression models up to the values of WV that
358 were defined as thresholds because this agrees with our understanding of the
359 trend, and it emphasizes the change in the decrease of the CUC with the WV .
360 In addition, this decision avoids leverage effects from the windiest event on
361 August 3; the analysis revealed that the results for this date were not outliers,
362 but a confirmation of the asymptotic trend.

363 Considering that the WV is the main factor decreasing the CUC , because
364 $WV_{m,2.3}$ was less than $WV_{a,2.3}$ (Table 3, Figures 2 and 3), it was expected that
365 the CUC would be greater for tall maize. Nevertheless, the opposite was true.
366 The reason for this outcome is that increases in h caused the drop in the CUC
367 with the WV to be more pronounced. The decrease in the CUC (%) was on the
368 scale of five times the average $WV_{grass,2}$ ($m\ s^{-1}$) for alfalfa but almost double this
369 value for tall maize. Considering $WV_{crop,2.3}$ instead of $WV_{grass,2}$, the differences
370 were greater and the threshold after which the CUC insignificantly decreased
371 was $3\ m\ s^{-1}$ for tall maize.

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

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

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

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

386 3.3.2. *Effect of the canopy on the sprinkler irrigation performance* 387 *through its influence on the water interception plane*

388 Both the WV (Dechmi et al., 2003; Playán et al., 2005; Tarjuelo et al.,
389 2000; Yazar, 1984) and the time of exposure (Burt, 2005; Lorenzini and De
390 Wrachien, 2005) have been shown to increase the $WDEL$. The canopy was
391 shorter for alfalfa than for maize; therefore the time of exposure was greater for
392 alfalfa. In addition, WV_a was greater than WV_m . Therefore, the $WDEL$ was
393 expected to be greater above the alfalfa. However, it was found to be less
394 because of the influence of the water interception plane. The $WDEL$ evaluated
395 at 2.25 m a.g.l was similar above the maize and alfalfa: $WDEL_{m,2.25}$ was 13 %
396 and $WDEL_{a,2.25}$ 12 %, while $WDEL_{a,0.9}$ was 10 % (values were averaged among
397 the ten irrigation events in Table 1).

398 The $WDEL$ comprises evaporation and wind drift losses. For a detailed
399 analysis, results were divided between mild ($WV_{grass,2} < 2.5 \text{ m s}^{-1}$) and windy
400 ($WV_{grass,2} > 2.5 \text{ m s}^{-1}$) conditions (Figure 5). In mild conditions, $WDEL_{m,2.25}$ was
401 9 %, $WDEL_{a,0.9}$ was 7 % and $WDEL_{a,2.25}$ 5 % (the values were significantly
402 different; paired t-test, two tails, $\alpha = 0.05$).

403 In mild conditions, we can assume that evaporation losses predominated
404 over drift losses. Concerning the comparison of the $WDEL$ at two different levels

405 above the alfalfa, $WDEL_{a,0.9}$ was greater than $WDEL_{a,2.25}$ because the time of
406 exposure was greater at 0.9 m. Because $WDEL_{m,2.25}$ was greater than
407 $WDEL_{a,2.25}$ despite the supposedly equal time of exposure, we inferred that the
408 heat transfer was greater above the maize. This explanation will also explain
409 why $WDEL_{m,2.25}$ was greater than $WDEL_{a,0.9}$. This explanation should be
410 confirmed because heat transfer was not evaluated in this experiment.

411 In windy conditions ($WV_{grass} > 2.5 \text{ m s}^{-1}$), the values of $WDEL$ greatly
412 increased and were notably greater at 2.25 m, irrespective of the crop irrigated:
413 $WDEL_{m,2.25}$, $WDEL_{a,0.9}$ and $WDEL_{a,2.25}$ were, respectively, 22, 17 and 28 %
414 (Figure 5). On the assumption that drift losses predominated over evaporation
415 in windy conditions, $WDEL_{a,2.25}$ exceeded $WDEL_{m,2.25}$ because WV_a exceeded
416 WV_m . However, the finding that $WDEL_{a,2.25}$ exceeded $WDEL_{a,0.9}$ contradicted
417 this explanation. The explanation we provide is that in windy conditions, the
418 errors in the estimation of $WDEL$ increase with the elevation of the
419 pluviometers. $WDEL_{2.25}$ was overestimated, as we subsequently explain.

420 When the drops are wind-drifted, their trajectories tend to be horizontal
421 with the major wind component. Because of the small difference between the
422 height of the nozzles (2.3 m a.g.l.) and the top of the pluviometers being located
423 at 2.25 m a.g.l., some drops might have flown directly below the opening of the
424 pluviometers. However, those drops might have entered the pluviometers
425 located at 0.9 m a.g.l. above the alfalfa canopy. This phenomenon would have
426 particularly affected the smallest drops and the secondary nozzle (for which the
427 insertion angle with the vertical is lower than for the main nozzle). It must also
428 be considered that the WV increases with the elevation. In addition, a geometric
429 issue has been found to be related. The plane containing the openings of the

430 pluviometers is horizontal and parallel to the surface. When the drops'
431 trajectories are vertical, the effective orifice section approaches its maximum. In
432 contrast, the effective orifice section decreases when the trajectory of the drops
433 departs from vertical, as when they are wind-drifted. Both assumptions explain
434 why, under windy conditions, $ID_{Ca,2.25}$ was lower than $ID_{Ca,0.9}$ (Table 1), and why
435 the $WDEL_{2.25}$ was overestimated with respect to the $WDEL_{0.9}$. Further research
436 is needed to confirm these explanations.

