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[Bassimba, D.D.M., Intrigliolo, D. S., Dalla Marta, A., Orlandini, S., Vicent, A. (2017). Leaf wetness duration in irrigated citrus orchards in the mediterranean climate conditions. Agricultural and Forest Meteorology, 234, 182-195.]

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The final publication is available at

[\[http://dx.doi.org/10.1016/j.agrformet.2016.12.025\]](http://dx.doi.org/10.1016/j.agrformet.2016.12.025)

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Equation Chapter 1 Section 1
Leaf wetness duration in irrigated citrus orchards in
the Mediterranean climate conditions

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19

Abstract

21

²²Leaf wetness (LW) is a key environmental variable for the development of foliar fungal
²³diseases of citrus. However, no information of LW duration (LWD) in Mediterranean citrus-
²⁴growing areas is available. LWD in six canopy positions and two leaf sides was studied with
²⁵visual observations and Spectrum LW sensors in a citrus orchard in Spain. The performance

26of Spectrum and Hobo LW sensors, and CART/SLD and RH LW models was assessed by
27receiver operating characteristic (ROC) curve analysis. The dynamics of LWD in three citrus
28orchards with flood irrigation and three with drip irrigation were evaluated using time-series
29models. LWD data from all experiments and recordings in 14 commercial citrus orchards
30illustrated the high frequency of LW periods, particularly those associated with dew. No
31substantial differences in LWD were detected among citrus canopy positions and leaf sides.
32An optimal dry/wet threshold of 2.85 for the Spectrum LW sensor, 75.88 for the Hobo LW
33sensor, 15.99 for the CART/SLD model, and 87.45% for the RH model was selected by
34ROC analysis. All the sensors and models evaluated showed a substantial strength of
35agreement with visual observations of LW, with area under the ROC curve of 0.89-0.93 and
36Cohen's Kappa index of 0.61-0.77. The RH model was recommended because of easier
37implementation in citrus orchards in Spain. Time-series models did not detect any significant
38increase in LWD associated with flood irrigation, but only after some rain events. High
39mesoclimatic relative humidity in the study area outweighed possible microclimatic changes
40induced by flood irrigation. Thus, negligible effects of flood irrigation in the infection of
41foliar fungal pathogens would be expected, but longer LWD in the lower canopy as well as
42potential effects on inoculum dynamics in the leaf litter cannot be excluded.

43

44**Keywords** flood, , sensors, models, relative humidity, ROC, ARIMA

45

461. Introduction

47

48As in many other crops, in citrus trees leaf wetness (LW) is a critical environmental factor
49for the epidemic development of foliar fungal diseases causing serious yield and quality
50losses. The incidence of melanose, caused by *Diaporthe citri* (H.S. Fawc.) F.A. Wolf., citrus

51scab, caused by *Elsinoë fawcettii* Bitanc. & Jenkins, and postbloom fruit drop, caused by
52*Colletotrichum acutatum* J.H. Simmonds, increases with longer LW duration (LWD). The
53epiphytic growth and infection of citrus leaves by *Zasmidium citri-griseum* (F.E. Fisher) U.
54Braun & Crous causing greasy spot disease was also enhanced by LW. Likewise, the
55presence of LW influenced the production, release and infection of ascospores of
56*Phyllosticta citricarpa* (McAlpine) van der Aa, the causal agent of citrus black spot
57(Timmer, 1999). *Alternaria* brown spot, caused by ACT-toxin-producing strains of
58*Alternaria alternata* (Fr.) Keissl., is the main fungal disease of mandarin in the
59Mediterranean Basin. Studies conducted in Spain found a positive relationship of LWD with
60the incidence of this disease (Bassimba et al., 2014).

61 Surface wetness was defined by Magarey et al. (2005) as the visible presence of
62water on a plant surface, such as leaves, stems, flowers or fruit which is driven by rain, dew,
63overhead irrigation and guttation. Dew can occur when water condensates from the air
64(dewfall) or evaporates from the soil (dewrise or distillation) and then is intercepted by the
65canopy (Garratt and Segal, 1988). LWD is a key component of disease prediction models
66and for decision support systems used for foliar fungal plant pathogens (De Wolf and Isard,
672007). However, despite its importance in plant disease epidemiology and the number of
68studies conducted elsewhere, LW is still considered a non-standard micro-meteorological
69variable and a standard system for its measurement is not available (Magarey et al., 2005).

70 The distribution and the duration of LW in citrus canopy was studied under the
71humid subtropical conditions of Florida, USA, by Santillan et al. (2010), who found
72heterogeneity among sensor heights and horizontal positions. Visual observations of LW in
73plants are usually carried out during the night and are labour consuming and can be affected
74by human error, so they are not routinely conducted. There are different types of sensors
75available for LW monitoring, including static, mechanical or electronic systems, but their

76accuracy is variable and frequent calibrations are usually needed (Rowlandson et al., 2015).
77Moreover, their operational capacity can be greatly reduced by some chemicals applied in
78the field such as copper (Magarey et al., 2005). Although widely used in research studies,
79LW sensors are rarely employed by growers.

80 Physical and empirical models have been used as an alternative to visual LW
81observations and sensoring (Magarey et al., 2005). Physical models, mostly based on energy
82balance equations, have good accuracy and are more suited for extrapolation. However,
83these process-based models need some specific data inputs, such as net radiation, which are
84not usually available in agro-meteorological stations. On the other hand, empirical models
85estimate LW building on statistical relationships with meteorological variables, like relative
86humidity (RH) or its variation in time, which are readily available under commercial field
87conditions (Sentelhas et al., 2008). In general, empirical LW models are relatively easy to
88handle, but their accuracy strongly depends on proper local calibration and evaluation. Both
89types of models, process-based and empirical, should consider specific plant architecture
90traits and thermal properties of the targeted plant and organ (Magarey et al., 2005). The
91evaluation of LW models for citrus under Mediterranean conditions would help to
92implement decision support systems, leading to a more efficient management of foliar fungal
93diseases, such as *Alternaria* brown spot of mandarins (Bassimba et al., 2014).

94 Several studies highlighted the critical role of dew and irrigation in the epidemic
95development of foliar fungal diseases in semi-arid environments, where rains are scarce most
96of the year (Agam and Berliner, 2006; Palti, 1981). Overhead irrigation is known to enhance
97the production, release and spread of fungal spores from infectious plant tissues. Longer
98LWD and higher infection efficiency have been also associated with this type of irrigation
99system (Palti, 1981). In fact, it was specifically recommended avoiding overhead irrigation
100for the management of foliar fungal diseases of citrus (Timmer, 1999). Nevertheless,

101overhead irrigation is seldom used in citrus-growing areas in the Mediterranean Basin and
102citrus orchards are typically flood- or drip-irrigated (Carr, 2012), with micro-irrigation with
103sprinklers placed at around 50 cm above soil surface being used in some specific locations
104(Alba et al., 2003).

