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Irrigation scheduling for *Humulus lupulus* (L.) cv. “Nugget”: climate and soil-plant relations

Hop (*Humulus lupulus* L.) yield depends greatly on weather conditions, particularly on rainfall, thus varying from year to year. In this sense, irrigation management is an essential tool for maintaining hop yields at an adequate level. However, hop water demands must be accurately estimated in order to develop an efficient irrigation strategy. The current study was performed over three years (2012–2014) in a 5-year old hop yard located in NW Spain. The hop yard was divided into two plots: in 2012, plot 1 was rain-fed and plot 2 was irrigated, whereas in 2013 and 2014 both plots were irrigated but to different water amounts. This work estimates the water status of hop cv. “Nugget” (2012–14) using leaf water stress indicators (LWSI) (relative water content and leaf water potential) and their relationships with soil water content (SWC). Moreover, a set of single crop coefficients (K_c) for the different phenological stages of the growing season has been developed for hop, under the common management conditions in Galicia (NW Spain). Soil water content at 80 cm depth was measured on 12 points per plot. Midday leaf water potential (Ψ_m), osmotic potential (Ψ_o), turgor pressure (Ψ_p) and relative water content (RWC) of the leaves were determined weekly from June to September on six plants per plot. Single K_c were estimated employing a soil water balance approach using previous data. Significant differences in SWC were detected between plots, especially by the end of the growing season. In 2013 and 2014, Ψ_m and Ψ_o were slightly more negative in plot 2 than in plot 1, 6 % and 2.5 %, respectively. Significant differences between plots were detected for Ψ_p and RWC in 2014, with plants in plot 1 showing the highest values for these LWSI. Using data from two seasons, significant coefficients of determination were observed for Ψ_p vs. SWC ($R^2 = 0.42$), Ψ_p vs. RWC ($R^2 = 0.41$) and Ψ_o vs. Ψ_m ($R^2 = 0.98$). The K_c values obtained for an average year were 0.69, 1.02 and 0.84 for the initial, mid-season and end stages of the hop-growing season. These results will enable hop growers in Galicia to manage irrigation more efficiently.

Descriptors: water status, leaf water stress index, soil water content, transpiration, growing degree days, yield

1 Introduction

Hop (*Humulus lupulus* L.) is an herbaceous perennial plant appreciated in several industries because of its female flowers, named hop cones, which contain bitter acids, including alpha and beta acids [1]. Currently, the beer brewing industry accounts for 98 % of the use of hop cones worldwide [2]. Hop cone yield and the concentrations of alpha and beta acids within the cones in a given cultivar depend on weather conditions and water availability over the growing season [3]. Water stress during flowering and,

especially, the stage of hop cone developmental can decrease hop yield and the concentration of alpha acids (a quality parameter) [4, 5]. In fact, hop yield losses because of extreme water scarcity have been reported in Europe in 2003 and 2013 [6, 7]. Since hop is a perennial plant, the effects of drought can accumulate and appear in subsequent years, leading to multi-year economic risks.

In this sense, hop is particularly vulnerable to climate change [3]. Due to their high leaf surface, hop plants require large amounts of water. In some growing areas, this can only be achieved by irrigation in most commercial fields in order to optimise yield and quality, although the irrigation water applied depends on the local climate conditions [8]. In arid regions, hop irrigation requirements have been found to be 700–800 mm per season, from mid-spring to shortly before harvest [9], however general hop water requirements (rainfall + irrigation + ground water contribution) vary from 500 to 700 mm per season. Although there are several irrigation systems used in hop yards, the most efficient one is the drip system [8]. Several reports concluded that irrigation improves hop yield without compromising alpha and beta acids concentrations [10, 11, 12]. However, in the current scenario of increasing water scarcity, due to climate change, and great competition for resources, it is relevant to obtain an accurate estimation of the crop water requirements in order to manage irrigation more efficiently. However, few

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studies focused on the determination of hop water requirements [13, 14, 15, 16] leading to contrasting results due to the different soil and weather conditions.