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

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

455 $CUC_{m,2.25}$ was 77 %, $CUC_{a,0.9}$ 87 % and $CUC_{a,2.25}$ 78 % (values averaged
456 among the ten irrigation events on Table 1).

457 Figure 6 complements Figure 4 by including the influence of the water
458 interception plane. The water collecting level has been found to be a major
459 factor explaining the differences in the CUC between maize and alfalfa. Given
460 the close relationship between the CUC and the WV , it was surprising that
461 $CUC_{2.25}$ was nearly equal between maize and alfalfa (Figure 6a and Figure 6c)
462 despite the difference between $WV_{m,2.3}$ and $WV_{a,2.3}$ (Figure 6b).

463 The differences between WV_a and WV_m at the level of the nozzles did not
464 satisfactorily explain the differences in the CUC between maize and alfalfa. In
465 contrast, the relationship between the CUC and the WV mainly depended on
466 the values of the WV above the plane of the nozzles, where the differences
467 between WV_a and WV_m diminished (Figure 3). For the events from August 24 to
468 October 10 (Table 1), the average difference between WV_a and WV_m decreased
469 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.

470 The maps in Figure 7 show the experimental area (Figure 1 of the
471 companion paper). The selected dates are representative of mild conditions
472 (September 19 and October 10) and windy conditions (August 24 and August
473 30) (Table 1). The ID_C decreased from the sprinklers toward the center. The
474 least irrigated areas were displaced according to the wind direction because the
475 wind drift. The irrigation uniformity decreased with the WV . The uniformity
476 decreased when the water collecting level increased. The distribution pattern of
477 $ID_{C,2.25}$ was similar above maize and alfalfa. The differences between WV_a and
478 WV_m might have caused the slight differences between the patterns of $ID_{Ca,2.25}$

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

481 **3.4. Prediction of the uniformity of the sprinkler irrigation above** 482 **different crops in windy conditions**

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

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

$$489 \quad CUC = 107.4 - 8.2927 WV_{grass,2} - 5.9314 h \quad (R^2 = 0.91) \quad (12)$$

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

$$491 \quad CUC = 98.6 - 7.8801 WV_{grass,2} \quad (R^2 = 0.79) \quad (13)$$

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

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

498 **4. Conclusions**

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

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

509 The horizontal wind velocity (WV) decreases the CUC and increases the
510 $WDEL$. The WV greatly decreases in proximity to the canopy. Consequently, at
511 the level of the nozzles, the WV was noticeably smaller above the maize than
512 above the alfalfa. However, the difference in the WV between the crops at the
513 nozzle level was not significant on the CUC of the ID_C because it was mainly
514 influenced by the WV above the nozzles, levels for which the WV was similar
515 above both crops. The assumption of the logarithmic wind profile under neutral
516 conditions, as considered in several sprinkler irrigation models to calculate the
517 vertical variation of the WV , overestimates the wind profile above the canopies.

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

523 The influence of h on $WDEL$ varies between mild and windy conditions.
524 In mild conditions, for which evaporation predominates over drift losses, lower
525 values of h imply greater time of exposure of the drops and increases in $WDEL$.
526 As a consequence, $WDEL$ was greater above the alfalfa canopy than above
527 maize. On the contrary, in windy conditions, $WDEL$ above the maize canopy
528 resulted greater than above alfalfa, despite the time of exposure was greater for

529 the latter. The results suggest that the ID_C was underestimated, thus the $WDEL$
530 was overestimated, when the distance between the nozzles and the
531 pluviometers is small as for maize. The underestimation increases under windy
532 conditions as a consequence of the wind drift which provokes that the trajectory
533 of the drops tends to be horizontal.

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

537 **Acknowledgements**

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

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676 **Nomenclature.**

677	τ	= <i>Shear stress</i>
678	ρ	= <i>Air density</i>
679	A	= <i>Area of the nozzles orifices (mm^2)</i>
680	<i>a.g.l.</i>	= <i>Above the ground level</i>
681	C_D	= <i>Discharge coefficient</i>
682	CUC	= <i>Christiansen's Uniformity Coefficient (%)</i>
683	$CUC_{a,z}$	= <i>CUC above alfalfa evaluated at the height z (%)</i>
684	$CUC_{m,z}$	= <i>CUC above maize evaluated at the height z (%)</i>
685	CUC_z	= <i>CUC evaluated at the height z (%)</i>
686	d	= <i>Displacement height (cm)</i>
687	EWP	= <i>Estimated wind velocity profile</i>
688	EWP_{crop}	= <i>Wind velocity profile estimated from $WV_{crop,2,3}$</i>
689	EWP_{grass}	= <i>Wind velocity profile estimated from $WV_{grass,2}$</i>
690	g	= <i>Gravity acceleration ($m\ s^{-2}$)</i>
691	h	= <i>Crop height (m)</i>
692	h_a	= <i>Height of the alfalfa crop (m)</i>
693	h_m	= <i>Height of the maize crop (m)</i>
694	ID_C	= <i>Irrigation depth averaged for the experimental area (mm)</i>
695	$ID_{Ca,z}$	= <i>ID_C collected above alfalfa at the height z (mm)</i>
696	$ID_{Cm,z}$	= <i>ID_C collected above maize at the height z (mm)</i>
697	$ID_{C,z}$	= <i>ID_C collected at the height z (mm)</i>
698	ID_D	= <i>Irrigation depth emitted by the sprinklers (mm)</i>
699	k	= <i>von Karman's constant (0.41)</i>
700	l	= <i>Spacing among laterals (m)</i>