105 In contrast to overhead sprinkle irrigation, surface irrigation systems seldom wet the
106canopy, but may influence orchard microclimate by increasing RH and LWD. Greater
107amounts of water are applied with flood irrigation, wetting almost all the soil surface
108whereas only a small proportion is wet by drip. Higher RH, longer LWD, and greater
109severity of foliar fungal diseases were reported with flood irrigation compared with drip
110irrigation in row crops and orchards (Goldhamer et al., 2002; Kamel et al., 2008; Palti, 1981;
111Scherer and Vanbruggen, 1995). Information about the dynamics of LWD in irrigated citrus
112orchards would help to select the most appropriate irrigation system for the integrated
113management of foliar fungal diseases.

114 Therefore, the objectives of this study were: (i) to describe the spatial distribution of
115LWD in the citrus canopy under Mediterranean conditions in Spain; (ii) to compare the
116performance of two sensors and two empirical LW models for estimating LWD; (iii) to
117estimate and describe LWD in commercial citrus orchards in different provinces of Spain,
118and (iv) to evaluate the influence of irrigation system on the dynamics of LWD in citrus
119orchards.

120

1212. Materials and methods

122

1232.1. *LWD observations and sensors*

124

125The trial was conducted at a site in Moncada, Spain at the Instituto Valenciano de
126Investigaciones Agrarias (IVIA) research station (39°N elevation 69 m). The experimental
127plot of mature bearing trees of tangor ‘Ortanique’ (*Citrus reticulata* Blanco x *C. sinensis*
128Osbeck) grafted on Carrizo citrange (*Poncirus trifoliata* (L.) Raf. x *C. sinensis*) was planted
129in 2005 on a 5 x 3 m spacing with a canopy diameter of about 3 m without intra-row free
130spaces between trees. Bottom and top canopy heights were about 0.5 and 2.5 m from the soil
131surface, respectively. The orchard was drip irrigated with four emitters per tree of 1 L h⁻¹
132each and rows were oriented north-south. The soil area wetted by emitters in the orchard was
133photographed at 300 ppi by a digital camera (Coolpix 4500, Nikon Corporation, JP)
134including a rule for scaled dimensioning. The soil area wetted, quantified by using Assess
135software (APS, USA), was of 11% of the soil surface per tree.

136 Visual observations of LW were carried out during nine nights (24, 25 January, 14
137April, 3 October, 12 December 2012, 17, 18, 22 April, and 27 May 2013) without rain and in
138calm wind conditions. The percentage of leaf area wet was assessed by a trained observer on
139both, leaf upperside and underside. At the beginning of the study, visual observations were
140confirmed by placing a water-sensitive paper (Syngenta AG, CH) on the leaf surface, which
141changed from yellow to blue in the presence of free water. Observations were made in six
142canopy positions: two sides of the tree (east and west) and three heights (1, 1.5 and 2 m) in
143each side.

144 In each canopy position, 10 leaves were randomly chosen every 15 min starting from
14517:00 pm until complete LW deposition during the night, and from sunrise to complete LW
146depletion in the morning. The average percentage of leaf surface covered with LW in each
14715-min period was calculated individually for each canopy position and both leaf sides.
148Percentage values were converted to binary values: 1 = wet leaf when $\geq 10\%$ of leaf surface
149wet and 0 = dry leaf when $< 10\%$ of leaf surface wet (Dalla Marta and Orlandini, 2010).

150Daily LWD from noon to noon were analysed descriptively. The Student's t-test was used to
151detect statistical differences among canopy positions and between leaf sides. Normality,
152homoscedasticity and independence were confirmed prior to analysis. The R software v.3.0.2
153(R-Core-Team, 2013) was used in all analyses.

154 Flat plate LW sensors were fixed at a 30-degree angle from the horizontal in the same
155canopy positions indicated above. Spectrum LW sensors (3666, Spectrum Technologies Inc.,
156USA, range 0-15) were placed in all six canopy positions. Hobo LW sensors (Hobo S-LWA,
157Onset Computer Corp., USA, range 0-100, resolution 0.59%) were placed only at 1.5 m in
158both sides of the tree. LW sensors were previously tested under field conditions resulting in
159a average coefficient of variation of 10.62% for Spectrum LW sensors and 11.18% for Hobo
160LW sensors (Sentelhas et al., 2004). As indicated by the manufacturers, LW sensors were
161not painted. Temperature and RH (WatchDog 450, accuracies $\pm 0.7^{\circ}\text{C}$ and $\pm 3\%$) were
162measured in both sides of the tree at 1.5 m. A rain gauge (7852, Davis Instruments Corp.,
163USA, accuracy $\pm 4\%$, resolution 0.2 mm) was deployed in the west side at 1.5 m. All
164environmental data were monitored at 15-min time intervals from 25 August 2011 to 29 May
1652013 covering the nine nights of visual observations of LW indicated above.

166 Daily LWD from noon to noon recorded by Spectrum LW sensors in each canopy
167position were analysed descriptively, excluding the days without LW. The optimal cut-off
168threshold (i.e. dry/wet) for the Spectrum LW sensor was set based on the performance
169assessment described below. Rainy (≥ 0.2 mm) and rainless (< 0.2 mm) days were analysed
170separately. The Student's t-test was used to detect statistical differences among canopy
171positions and between rainy and rainless days. Normality, homoscedasticity and
172independence were confirmed prior to analysis.

173

1742.2. *Evaluation of LW sensors and models by ROC analysis*

175

176Spectrum and Hobo LW sensors, and CART/SLD and RH models were evaluated as
177estimators of LWD in citrus leaves in the same orchard described above. The RH model
178considers presence of LW when RH is greater than or equal to a cut-off threshold (Sentelhas
179et al., 2008). The CART/SLD model utilizes air temperature (T), dew point depression (air
180temperature – dew point temperature) (DPD), wind speed (W), and RH as inputs (Kim et al.,
1812002). The model considers four different categories according to threshold values of 3.7°C
182for DPD, 2.5 m s⁻¹ for W, and 87.8% for RH. Time units are classified as dry if either DPD ≥
1833.7°C (category 1) or W ≥ 2.5 m s⁻¹ and RH < 87.8% (category 4). For category 2 (DPD <
1843.7°C, and W < 2.5 m s⁻¹) time units are classified as wet if the following inequality is met:
185

$$186(1.6064\sqrt{T} + 0.0036T^2 + 0.1531RH - 0.4599W \cdot DPD - 0.0035T \cdot RH) > 14.4674 \quad (1)$$

187

188For category 3 (DPD < 3.7°C, W ≥ 2.5 m s⁻¹, and RH ≥ 87.8%) time units are classified as
189wet if the following inequality is met:

190

$$191(0.7921\sqrt{T} + 0.0046RH - 2.3889W - 0.0390T \cdot W + 1.0613W \cdot DPD) > 37.0 \quad (2)$$

192

193 Sensors and models performances were assessed by receiver operating characteristic
194(ROC) curve analysis. This statistical method is particularly indicated when a binary
195classification variable (i.e. wet leaf wet vs. dry leaf) is estimated based on a continuous
196variable (i.e. outputs of LW sensors and models). Typically, ROC curves show the
197proportion of correctly classified negative observations (specificity) in the x axis and the
198proportion of correctly classified positive observations (sensitivity) in the y axis as the
199continuous variable moves over its range of values. The area under the ROC curve (AUC) is

calculated by trapezoids. Higher AUC values indicate better classification performance of the estimator being evaluated, with a maximum value of 1 for a perfect estimator and 0.5 for a non-discriminant one (Metz, 1978). The optimal cut-off threshold for the estimator is chosen among all possible values of the continuous variable based on the Youden's J statistic:

$$J = \frac{ad - bc}{(a + b)(c + d)} \quad (3)$$

where a are true positives, b are false negatives, c are false positives, and d are true negatives. This index maximizes the distance to the non-discriminant (diagonal) line, with a value of zero when the estimator reports the same proportion of false and true positives, and the value unity when there are neither false positives nor false negatives (Youden, 1950).