In this context, the aims of this research are i) to determine the hop (cv. "Nugget") water status by assessing leaf water stress indicators (LWSI) and establishing relationships between soil and plant indicators, ii) to develop a dataset of single crop coefficients (K_c) for each phenological stage to facilitate irrigation scheduling in commercial hop yards.

2 Materials and methods

2.1 Site description

The study was conducted over three seasons (2012-2014) in an experimental hop yard (*Humulus lupulus* L. cv. "Nugget") located at the "Centro de Investigaci3n Agrarias de Mabegondo" (CIAM) in A Coru3a, Galicia, NW Spain, (43° 14' 3.7" N, 8° 15' 12.9" W, elevation 60 m). The field was approximately flat and 1 ha in surface. The crop was established in 2007, with 3 x 2 m spacings (1667 plants/ha) and trellised to 6 m height. Orientation of the rows was East-West. The hop yard was divided into two plots corresponding to two different drip irrigation sectors, with 0.5 ha per plot. Plot 1 referred to the lower part of the field, close to a small river, and Plot 2 referred to the upper part of the field.

Soil at the site was silt-loam textured, with 34 %, 47 % and 19 % sand, silt and clay, respectively. Soil organic matter content was 6.7 % on average. Soil water content at field capacity was 0.38 m³/m³, while it was 0.18 m³/m³ at wilting point. Consequently, the total available water down to 0.8 m depth was 168 and 160 mm in Plot 1 and Plot 2, respectively [15].

The climate of the site is Atlantic of the typical warm-summer

Table 1 Abbreviations used within the text

| Abbreviation | Description |
|------------------------|--|
| ET _o | reference evapotranspiration |
| GDD | growing degree days |
| K _c | single crop coefficient |
| K _{c Hop} | hop single crop coefficient |
| K _{c Hop end} | end season hop single crop coefficient |
| K _{c Hop ini} | initial hop single crop coefficient |
| K _{c Hop mid} | midseason hop single crop coefficient |
| K _{cb} | basal crop coefficient |
| K _{cb Hop} | hop basal crop coefficient |
| K _e | soil evaporation coefficient |
| LWSI | leaf water stress indicators |
| RWC | relative water content |
| SWC | soil water content |
| Ψ _m | midday leaf water potential |
| Ψ _o | osmotic potential |
| Ψ _p | turgor pressure |

Table 2 Summary of weather variables at the studied hop yard from March to September in 2012, 2013 and 2014. Temperatures, relative humidity and wind speed are averaged for the period, while global irradiation, rainfall and reference evapotranspiration (ET_o) are totals for the period

| Variable | Units | 2012 | 2013 | 2014 |
|---------------------|-------------------|--------|--------|--------|
| Maximum temperature | °C | 21.1 | 20.7 | 22.1 |
| Minimum temperature | | 9.5 | 9.6 | 10.1 |
| Mean temperature | | 15.2 | 15.1 | 16.0 |
| Relative humidity | % | 76.3 | 80.6 | 80.7 |
| Wind speed | m/s | 1.6 | 1.6 | 1.4 |
| Global irradiation | MJ/m ² | 3712.4 | 3710.0 | 3661.4 |
| Rainfall | mm | 385.8 | 498.6 | 383.9 |
| ET _o | | 669.3 | 671.4 | 691.3 |

Table 3 Irrigation amounts applied, rainfall and ground water contribution over the study period (2012–2014)

| Year | Location | Treatment | Events | Irrigation depth (mm) | Rainfall + Irrigation+ Ground water contribution (mm) |
|------|----------|------------|--------|-----------------------|---|
| 2012 | Plot 1 | Rain-fed | 0 | 0 | 511 |
| | Plot 2 | Irrigation | 14 | 128 | 624 |
| 2013 | Plot 1 | Irrigation | 15 | 69 | 701 |
| | Plot 2 | Irrigation | | 58 | 666 |
| 2014 | Plot 1 | Irrigation | 15 | 148 | 633 |
| | Plot 2 | Irrigation | | 141 | 581 |