701	MAE_{Com}	= Mean Absolute Error for the anemometers comparison ($m s^{-1}$)
702	ME_{WP}	= Mean Error for the estimation of the wind profile ($m s^{-1}$)
703	MWP	= Measured wind velocity profile
704	p	= Pressure in nozzle (kPa)
705	Q	= Sprinkler flow rate ($l s^{-1}$)
706	r	= Sample linear correlation coefficient
707	R^2	= Coefficient of determination
708	RH	= Air relative humidity (%)
709	$RMSE_{Com}$	= Root mean square error for the anemometers comparison ($m s^{-1}$)
710	$RMSE_{WP}$	= Root Mean Square Error for the estimation of the wind profile ($m s^{-1}$)
711	s	= Spacing among sprinklers along the lateral (m)
712	SD	= Standard deviation
713	T	= Air temperature ($^{\circ}C$)
714	t	= Operating time of the irrigation event (s)
715	$WDEL$	= Wind drift and evaporation losses (%)
716	$WDEL_{a,z}$	= WDEL above alfalfa estimated at the height z (%)
717	$WDEL_{m,z}$	= WDEL above maize estimated at the height z . (%)
718	$WDEL_z$	= WDEL estimated at the height z (%)
719	WV	= Wind velocity ($m s^{-1}$)
720	WV_a	= WV above alfalfa ($m s^{-1}$)
721	$WV_{crop,z}$	= WV_z above the crops at the height z ($m s^{-1}$)
722	WV_{grass}	= WV above grass ($m s^{-1}$)
723	WV_m	= WV above maize ($m s^{-1}$)
724	WV_z	= WV at the height z ($m s^{-1}$)
725	WV^*	= Friction velocity over a vegetated surface

- 726 WV_g^* = *Friction velocity for a bare soil*
- 727 z = *Height above the ground level (m)*
- 728 z_0 = *Roughness length of a vegetated surface (cm)*
- 729 z_{0g} = *Roughness length of a bare soil (cm)*

730 **List of Tables**

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

Date	T (°)	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

735 Table 2: Mean Absolute Error (MAE_{Com}) for each anemometer and maximum value of
 736 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

737 ^a Values calculated according to the equations 6 and 7, respectively.

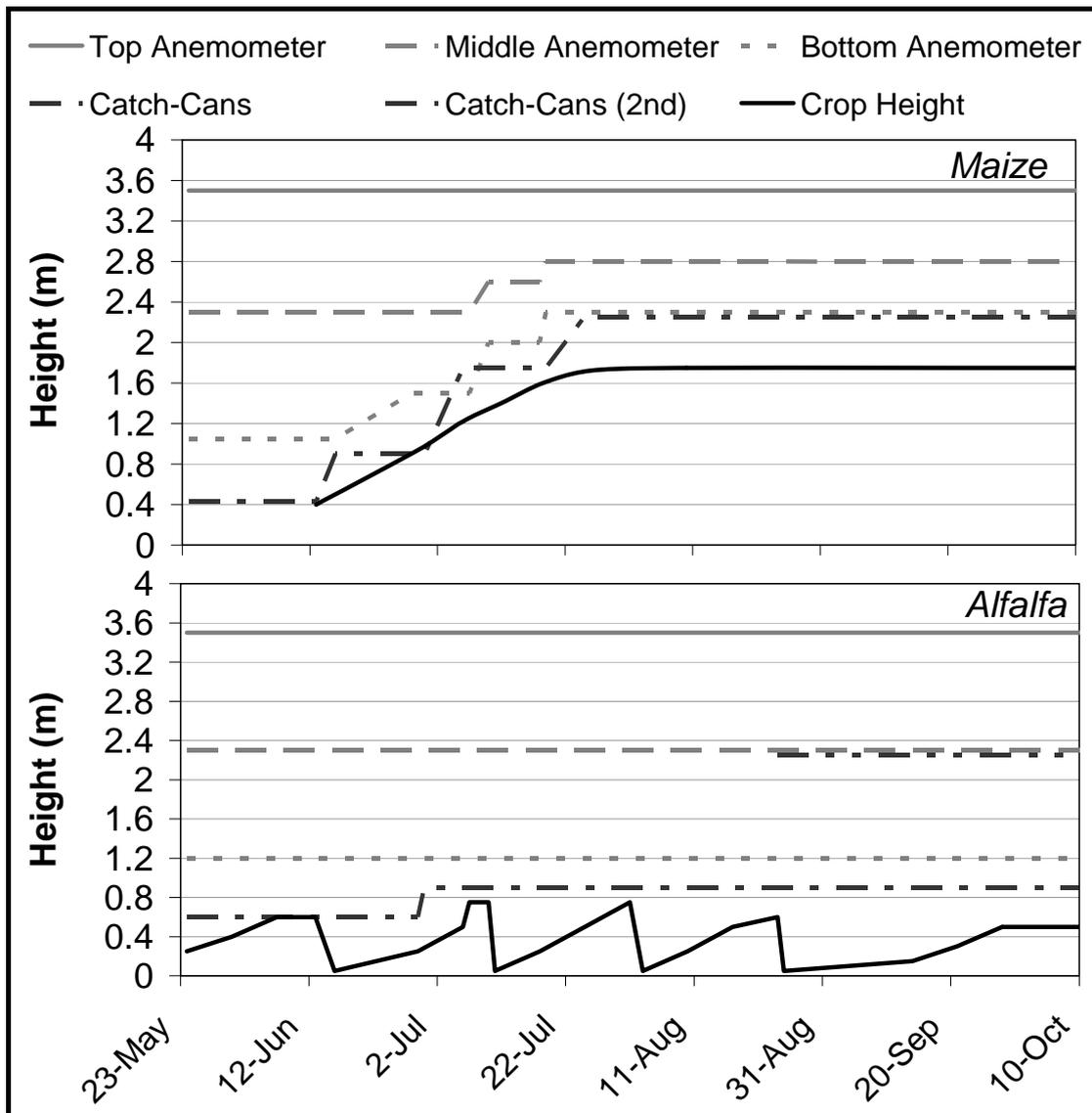
738 Table 3: Irrigation date, wind velocity averaged during the irrigation event at 2 m above
739 grass ($WV_{grass,2}$); height of the crop (h); mean error (ME_{WP}) and root mean square error
740 ($RMSE_{WP}$) in the estimation of the wind velocity profile according to the logarithmic
741 profile using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