Visual observations of LW and the outputs of LW sensors and models were used to calculate ROC curves separately for each of the six canopy positions and two leaf sides using the pROC package for R (Robin et al., 2011). Additionally, ROC curves were calculated by merging all canopy positions for leaf upperside and underside, respectively. The presence or absence of LW recorded at 15-min time steps in visual observations was considered as the binary classification variable. According to the ROC terminology, the 15-min periods with observed LW were denoted as cases and the 15-min periods without LW as controls. The outputs of the LW sensors and models were evaluated as continuous estimators of this binary classification variable.

The DeLong's method was used to calculate the 95% confidence intervals (CI) of AUCs (DeLong et al., 1988). Values of AUC obtained with the different LW sensors and models at 1.5 m were contrasted by the DeLong's paired test, separately for leaf upperside and underside (DeLong et al., 1988; Robin et al., 2011). The 95% CI of sensitivity and

specificity obtained with the LW sensors and models operating with their optimal cut-off thresholds were computed using stratified bootstrap, which is based on random resampling with replacement (Fawcett, 2006). Finally, the Cohen's kappa index (Landis and Koch, 1977) was used to evaluate the agreement between visual observations of LW and the outputs of LW sensors and models operating with their optimal cut-off thresholds.

2.3. LWD estimation in commercial citrus orchards

LW recordings were obtained from 14 commercial citrus orchards located in the provinces of Tarragona (TA), Castelló (CS), Valencia (VA), Alicante (AL), Murcia (MU), Sevilla (SE), and Huelva (HU), the main citrus-growing regions in Spain (Table 1). Crop management, fertilization and pest management followed recommended practices. Trees were pruned each year so that the canopy size remained almost constant during the period of study. Spectrum sensors for temperature and RH (WatchDog 450), LW (3666), and rainfall (WatchDog 1120, accuracy $\pm 2\%$) were located within a row at 1.5 m above the soil surface, about the top one-quarter of the canopy height (Magarey et al., 2005). LW sensors were placed with a northerly exposure and fixed at a 30-degree angle from the horizontal. Data were collected hourly and a cut-off threshold of 2.85 was used for the LW sensor based on the performance evaluation described above.

Descriptive statistics were obtained for LWD in each orchard, excluding the days without LW. The performance of the RH model was evaluated with ROC analysis using LW data recorded by Spectrum LW sensors. The presence or absence of LW recorded at hourly time steps by the Spectrum LW sensors was considered as the binary classification variable and RH as the continuous estimator. The agreement between the RH model operating with

the optimal cut-off threshold in each orchard and the Spectrum LW sensor was evaluated by the Cohen's kappa index.

251

2522.4. *LWD dynamics in citrus orchards with flood or drip irrigation*

253

The dynamics of daily LWD was evaluated in six commercial citrus orchards of Clementine 'Orogrande' (*C. reticulata*) grafted on Carrizo citrange at Carlet, Spain, (39.14°N elevation 35 m). Trees were planted between 2002 and 2005 on a 5 x 3-m spacing and the rows ran directly north to south. Three orchards were flood irrigated (orchard 1-flood, orchard 2-flood, and orchard 3-flood) whereas other three orchards were drip irrigated (orchard 1-drip, orchard 2-drip, and orchard 3-drip). Soil water content in the orchards was determined gravimetrically in the 0-0.3 m soil depth via undisturbed soil cores extracted during the experimental period each year in two transects and six samples per transects. As drip irrigation does not wet uniformly the orchard floor, this was done to obtain a representative value of the soil water content for the entire orchard floor.

264 Flood irrigation events moistened the entire orchard floor with ~70 mm of water. The total amount of water was applied at once in a period of about one hour. To monitor the timing of irrigation events, a frequency domain reflectometry soil moisture sensor (EC-5, Decagon Devices Inc., USA, accuracy $\pm 3\%$) was installed in each orchard at a depth of 0.25 m from the soil surface. An irrigation event was considered when the soil moisture content increased by at least 10% under absence of rainfall events. Drip irrigation was applied with pressure compensated emitters (Model PC, Netafim, IL) with a discharge rate of 4 L h⁻¹. The soil area wetted by emitters in each orchard was quantified as described above obtaining the values of 19.1%, 10.7% and 14.3% of the soil allotted per tree, for orchards 1-drip, 2-drip and 3-drip, respectively.

274 Sensors of temperature and RH (Hobo S-THB-M002, accuracies $\pm 0.13^{\circ}\text{C}$ and $\pm$
275 2.5% RH), LW (Hobo S-LWA) and rain (Davis 7852) were deployed in each orchard.
276 Environmental monitors were located within the row at about 1.5 m above the soil surface.
277 LW sensors were placed with a northerly exposure and fixed at a 30-degree angle from the
278 horizontal. A cut-off threshold of 75.88 was selected based on the performance evaluation
279 described above. Orchards were continuously monitored at hourly time steps during the
280 irrigation season each year, from 19 June to 30 October in 2012, and from 4 April to 14
281 November in 2013. Orchard 2-drip and orchard 2-flood were monitored only from 27 June to
282 25 November and from 14 May to 14 November, respectively, due to sensor failure.

283 Univariate time-series analysis was used to describe the dynamic of daily LWD in
284 each of the six irrigated citrus orchards. These models are commonly used with time-series
285 data to identify potential underlying factors and predict future values based on past data
286 (Hyndman and Athanasopoulos, 2013). The non-seasonal autoregressive integrated moving
287 average (ARIMA) (p, d, q) model was used, where p is the number of autoregressive terms
288 (i.e. number of time lags), d is the number of non-seasonal differences (i.e. number of times
289 the data have had past values subtracted), and q is the number of moving average terms. The
290 most appropriate ARIMA model for each orchard and year was identified, parameterized and
291 checked using the forecast and tseries packages for R (Hyndman et al., 2014; Trapletti and
292 Hornik, 2013). A trend in mean was identified by plotting the data, so time series were
293 stationary (i.e. constant variance and mean) by taking one sequential difference of the data
294 ($d = 1$). Time-series models were identified as ARIMA (1, 1, 1) using the auto.arima
295 function implemented in the forecast package for R, and by plotting the autocorrelation
296 (ACF) and partial autocorrelation (PACF) functions. The equation for this model can be
297 written as:

298

$$y_t = y_{t-1} + \phi (y_{t-1} - y_{t-2}) - \theta e_{t-1} \quad (4)$$

300

301 where y is the number of LW hours per day, t is time in days, ϕ is the autoregressive
 302 parameter, θ is the parameter of the lagged forecast error, and e_{t-1} denotes the error at period
 303 $t-1$. Parameter values were estimated by maximum likelihood and their significance was
 304 analysed by the Wald test statistic using the aod package for R (Lesnoff and Lancelot, 2012).
 305 Residuals of each model were evaluated for white noise (i.e. zero mean, uncorrelated, equal
 306 variances, and normally distributed). The Ljung-Box test statistic was used to evaluate
 307 potential correlation and heterocedasticity in the residuals and the Shapiro-Wilk test to assess
 308 if they were normally distributed (Cromwell et al., 1994). The presence of outliers and
 309 interventions was evaluated by plotting model residuals along the experimental period
 310 (Alwan and Roberts, 1988). The iterative procedure described by Chang et al. (1988) for
 311 additive and innovative outlier detection was also used with the package TSA for R (Sik and
 312 Ripley, 2012). The mean absolute error (MAE) for the time-series model in each orchard
 313 was calculated.