Mediterranean type (Csb) according to the Köppen-Geiger classification, with a dry and warm summer [17]. Weather data, including maximum and minimum temperatures, wind speed and rainfall, were collected from an automatic station (Mabegondo, managed by MeteoGalicia) located near the hop yard. Reference evapotranspiration (ET_o) was computed according to the standard methodology [18]. The three years in which the experiment was carried out presented similar weather conditions for the hop growing cycle, from March to September (Table 1) with mean temperatures ranging from 15 to 16 °C, solar radiation around 3700 MJ/m², relative humidity between 76 and 80 % and ET_o ranging from 669 to 691 mm. In contrast, rainfall was 30 % higher in 2013 than in 2012 and 2014 (Table 2).

As presented in a previous work [15], in 2012, rainfall was concentrated in April and May whereas July, August and September were dry months. In 2013, rainfall concentrated in March and April while July to September was a dry period. In 2014, rainfall was more evenly distributed over the growing season. Summer months showed high daily ET_o values, up to 6 mm/day. Nevertheless, ET_o was highly variable due to the natural variability of solar radiation, temperature and wind speed.

2.2 Experimental design

In 2012, two treatments were considered: Plot 1 was rain-fed and Plot 2 was irrigated. Due to the low yield obtained in 2012 under

rain-fed conditions, this treatment was removed and substituted for a control with a lower irrigation dose (Plot 2 was the control thereafter), for this reason in 2013 and 2014, both plots were irrigated to different water amounts (Table 3). Irrigation started in early July and ended few days before harvest. In general, the interval between irrigation events was four days. A drip irrigation system was used. The lateral pipes were equipped with non-compensating emitters (2 L/h) spaced 50 cm along the crop row, resulting in four emitters per plant. The variability of discharges along the laterals was assessed through field evaluations. Net application rates varied between 3.9 and 9.9 mm.

2.3 Field determinations

Measurements were performed on eight rows per plot, six replications of one plant per plot. Crop height was determined visually each measurement day. Phenological stages were assessed weekly using the BBCH scale [19]. In order to characterize the dynamics of the crop over the growing season, growing degree days (GDD) were calculated on a daily basis using 5 °C as base temperature [5], and then summed up to obtain the cumulative monthly values.

Soil-plant measurements were performed from June to September, a period when hops (bines) have at least 1 m height and have leaves large enough to determine the LWSI. Six plants were randomly selected, three in each plot (Plot 1 and Plot 2).

Soil water content (SWC) was monitored with a TDR100 equipment (Campbell Scientific, Logan, UT, USA), which operates in the field using the PCTDR software [20]. Stainless steel rods were installed in line with the plants and on both sides of the rhizome, at 0.8 m depth in order to integrate SWC over the whole rooting depth. The equation of *Topp et al.* [21] relating the SWC with the measured bulk dielectric constant was used since it is appropriate for most loamy soils [22]. The SWC was measured in 12 points per plot. Measurements were performed two days after irrigation in order to avoid biases. The total number of SWC measurements was 9, 11 and 10 in 2012, 2013 and 2014, respectively.

The measurement of leaf water potential at midday (Ψ_m) was carried out with a water activity meter (WP4 model, Decagon Devices Inc., Washington, USA), according to previous works [23, 24]. Measurements were made on leaves at 1 m height early in the season and at 1.5 m from the moment when plants reached this height. Three leaves per plot and day were used for these determinations. Healthy and adult leaves with a similar state of development and exposed to solar radiation were collected. In addition, osmotic potential (Ψ_o) was determined in the same leaves through a process of freeze-thaw in liquid nitrogen, and subsequent determination of turgor pressure (Ψ_p). The relative water content (RWC) was determined by granulometry on six leaves per plot/day [25].

In the 2012 season, hop cone yield was

assessed using all plants from three rows per treatment. In 2013 and 2014, six plants per treatment were cut off at ground level and the number of stems per bine were recorded (data not shown). Fresh weight of hop cones per plant was determined and, then, four samples per plant (approximately 250 g of hop cones per sample) were collected and dried at 55 ± 5 °C until constant weight to determine hop dry weight. From these data, yield in dry weight was calculated and referred to 10 % of humidity.