Date	$WV_{grass,2}$ ($m s^{-1}$)	h (m)		ME_{WP} ($m s^{-1}$)		$RMSE_{WP}$ ($m s^{-1}$)			
		A	M	A	M	EWP_{crop}		EWP_{grass}	
						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

743 ^a Above maize, the WV was monitored at 2.0 m instead of at 2.3 m.

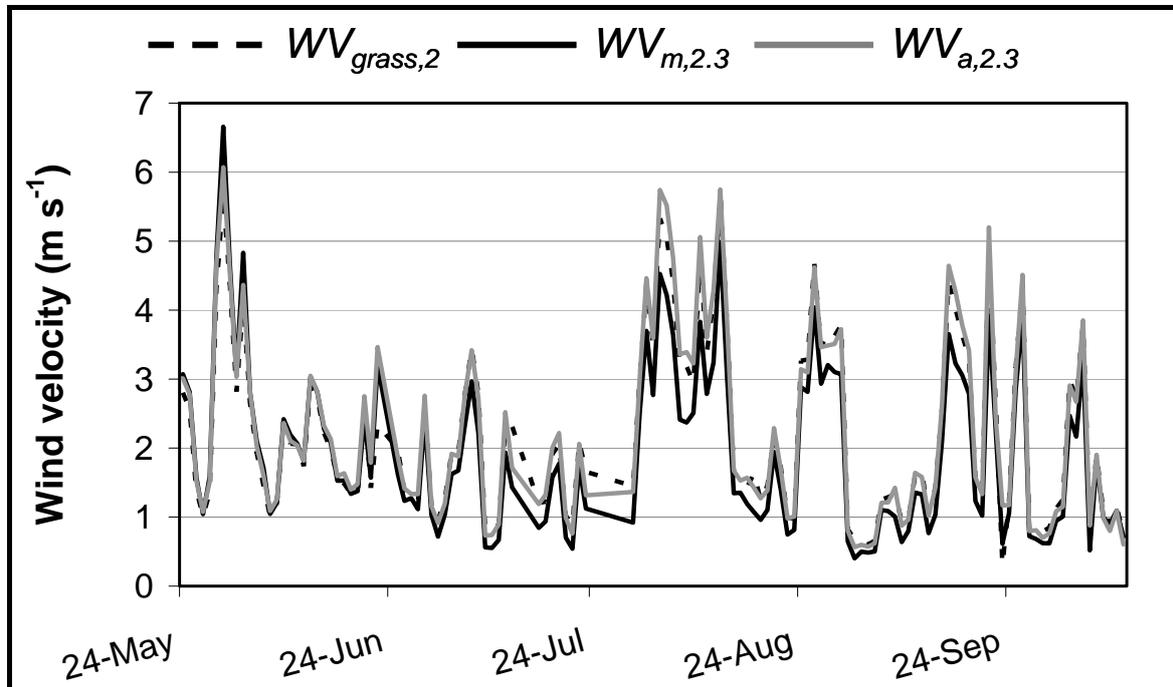
744 **List of Figures**

745 *Figure 1. Crop height and elevation of the anemometers and pluviometers during the*
 746 *2006 irrigation season for maize and alfalfa. Above alfalfa, two collections of*
 747 *pluviometers were used: one above the canopy and the other at the same elevation*
 748 *than those above the maize canopy after August 23.*