314

315 **3. Results**

316

317 **3.1. LWD observations and sensors**

318

319 The minimum LWD visually observed on leaf upperside ranged from 11.2 h in the west side
 320 of the tree to 12.2 h at 1 m in the east side (Fig. 1). Median values ranged from 13.2 h at 2 m
 321 in the west side to 14 h at 1 m in the same side. The maximum LWD observed ranged from
 322 16.2 h at 1 and 1.5 m in the west side to 16.7 h at 1.5 m in the east side. On leaf underside,
 323 the minimum LWD ranged from 11.2 h in the west side to 11.7 h at 1.5 and 2 m in the east

side. Median values ranged from 13.2 h at 2 m in the west side and at 1 and 1.5 m in the east side to 14 h at 1 m in the west side. Maximum LWD ranged from 16.2 h at 1 and 1.5 m in the west side to 16.7 h at 1.5 m in the east side. No statistically significant differences in LWD were detected among canopy positions and leaf sides (Student's t-test $P > 0.05$).

When considering LWD recorded by Spectrum LW sensors, excluding the days without LW, the minimum LWD during rainless days was 1 h in all six canopy positions (Fig. 2). Maximum LWD ranged from 16 h at 1 m in the west side to 21 h at 1.5 m in the east side. Median LWD ranged from 6 h at 1 and 2 m in the west side to 9 h in all canopy heights in the east side. The minimum LWD in rainy days ranged from 1 h at 2 m in the east side to 3 h at 1 and 2 m in the west side. Six outliers were detected in the west side, with a maximum LWD of 32 h, and nine outliers in the east side with a maximum LW of 46 h. Median values of LWD were 12 h in all canopy positions, except 13 h at 1.5 m in the west side. In rainless days, significant differences in LWD were detected at heights of 1 m and 2 m in the west side compared with 1 and 2 m in the east side (Student's t-test $P < 0.05$). No statistically significant differences in LWD were detected among canopy positions (Student's t-test $P > 0.05$) in rainy days. In all six canopy positions, significantly longer LWD was recorded during rainy days than in rainless days (Student's t-test $P < 0.05$).

3.2. Evaluation of LW sensors and models by ROC analysis

The total number of controls/cases was 1741/3164 (upperside) and 1764/3141 (underside) for the Spectrum LW sensor, 577/1058 (upperside) and 585/1050 (underside) for the Hobo LW sensor and RH model, and 383/989 (upperside) and 384/988 (upperside) for the CART/SLD model. The optimal cut-off threshold selected based on Youden's J statistic for the Spectrum LW sensor ranged from 4.05 in the west side to 0.95 in the east side at a canopy

349 height of 2 m (Table 2). For the Hobo LW sensor the optimal cut-off threshold selected was
350 95.59 in the west side and 77.94 in the east side. Wind velocity was always $< 2.5 \text{ m s}^{-1}$
351 during visual observations of LW, thus only the inequality 1 of CART/SLD model was
352 evaluated. The optimal cut-off threshold was 15.97 for the west side and 16.25 for the east
353 side. The optimal cut-off threshold selected for the RH model was 91.25% in the west side
354 and 87.35% in the east side. The lowest performance was obtained with the Spectrum LW
355 sensor at 1.5 m in the east side, with a value of AUC (95% CI) of 0.86. The highest
356 performance was obtained with the RH model for the same canopy position, with a value of
357 AUC (95% CI) of 0.96. The lowest agreement with visual observations of LW was achieved
358 by the RH model in the west side and the highest by the Hobo LW sensor in the east side,
359 with values of Cohen's Kappa index of 0.62 and 0.83, respectively.

360 When the performance of LW sensors and models was evaluated combining all canopy
361 positions available, AUC values ranged from 0.88 to 0.94 (Fig. 3). These values
362 corresponded to the lowest and highest 95% CI obtained with the Spectrum LW sensor and
363 the RH model. The optimal cut-off threshold selected was 2.85 for the Spectrum LW sensor,
364 75.88 for the Hobo LW sensor, 15.99 for the CART/SLD model, and 87.45% for the RH
365 model. The specificity associated with these optimal cut-off thresholds ranged from 0.81
366 with the Spectrum LW sensor to 0.87 with the CART/SLD model. Sensitivity ranged from
367 0.84 with the CART/SLD model to 0.95 with the Hobo LW sensor. Considering only canopy
368 positions at 1.5 m height, the RH model yielded an AUC value significantly higher
369 (DeLong's paired test $P < 0.01$) than the other LW sensors and models evaluated, both for
370 leaf upperside and underside. No significant differences in AUC were detected among LW
371 sensors and CART/SLD model, except for leaf underside where the AUC of the CART/SLD
372 model was higher than the Spectrum LW sensor (DeLong's paired test $P < 0.01$). Cohen's

373 Kappa index ranged from 0.61 for the CART/SLD model to 0.77 for the Spectrum and Hobo
374 LW sensors.

375

376 3.3. *LWD estimation in commercial citrus orchards*

377

378 Excluding the days without LW, the minimum LWD was 1 h in all orchards (Fig. 4). The
379 first quantile ranged from 3 h at Tivenys, Aljaraque and Jávea to 5 h at Aznalcazar. The
380 lowest median LWD was 5 h recorded at Aljaraque and the highest was 10 h recorded at
381 Gandía and Monserrat. Mean LWD ranged from 6.7 h at Aljaraque to 12.7 h at Gandía. The
382 third quartile was 9 h at Aljaraque and 15 h at Gandía. Maximum LWD ranged from 25 h at
383 Deltebre to 94 h at Gandía. Outliers were detected in all orchards, except at Deltebre. The
384 average proportion of outliers was 0.021, with a maximum of 0.057 recorded at Gandía. The
385 average proportion of days with LW and rain was 0.264, with a minimum of 0.155 at
386 Monserrat and a maximum of 0.535 at Isla Cristina.

387 When the RH model was assessed using LW data from Spectrum LW sensors
388 deployed in commercial citrus orchards, the lowest optimal cut-off threshold based on
389 Youden's J statistic was 72.5 % at Gandía and the highest was 89.5 % at Chiva (Table 3).
390 The lowest performance of the RH model was obtained at Isla Cristina, with an AUC of
391 0.65, and the highest performance at Amposta and Monserrat, with AUCs of 0.97. Median
392 values of specificity with the RH model ranged from 0.73 at Aljaraque to 0.91 at Monserrat.
393 The lowest median value of sensitivity was 0.43 obtained at Isla Cristina and the highest was
394 0.93 at Almonte. The lowest agreement between the Spectrum LW sensor and the RH model
395 was obtained at Isla Cristina and the highest at Monserrat, with values of Cohen's Kappa
396 index of 0.32 and 0.83, respectively.

397

3983.4. *LWD dynamics in citrus orchards with flood or drip irrigation*

399

400The period evaluated in 2012 was 133 days in all orchards, and the number of days with LW
401ranged from 110 in orchard 1-drip to 124 in orchard 3-drip and orchard 1-flood (Fig. S1).
402Excluding the days without LW, average LWD ranged from 8.9 h day⁻¹ in orchard 2-flood to
4039.9 h day⁻¹ in orchard 3-drip. Minimum LWD was 1 h day⁻¹ in all orchards and maximum
404daily LWD was 22 h day⁻¹, except in orchard drip-2 with 20 h day⁻¹. The interval between the
4051st and 3rd quantile of daily LWD ranged from 6-13 h day⁻¹ in orchard 1-drip to 7-11 h day⁻¹
406in orchard 3-flood. A total of 15 days with measurable rain (≥ 0.2 mm) was recorded,
407ranging between 0.4-106 mm day⁻¹ and 14.5 mm day⁻¹ on average. In the flood irrigated
408orchards, a total of three irrigations were recorded and the average soil water content varied
409from 11% to 34%, values registered only immediately after the irrigation events. In the drip
410irrigated orchards, the average soil water content in the wet soil portions under the emitters
411varied from 25% to 32%. Considering that only a small portion of the entire soil orchard was
412wetted by the drip system, this corresponded to an overall soil orchard water content ranging
413from 12% to 14%.

414 In 2013, the time periods evaluated comprised 131 days in orchard 2-drip for up to
415224 days in orchard 3-drip (Fig. S2). The number of days with LW ranged from 113 in
416orchard 2-drip to 175 in orchard 1-flood. Excluding the days without LW, minimum LWD
417was 1 h day⁻¹ in all orchards and maximum daily LWD was 20-23 h day⁻¹. Average daily
418LWD ranged from 6.8 h day⁻¹ in orchard 1-drip to 9.1 h day⁻¹ in orchard 2-drip. The interval
419between the 1st and 3rd quantile of daily LWD ranged from 4-9 h day⁻¹ in orchard 1-drip to 5-
42011 h day⁻¹ in orchard 2-flood and orchard 3-flood. A total of 13 days with measurable rain
421were recorded in orchard 2-drip, 23 days in orchard 2-flood, and 30 days in the other.
422Rainfall ranged from 0.2 mm day⁻¹ to 53.4 mm day⁻¹, with an average of 7.1 mm day⁻¹. The

number of flood irrigation events was 8 in orchard 1-flood, 7 in orchard 2-flood, and 6 in orchard 3-flood.

When time-series data were fitted to the ARIMA (1, 1, 1) model, the estimate of the autoregressive parameter ($\hat{\phi}$) ranged from 0.1060 ± 0.0907 in orchard 3-drip in 2013 to 0.3567 ± 0.0896 in the same orchard but in 2012 (Table 4). The moving average parameter ($\hat{\theta}$) ranged from -0.9801 ± 0.0426 in orchard 2-drip to -0.8216 ± 0.0577 in orchard 3-drip in 2013. The lowest MAE was 3.17 h in orchard 1-flood in 2012 and the highest was 3.91 h in orchard 2-flood in 2013. Residuals of the time-series models were confirmed as white noise, with a mean lower than 0.9, uncorrelated (Ljung-Box test $P > 0.05$), homoscedastic (Ljung-Box test $P > 0.05$) and Gaussian (Shapiro-Wilk test $P > 0.05$).

When model residuals were plotted along the continuous time periods evaluated in each orchard, two days were higher than twice the standard deviation of the residuals in 2012 (Fig. 5). In orchard 2-drip and orchard 3-drip, one additional day was also over this threshold. Only one day was higher than three-fold the standard deviation of the residuals. In 2013, the number of days higher than twice the standard deviation of the residuals ranged from one in orchard 2-drip to ten in orchard 1-drip (Fig. 6). In orchard 1-drip and 3-drip, only two days were over three-fold the standard deviation of the residuals. All days potentially out of range coincided with rain events but none with flood irrigation events. When the formal statistical test for interventions was applied, only one innovative outlier was detected in the orchards in 2012. The value of λ ranged from 3.55 in orchard 1-drip to 3.86 in orchard 3-drip. This outlier was detected on 28 September 2012, with rainfall of 106 mm day^{-1} .

4. Discussion and conclusions

448 Our results illustrated the relative high frequency of LW periods in citrus orchards in Spain.
 449 In the orchards with flood or drip irrigation where LWD dynamics were studied, the
 450 proportion of days with LW was 82.7-93.2% in 2012 and 63.7-85.2 % in 2013. Excluding
 451 the days without LW, average LWD was 8.9-9.9 h day⁻¹ in 2012 and 6.8-9.1 h day⁻¹ in 2013.
 452 In the 14 commercial citrus orchards monitored in seven provinces in Spain, considering
 453 only the days with LW, average LWD was 6.7-12.7 h (Fig. 4). As expected, significantly
 454 longer LWD ($P < 0.05$) were recorded during rainy days than in rainless days (Fig. 2).
 455 Nevertheless, the proportion of days with LWD during rainless days was 73.6%,
 456 demonstrating the importance of dew in LW formation as has been indicated by previous
 457 studies in semi-arid regions (Agam and Berliner, 2006). Although difficult to compare
 458 because of different experimental designs and LW estimation approaches, LWD obtained in
 459 our study were relatively similar to those described by previous studies in citrus. In Florida,
 460 Santillan et al. (2010) recorded mean LWD of 2.5-5.4 h day⁻¹ in rainless days and 9.7-12.2 h
 461 day⁻¹ in rainy days using dielectric LW sensors (LWS-L, Decagon Devices, Inc., USA). In
 462 Spain, Vicent and García-Jiménez (2008) reported LWD of 1-12 h day⁻¹ in citrus orchards
 463 with the same Spectrum LW sensors used in our study.

464 No statistical differences of visually observed LWD were detected between canopy
 465 positions and between leaf upperside and underside, though the period of study ($n = 9$ days)
 466 was probably too short (Fig. 1). Although the presence of LW on leaf underside has been
 467 previously reported in other plant species (Brewer and Smith, 1997), to our knowledge this
 468 was the first evidence in citrus trees. Our results showed that LW frequency and duration
 469 was similar in both sides of the leaf. Citrus leaves have higher density of stomata in the
 470 underside (Syvertsen and Lloid, 1994) and greater infection efficiency by foliar fungal

471 pathogens would be expected in this side. Therefore, fungicide sprays should provide
472 adequate coverage of both sides of the leaves.