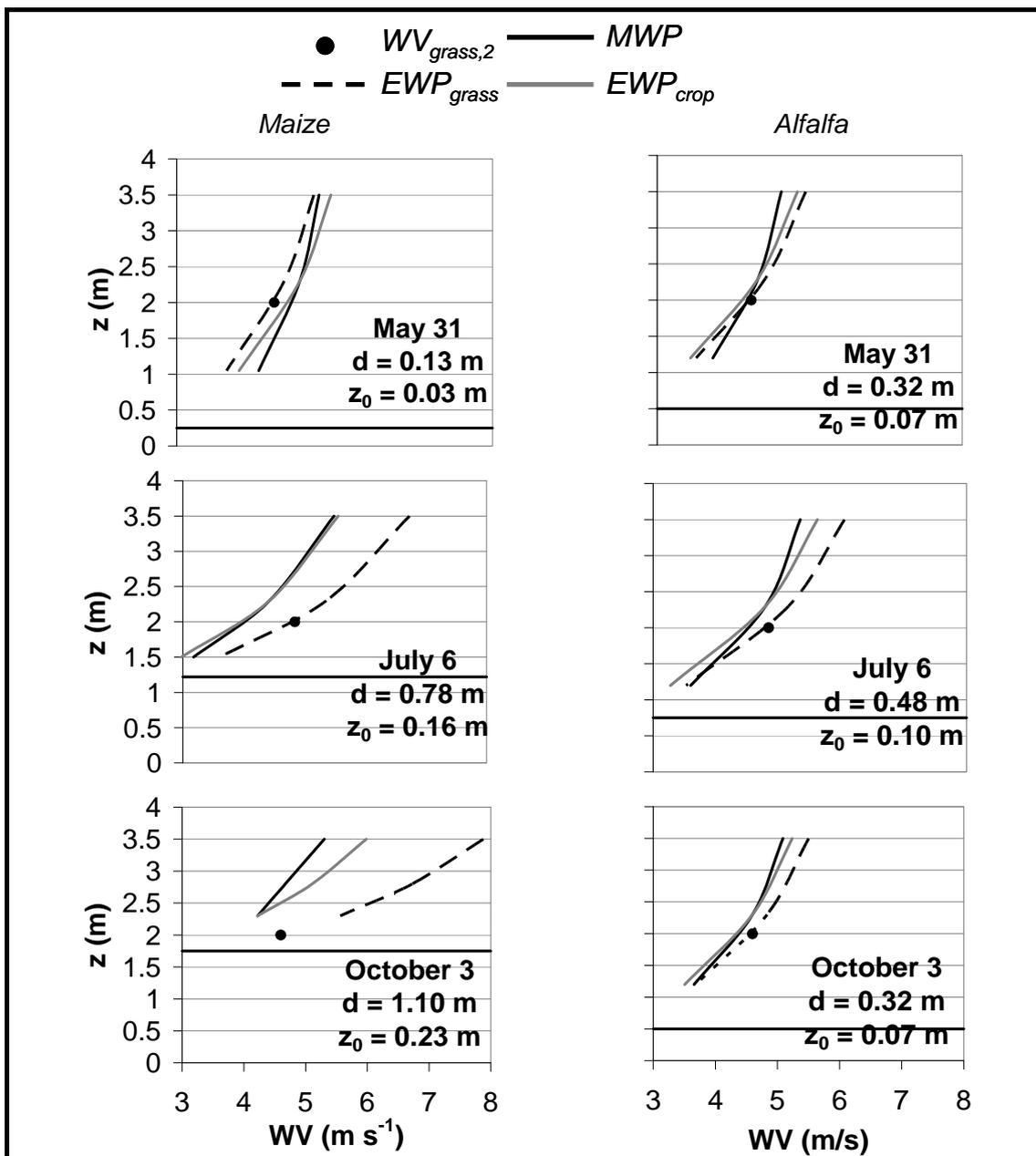
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750 Figure 2. Evolution of the daily average wind velocity measured at 2 m above the
751 ground level (a.g.l.) above grass ($WV_{grass,2}$) and at 2.3 m a.g.l. above maize (WV_m) and
752 alfalfa (WV_a).