473 With a longer period of study ($n = 643$ days), LW sensors detected significantly ($P <$
474 0.05) lower LWD at 1 and 2 m in the west side of the canopy compared with the east side,
475 but only in rainless days and differences were not substantial (Fig. 2). In their study in
476 Florida, Santillan et al. (2010) did not observe significant differences in LWD among canopy
477 positions in rainy days. In São Paulo, Brazil, Santos et al. (2008) did not detect differences in
478 LWD in cotton canopies, but longer LWD were detected in the lower canopy of coffee plants
479 and the upper canopy of banana plants. Sentelhas et al. (2006) also found longer LWD in the
480 higher canopy of apple trees in Iowa, USA, and corn plants in Ontario, Canada. Sentelhas et
481 al. (2005) reported longer LWD at the top canopy in apple in Iowa and corn in Ontario, but
482 not in grapes and young coffee plants in São Paulo. Longer LWD on the lower canopy of
483 citrus trees would be expected in irrigated semi-arid regions, where dew rise from soil has
484 been suggested to be the primary source of dew (Santillan et al., 2010). However, no
485 significant differences in LWD ($P > 0.05$) were detected among canopy heights in our study
486 (Fig. 2). In any case, information on the spatial variability of LWD in citrus canopies may
487 help to define optimal pruning and training systems to minimize LWD and improve disease
488 management (Dalla Marta et al., 2008).

489 Although excellent performance was obtained with the two LW sensors used in our
490 study, an absolute agreement with visual observations of LW was not achieved, as illustrated
491 by the values of AUC and Cohen's Kappa index (Fig. 3). Only few studies compared LW
492 sensors with visual observations, but all of them reported differences in LWD between these
493 two methods of LW estimation (Dalla Marta et al., 2008; Dalla Marta and Orlandini, 2010;
494 Magarey et al., 2006). Differences in surface characteristics between leaves and sensors may

influence LW deposition and subsequent estimation. Moreover, slight LW condensations may be missed by the human eye but detected by the electronic circuit of a sensor.

Predefined cut-off thresholds are generally required for the evaluation of LW sensors and models (Magarey et al., 2005). Nevertheless, these thresholds may be not necessarily the optimal ones maximizing sensor or model performance. Several statistical methods, such as the bias term in the mean squared error or the regression between observations and predictions, have been used to evaluate the agreement between sensors or models with visual observations (Dalla Marta et al., 2007; Sentelhas et al., 2008). With these statistical methods it is possible to identify problems of under- or over-prediction by the sensor or model, but only on the average. The critical success index (CSI) has been also used to compare the proportion of time units correctly classified wet or dry (Dalla Marta et al., 2005; 2007). However, for this method it is also necessary to predefine a cut-off threshold.

Our study was the first using ROC analysis to evaluate LW sensors and models with visual observations. With ROC analysis, all possible cut-off thresholds of the sensor or model were evaluated and the optimal one was selected to minimize both false positives and false negatives in each case (Metz, 1978). An optimal cut-off threshold of 2.85 was selected for the Spectrum LW sensor, 75.88 for the Hobo LW sensor, 15.99 for the CART/SLD model, and 87.45% for the RH model (Fig. 3). Cohen's Kappa index indicated a substantial strength of agreement with observed LW of the two LW sensors and two LW models operating with the optimal cut-off thresholds (Landis and Koch, 1977), so they would be adequate to estimate LWD on both sides of citrus leaves.

Several studies have indicated a positive relationship between average RH and the presence of LW in plants. Smith (1958) was the first to suggest a threshold of 90% RH for LW formation, indicating that 100% RH was not needed when leaf temperature is lower than the air temperature. Sentelhas et al. (2008) demonstrated that the RH threshold to estimate

LW on plants may differ depending on the geographical location. Other studies have indicated a poor relationship between the periods of high RH and LW (Francel and Panigrahi, 1997; Lomas and Shashoua, 1970). Moreover, Jones et al. (1980) warned that using a RH threshold may overestimate disease risk in some situations.

In our study, the RH model showed good specificity (0.83-0.84) and sensitivity (0.89-0.90) (Fig. 3) and its AUC value was significantly higher ($P < 0.01$) when contrasted with the other LW estimators evaluated. Furthermore, the RH model showed good performance in commercial citrus orchards in seven provinces in Spain, with AUC values higher than 0.83 in 12 of 14 sites (Table 3). Considering that on-field sensors of temperature and RH are common in citrus orchards in Spain, the RH model could be easily adopted by growers to estimate LWD in commercial conditions. As indicated above, a cut-off threshold of 87.45% RH would be recommended to estimate LW in both sides of the citrus leaves. The adoption of the RH model will facilitate the implementation of prediction models to optimize the management of foliar fungal diseases of citrus in Spain, such as *Alternaria* brown spot of mandarin. Estimated LW data would be also useful for risk assessments of exotic foliar fungal pathogens (Bregaglio et al., 2011). Our results were in line with the recent review by Rowlandson et al. (2015), who recommended the use of simple empirical models based on RH thresholds to estimate LW avoiding the difficulties associated with sensors.

Time-series ARIMA models have been previously used in irrigation management studies (Aljoumani et al., 2012; Nasser et al., 2013), but no references of this statistical method applied to LW estimation were found. Conventional experimental designs, for instance including both irrigation systems and the same timings in all orchards, were not technically feasible in our study. Moreover, considering the measures needed to minimize interplot interference. Our approach using time-series ARIMA allowed detecting short and long term increases in LWD following irrigation or rain events in each orchard, even though

545 they had different irrigation and rain timings. The MAE obtained with ARIMA models was
546 3.1-3.9 h (Table 4), which was in line with the values reported for other LW models. Values
547 of MAE between 2.9 h and 5.1 h have been obtained with the CART/SLD model (Kim et al.,
548 2004), between 1.3 h and 6.5 h with RH, Fuzzy and CART/SLD models (Kim et al., 2010),
549 and between 1.8 h and 4.4 h with three LW models based on RH thresholds (Sentelhas et al.,
550 2008).

551 Several studies have indicated the importance of irrigation increasing LWD and
552 incidence of foliar fungal diseases (Palti, 1981). Longer durations of overhead irrigation
553 have been associated with higher incidences of fruit rot caused by *Phytophthora cactorum*
554 (Lebert & Cohn) J. Schröt. in apple and pear, bull's eye rot caused by *Neofabraea* spp. in
555 pear, and panicle and shoot blight of pistachio caused by *Botryosphaeria dothidea* (Moug.)
556 Ces. & De Not (Grove and Boal, 1991; Henriquez et al., 2008; Michailides and Morgan,
557 1992).

558 The effect of surface and subsurface irrigation systems on LWD has been associated
559 with increasing dewrise as a result of soil water evaporation, particularly in semi-arid areas
560 (Palti, 1981). Increasing frequencies of furrow irrigation have been associated with longer
561 LWD and higher incidence of white mold disease on dry edible beans, caused by *Sclerotinia*
562 *sclerotiorum* (Lib.) de Bary (Blad et al., 1978). Furrow irrigation increased LWD compared
563 with buried drip irrigation in lettuce fields in California, USA (Scherin and Vanbruggen,
564 1995). Earlier infections of *Botrytis cinerea* Pers. have been observed on furrow irrigated
565 tomatoes compared with drip irrigation under greenhouse conditions (Kamel et al., 2008).
566 Goldhamer et al. (2002) found higher RH, longer LWD and higher incidence of *Alternaria*
567 spp. with flood irrigation compared with buried drip irrigation in pistachio orchards in
568 California.

569 In our study, the time-series analysis did not detect any significant intervention
570 associated with flood irrigation events increasing LWD (Fig. 5 and Fig. 6). Significant
571 increases in LWD in the study orchards were associated only with some rain events.
572 Although Spain and California have relatively similar climates, values of average RH
573 recorded in our study were notably higher to those reported in pistachio orchards in
574 California by Goldhamer et al. (2002). Average RH in our study was 60.7-82.8% in the
575 orchards with flood irrigation and 60.9-85.2% in the orchards with drip irrigation. However,
576 average RH reported by Goldhamer et al. (2002) was 40-75% with flood irrigation and 38-
577 68% with buried drip irrigation.

578 The pistachio orchards studied in California were located inland, about 150 km away
579 from the coastline. However, citrus orchards in our study were located close to the sea (~15
580 km) to avoid frost damage, as it is the case of most citrus-growing areas in central-eastern
581 Spain. Consequently, they were frequently exposed to dominant sea winds with high RH.
582 This high mesoclimatic RH outweighed possible microclimatic changes induced by flood
583 irrigation in citrus orchards. In addition, because citrus orchards have discontinuous canopies
584 with high degree of coupling between trees and the atmosphere, there are conditions of high
585 air turbulence inside citrus orchards as compared for instance with field crops with full
586 ground cover (Jarvis, 1985). The aerodynamics characteristics of citrus orchards, favour then
587 the effects of mesoclimatic conditions over the potential orchard effects of the irrigation
588 system on tree microclimate. However, it is important to note that the lowest canopy height
589 evaluated in our study was 1 m. Thus, effects of surface irrigation inducing longer LWD on
590 the lower canopy and the leaf litter cannot be excluded. This microclimatic modification
591 might enhance fungal infection and inoculum production at the base of the canopy (Palti,
592 1981).

593 As discussed above, dewrise from soil has been suggested as the primary source of
594dew in irrigated citrus orchards in semi-arid regions, where RH was presumed to be low
595(Santillan et al., 2010). However, the high mesoclimatic RH recorded in our study suggests
596that dewfall originated from air would be also an important source of LW in the study area.
597Thus, in contrast to previous studies in other crops and regions, negligible effects of flood
598irrigation in the infection by foliar fungal pathogens would be expected in citrus areas in
599central-eastern Spain. Nevertheless, higher infection in the lower part of the canopy
600associated with flood irrigation may be conceivable. Moreover, potential effects of surface
601irrigation on inoculum dynamics and survival should be also considered (Vicent et al.,
6022011).

603

604**Acknowledgments**

605

606Research funded by INIA RTA2010-00105-00-00-FEDER. AV was supported by DOC-
607INIA and DDMB by AECID-Spain and INAGBE-Angola. We thank the Plant Health
608Services from Catalunya, Comunitat Valenciana, Murcia and Andalucía for the maintenance
609of meteorological stations in commercial citrus orchards.

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752**Table 1** Commercial citrus orchards in seven provinces in Spain where Spectrum leaf wetness sensors were deployed.

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Locality ¹	Coordinates		Cultivar	Rootstock	Age (years)	Tree spacing (m)	Row direction	Irrigation system	Period studied
	Longitude	Latitude							
Deltebre (TA)	0.68918	40.72138	Navelate	Carrizo	>15	7 x 5	N-S	Drip	2008-2009
Tivenys (TA)	0.49533	40.89711	Navelate	Cleopatra	>15	5 x 5	NE-SW	Drip	2008-2009
Burriana (CS)	0.02119	39.91506	Okitsu	Carrizo	<10	5 x 3	NW-SE	Drip	2008
Chilches (CS)	-0.16776	39.76541	Clemenules	Carrizo	>15	5 x 3	NW-SE	Drip	2008-2009
Alzira (VA)	-0.43012	39.13371	Nova	Carrizo	>15	4 x 4	NE-SW	Flood	2008-2011
Chiva (VA)	-0.60092	39.46971	Fortune	Carrizo	>15	5 x 4	N-S	Drip	2003-2005
Gandía (VA)	-0.22783	38.96175	Clemenules	Carrizo	>15	5 x 4	N-S	Drip	2008-2009
Montserrat (VA)	-0.54356	39.36586	Nova	Carrizo	16	4.5 x 2	E - W	Drip	2008-2009
Jávea (AL)	0.17799	38.77829	Lane-Late	Carrizo	>10	5 x 4	N-S	Flood	2008-2010
Palma (MU)	-0.98492	37.66077	Navel-Powell	Cleopatra	>20	5 x 3	E-O	Drip	2008-2012
Aznalcázar (SE)	-6.24727	37.25718	Valencia	Carrizo	>10	6 x 3	N-S	Drip	2008-2009
Aljaraque (HU)	-6.98527	37.31334	Lane-Late	Carrizo	>10	8 x 4	N-S	Drip	2008
Almonte (HU)	-6.54907	37.12170	Clemenules	Carrizo	>10	8 x 2.5	E-W	Drip	2008-2010
Isla Cristina (HU)	-7.32495	37.23560	Fortune	Carrizo	>20	8 x 4	NW-SE	Drip	2008-2009

754¹ Provinces: TA, Tarragona; CS, Castelló; VA, Valencia; AL, Alicante; MU, Murcia; SE, Sevilla; HU, Huelva.

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757**Table 2** Area under the receiver operating characteristic curve (AUC), optimal cut-off threshold (dry/wet) and Cohen’s Kappa index (k) for
 758Spectrum and Hobo sensors and CART/SLD and RH models as estimators of visual observations of leaf wetness at six canopy positions and leaf
 759upperside and underside in a citrus orchard at Moncada, Spain.
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Canopy location		Estimator	Leaf upperside			Leaf underside		
Side	Height		AUC	Threshold ²	k	AUC	Threshold	k
West	2 m	Spectrum	0.92 (0.89-0.94) ¹	4.05	0.79	0.91 (0.89-0.94)	4.05	0.79
		Hobo	0.89 (0.87-0.91)	95.59	0.73	0.89 (0.87-0.92)	95.59	0.74
	1.5 m	Spectrum	0.90 (0.87-0.93)	3.90	0.75	0.90 (0.87-0.92)	4.45	0.74
		Hobo	0.89 (0.87-0.91)	95.59	0.73	0.89 (0.87-0.92)	95.59	0.74
	1 m	CART/SLD	0.91 (0.88-0.94)	15.97	0.65	0.91 (0.89-0.94)	15.97	0.66
		RH	0.92 (0.90-0.94)	91.25	0.62	0.93 (0.91-0.94)	91.25	0.63
East	2 m	Spectrum	0.93 (0.91-0.95)	3.15	0.78	0.92 (0.90-0.94)	3.15	0.77
		Hobo	0.89 (0.87-0.92)	77.94	0.83	0.89 (0.87-0.92)	77.94	0.83
	1.5 m	Spectrum	0.88 (0.85-0.91)	0.95	0.79	0.89 (0.87-0.91)	0.95	0.79
		Hobo	0.90 (0.88-0.92)	77.94	0.83	0.89 (0.87-0.92)	77.94	0.83
	1 m	CART/SLD	0.93 (0.91-0.95)	16.25	0.64	0.93 (0.91-0.95)	16.25	0.64
		RH	0.94 (0.92-0.96)	87.35	0.74	0.94 (0.92-0.96)	88.05	0.74

761 ¹ 95% confidence interval computed with DeLong’s method.
 762 ² Based on Youden's J statistic.
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Table 3 Area under the receiver operating characteristic curve (AUC), optimal cut-off threshold (dry/wet), Cohen's Kappa index (k), specificity and sensitivity for the RH model as estimator of leaf wetness recorded by Spectrum sensors in 14 commercial citrus orchards in Spain.