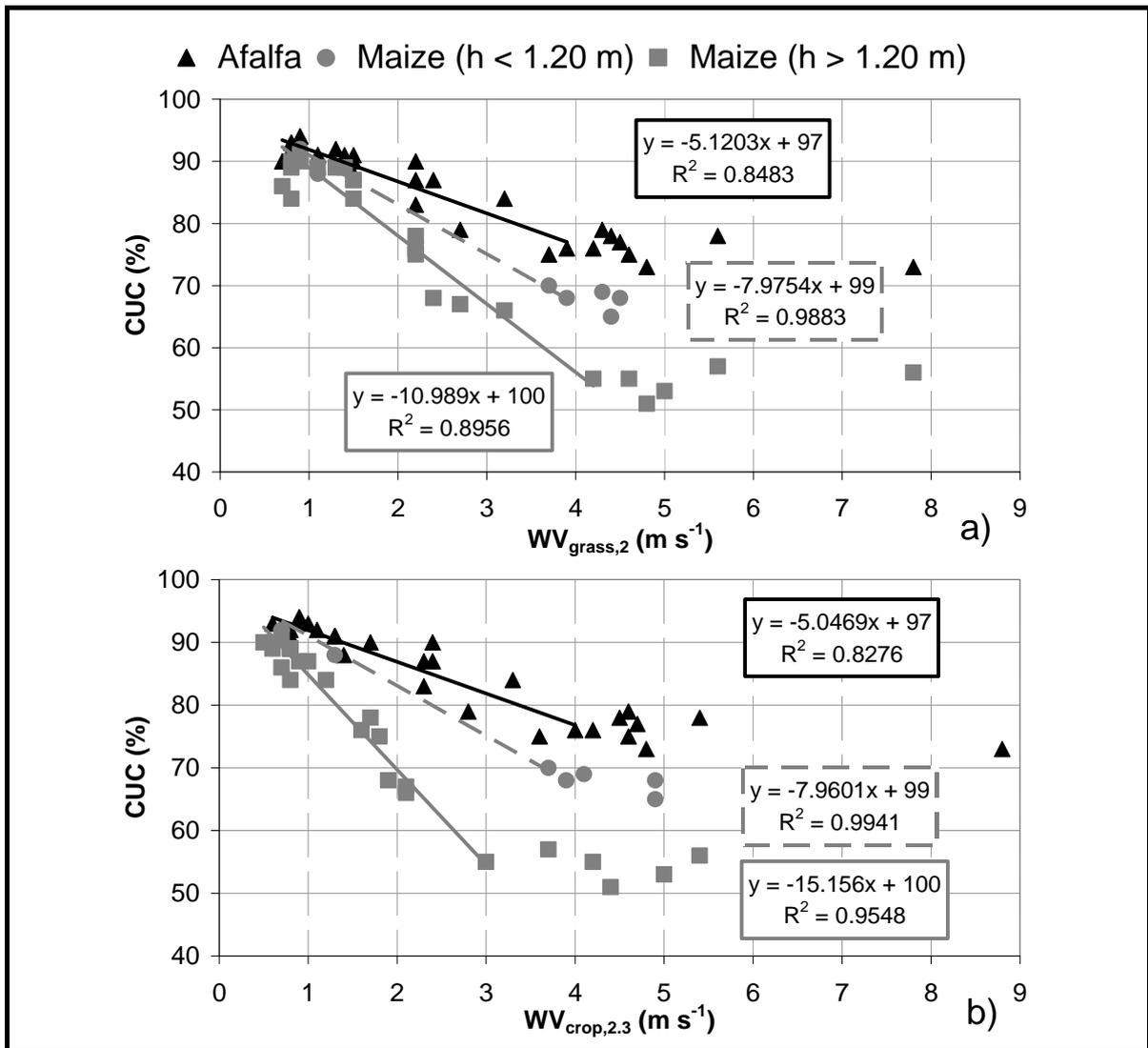


753

754 Figure 3. Measured wind velocity profiles (MWP) from the recordings at three levels
 755 above the canopy for three irrigation events. Wind profiles estimated according to the
 756 logarithmic profile under neutral stability conditions from the wind velocity monitored at
 757 2.3 m a.g.l. above the crop (EWP_{crop}). The same estimated from the wind velocity
 758 monitored simultaneously at 2 m a.g.l. above grass ($WV_{grass,2}$) (EWP_{grass}). The
 759 horizontal black line represents the height of the crop. The plane of displacement (d)
 760 and the roughness length (z_0) are calculated from h via the Eqs. 3 and 4.

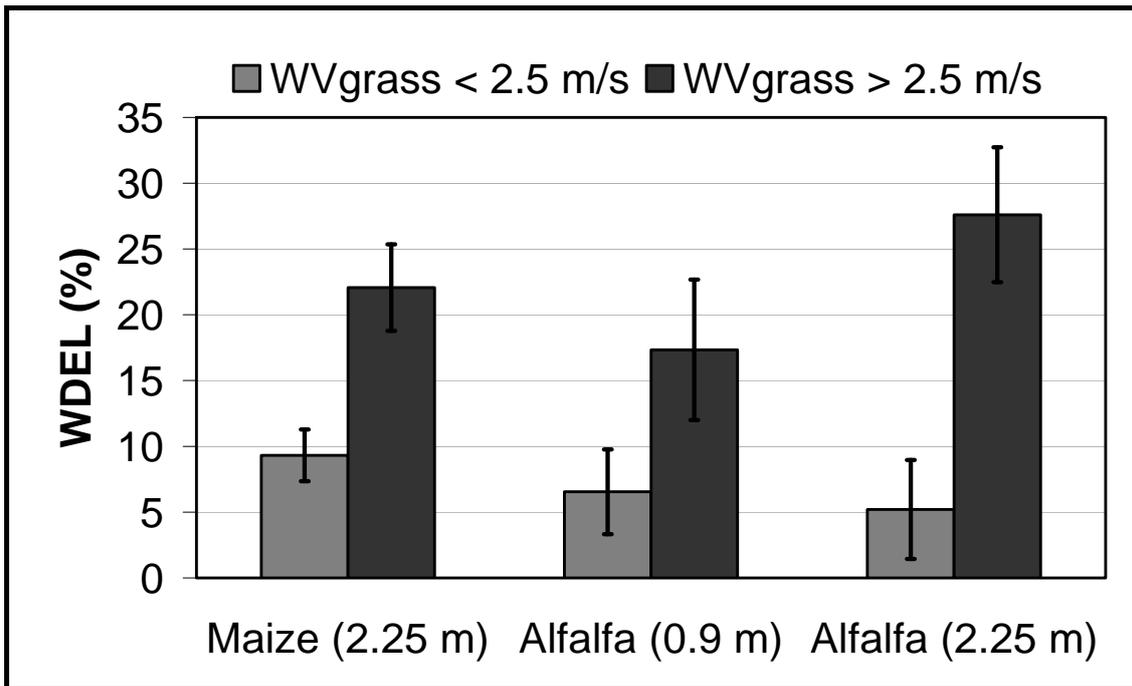


761 Figure 4. Influence of the crop height (h) on the relationship between the Christiansen's
 762 Uniformity Coefficient (CUC) of the irrigation depth collected above the canopy and the
 763 wind velocity measured above grass at 2 m ($WV_{grass,2}$) (a); the same for the wind
 764 velocity measured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