Orchards ¹	AUC	Threshold ³	k	Specificity ⁴	Sensitivity ⁴
Amposta (TA)	0.97 (0.96-0.98) ²	85.5	0.80	0.88 (0.87-0.89)	0.93 (0.92-0.94)
Tivenys (TA)	0.94 (0.94-0.95)	84.5	0.69	0.85 (0.84-0.86)	0.92 (0.91-0.93)
Burriana (CS)	0.96 (0.95-0.97)	85.5	0.75	0.87 (0.86-0.88)	0.89 (0.88-0.90)
Chilches (CS)	0.93 (0.92-0.94)	83.5	0.73	0.84 (0.83-0.85)	0.90 (0.89-0.91)
Alzira (VA)	0.87 (0.86-0.88)	84.5	0.68	0.86 (0.85-0.87)	0.83 (0.82-0.84)
Chiva (VA)	0.92 (0.92-0.93)	89.5	0.66	0.83 (0.82-0.84)	0.89 (0.88-0.90)
Gandía (VA)	0.83 (0.82-0.84)	72.5	0.54	0.84 (0.83-0.85)	0.69 (0.68-0.71)
Montserrat (VA)	0.97 (0.96-0.97)	83.5	0.83	0.91 (0.90-0.92)	0.92 (0.91-0.93)
Jávea (AL)	0.96 (0.95-0.97)	87.5	0.80	0.90 (0.89-0.91)	0.90 (0.89-0.91)
Palma (MU)	0.90 (0.89-0.91)	82.5	0.71	0.90 (0.89-0.91)	0.79 (0.78-0.80)
Quema (SE)	0.93 (0.92-0.94)	82.5	0.74	0.84 (0.83-0.85)	0.91 (0.90-0.92)
Aljaraque (HU)	0.90 (0.89-0.91)	87.5	0.41	0.73 (0.72-0.74)	0.92 (0.91-0.94)
Almonte (HU)	0.91 (0.90-0.91)	81.5	0.67	0.77 (0.76-0.78)	0.93 (0.92-0.94)
Isla Cristina (HU)	0.65 (0.64-0.66)	87.5	0.32	0.88 (0.87-0.89)	0.43 (0.41-0.44)

Tarragona; CS,
Valencia; AL,
Murcia; SE,
Huelva.
interval
DeLong's

³ Based on Youden's J statistic.

⁴ Median and 95% confidence interval computed with stratified bootstrap for the optimal cut-off threshold.

Table 4 Time-series models ARIMA (1,1,1) fitted to daily leaf wetness durations recorded by Hobo sensors in three citrus orchards with flood irrigation and three with drip irrigation in 2012 and 2013.

Year/orchard	Autoregressive parameter ($\hat{\phi}$)	Moving average parameter ($\hat{\theta}$)	MAE ¹
2012			
Orchard 1-flood	0.2439±0.0884	-0.9543±0.0224	3.17
Orchard 2-flood	0.2186±0.0889	-0.9569±0.0238	3.50
Orchard 3-flood	0.2853±0.0889	-0.9656±0.0281	3.54
Orchard 1-drip	0.2298±0.0935	-0.9235±0.0345	3.78
Orchard 2-drip	0.3369±0.0916	-0.9286±0.0326	3.41
Orchard 3-drip	0.3567±0.0896	-0.9334±0.0299	3.21
2013			
Orchard 1-flood	0.2614±0.1145	-0.8740±0.0788	3.72
Orchard 2-flood	0.2966±0.0777	-0.9683±0.0266	3.91
Orchard 3-flood	0.1912±0.0930	-0.8587±0.0580	3.85
Orchard 1-drip	0.2398±0.0880	-0.8863±0.0507	3.43
Orchard 2-drip	0.2422±0.0931	-0.9801±0.0426	3.72
Orchard 3-drip	0.1060±0.0907	-0.8216±0.0577	3.44

¹ Mean absolute error

Fig. 1. Duration of visually observed leaf wetness periods during nine nights in a citrus orchard at Moncada, Spain, showing box-whisker plots for three canopy heights (1, 1.5 and 2 m), two sides of the tree (west and east), and two sides of the leaf (upperside and underside).

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802**Fig. 2.** Duration of leaf wetness periods recorded by Spectrum sensors from 25 August 2011
803to 29 May 2013 in a citrus orchard at Moncada, Spain, showing box-whisker plots for three
804canopy heights (1, 1.5 and 2 m), two sides of the tree (west and east), and rainy (≥ 0.2 mm)
805and rainless days.

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811**Fig. 3.** Receiver operating characteristic (ROC) plots with curve, area under the ROC curve
 812(AUC) with 95% confidence interval, optimal cut-off threshold (dry/wet) with 95%
 813confidence intervals for specificity and sensitivity, and Cohen's Kappa index (k) obtained
 814with Spectrum and Hobo sensors, and CART/SLD and RH models using visual observations
 815of wetness on leaf upperside and underside during nine nights in a citrus orchard at
 816Moncada, Spain. The diagonal line is the 'no discrimination' line.

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Fig. 4. Box-whisker plots of the duration of leaf wetness periods recorded with Spectrum sensors in 14 citrus orchards in Tarragona (TA), Castelló (CS), Valencia (VA), Alicante (AL), Murcia (MU), Sevilla (SE), and Huelva (HU) provinces in Spain (n = number of leaf wetness periods).

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833**Fig. 5.** Residuals of ARIMA (1,1,1) models for daily leaf wetness duration along
 834experimental periods in three citrus orchards with flood irrigation and three with drip
 835irrigation in 2012. Standard deviation of the residuals represented by red dashed lines (2x)
 836and blue dashed lines (3x). Blue dots are rain events (> 0.2 mm) and red dots are flood
 837irrigation events.

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Fig. 6. Residuals of ARIMA (1,1,1) models for daily leaf wetness duration along experimental periods in three citrus orchards with flood irrigation and three with drip irrigation in 2013. Standard deviation of the residuals represented by red dashed lines (2x) and blue dashed lines (3x). Blue dots are rain events (> 0.2 mm) and red dots are flood irrigation events.

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2012

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851 **Fig. S1.** Daily leaf wetness duration along experimental periods in three citrus orchards with
 852 flood irrigation and three with drip irrigation in 2012. Blue dots are rain events (> 0.2 mm)
 853 and red dots are flood irrigation events.

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858**Fig. S2.** Daily leaf wetness duration along experimental periods in three citrus orchards with
859flood irrigation and three with drip irrigation in 2013. Blue dots are rain events (> 0.2 mm)
860and red dots are flood irrigation events.