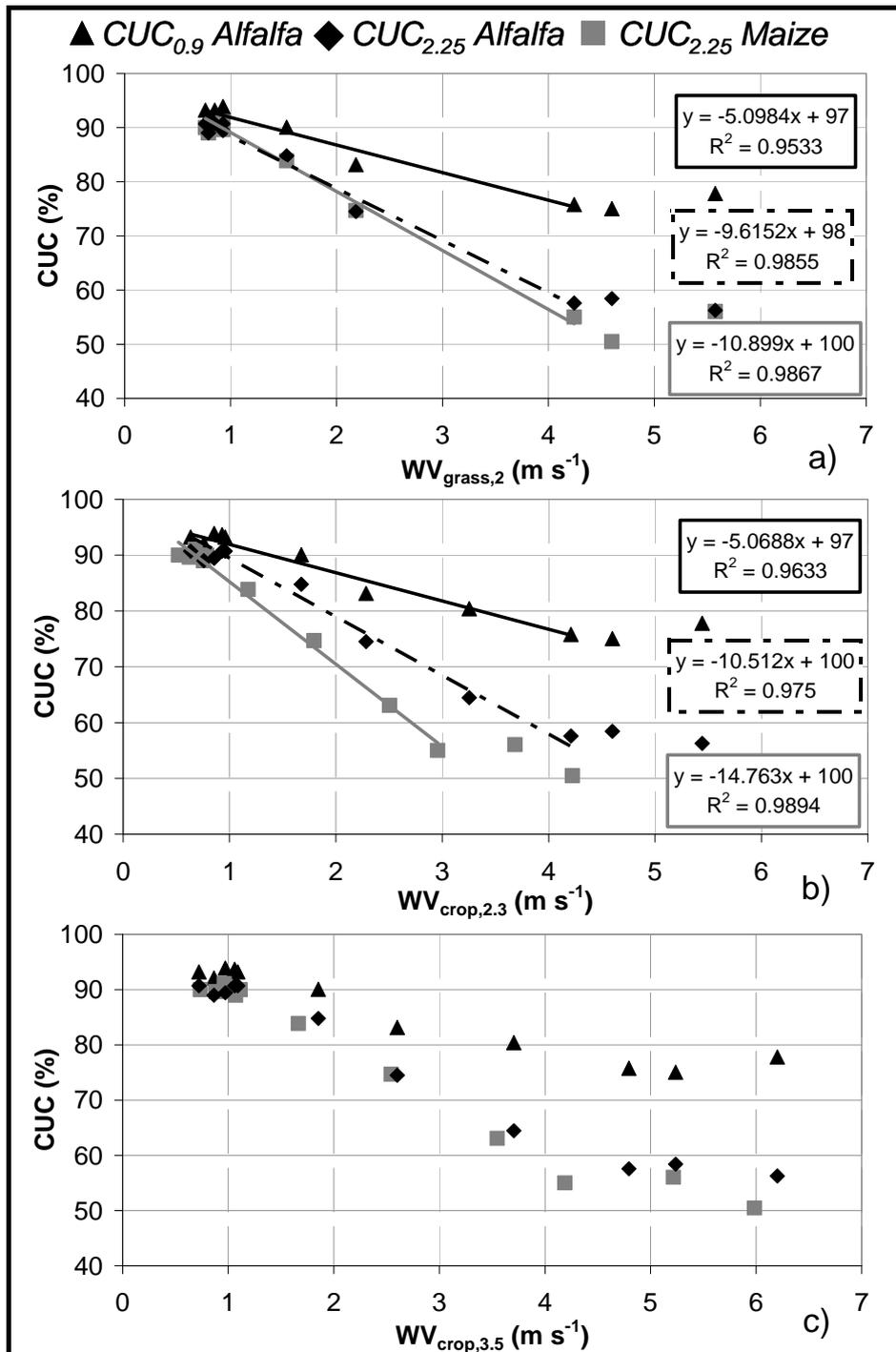
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767 Figure 5. Influence of the water interception plane and of the wind velocity (measured
768 above grass at 2 m, $WV_{grass,2}$) on the wind drift and evaporation losses (WDEL). The
769 water interception plane was 2.25 and 0.9 m a.g.l. above the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



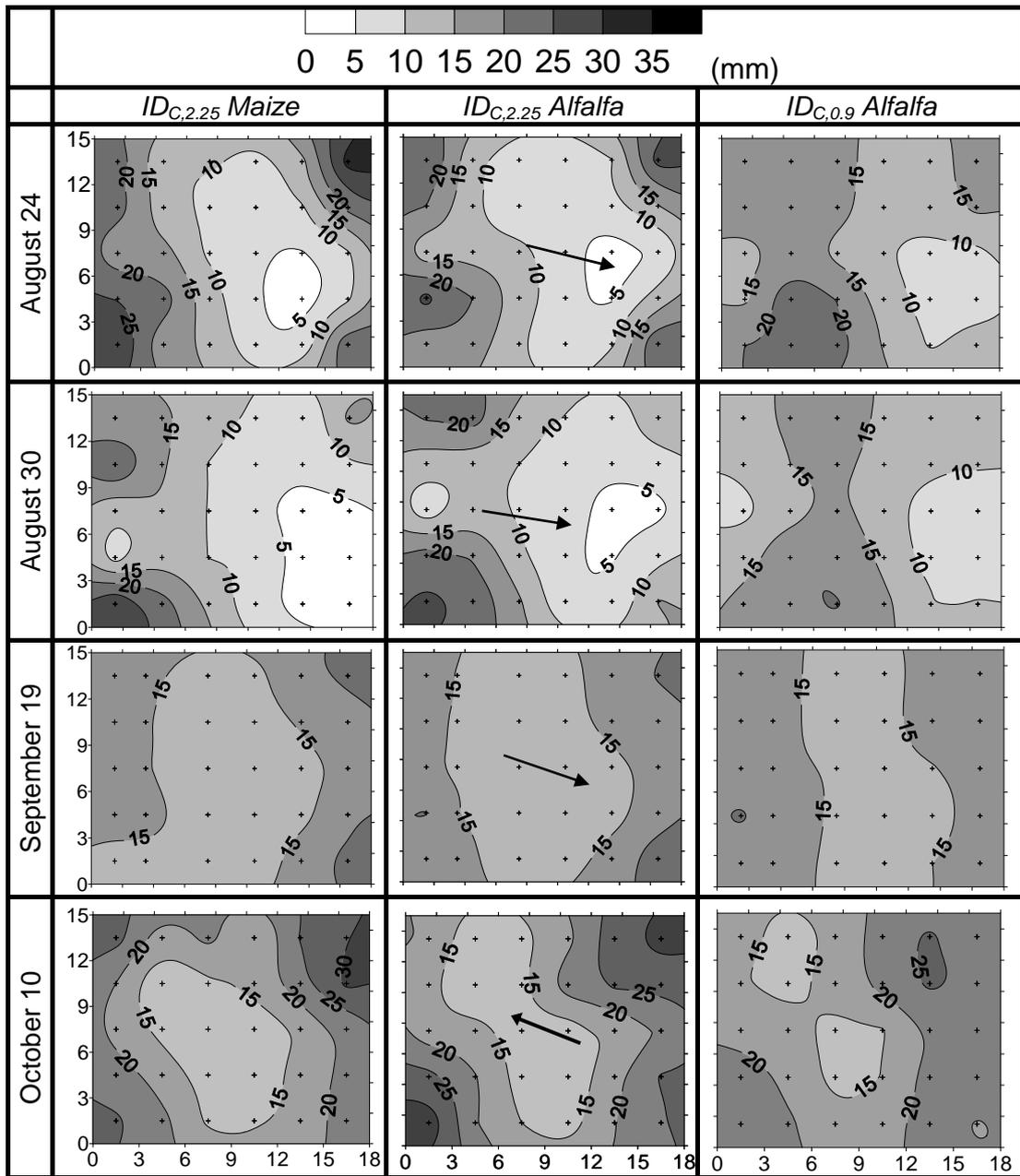
773

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



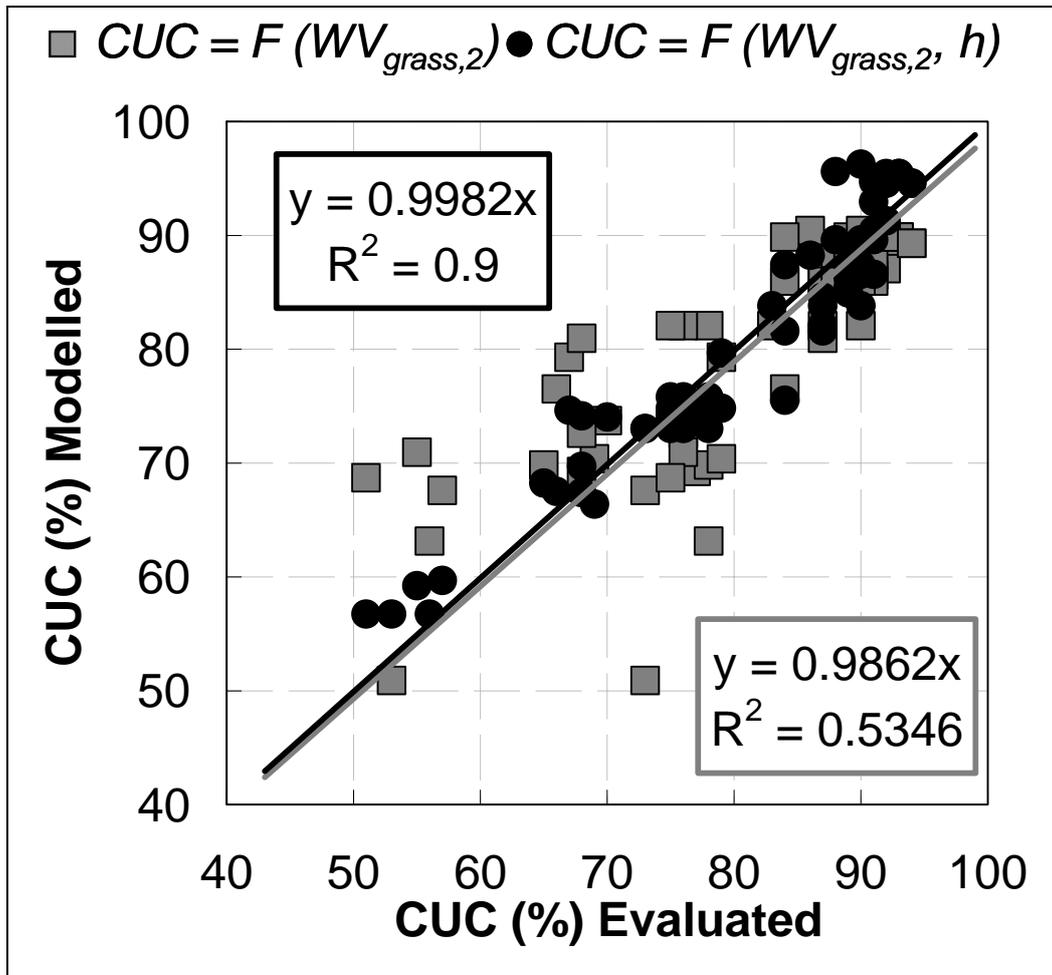
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780 Figure 7. Contour lines maps within the experimental plot between four sprinklers (in
 781 the corners) estimated from the irrigation depth (ID_C) collected into pluviometers
 782 (crosses) located at 2.25 m ($ID_{C,2.25}$) above maize and alfalfa,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



785

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



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