2.4 Assessment of the single crop coefficients for hop

In a previous study [15], a modelling approach was used for obtaining the basal crop coefficient (K_{cb}) of hop bines under the conditions of NW Spain. In the current study, the single crop coefficient (K_c) was calculated from the sum of the $K_{cb\text{Hop}}$ and soil evaporation coefficient (K_e) obtained after the calibration and validation previously developed [15]. Three K_c values were determined at initial, midseason and end-season, as defined by *Allen et al.* [18]. This information supports the construction of a crop coefficient curve adapted to Galician conditions, as an average of the three study years. Final data were determined taking into account only hop water requirements, cover crop water requirements were not considered, more details about crop coefficients and the modelling process were included in a previous work [15].

2.5 Statistical analysis

An analysis of variance was performed (SPSS Statistical Package, SPSS, Chicago, IL, USA) in order to assess the effect of the irrigation amount on the soil and plant traits measured. Differences were considered significant at $p < 0.05$. Linear regression was used to detect relations among the indicators measured in the field.

3 Results

3.1 Weather conditions and hop growth

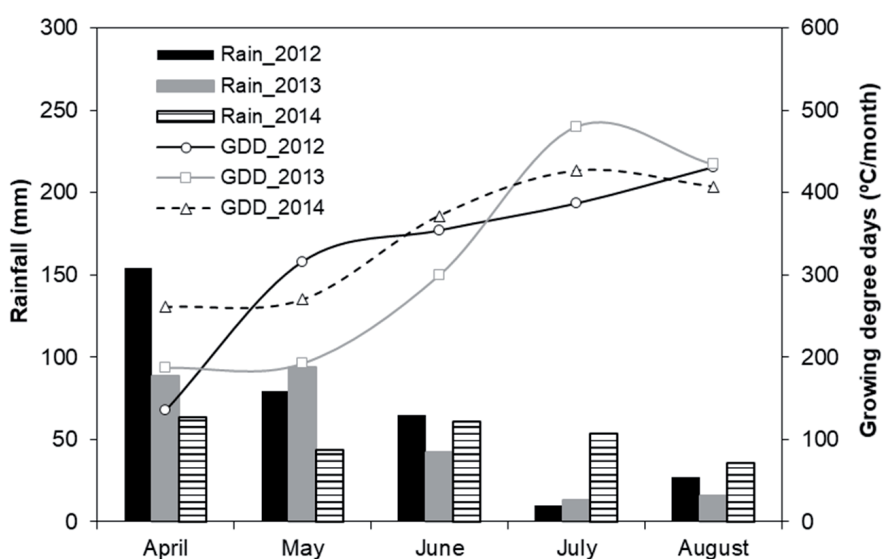


Fig. 1 Monthly rainfall and growing degree-days (GDD) for hop (*Humulus lupulus* L. cv. "Nugget") grown in NW Spain during the 2012–2014 seasons

Table 4 Dates of occurrence of the main hop coefficient-curve stages and their respective plant heights over each studied growing season

| Coeff. Curve stages | 2012 | | 2013 | | 2014 | |
|---------------------|--------------|------------|--------------|------------|--------------|------------|
| | Date | Height (m) | Date | Height (m) | Date | Height (m) |
| Initiation | 22 March | 0.01 | 15 April | 0.01 | 11 March | 0.05 |
| Start rapid growth | 10 May | 0.10 | 19 May | 0.15 | 20 April | 0.15 |
| Start mid-season | 15 July | 5.00 | 30 July | 5.50 | 10 July | 6.00 |
| Start maturity | 15 August | 6.00 | 25 August | 6.00 | 10 August | 6.00 |
| Harvesting | 11 September | 6.00 | 13 September | 6.00 | 04 September | 6.00 |

Figure 1 shows the evolution of GDD and monthly rainfall over the three seasons studied, explaining the differences observed in the hop phenological stages among years (Table 4). In 2012, the beginning of the growing season was cooler and wetter than in 2013 and 2014. However, May and June in 2012 were warmer than in 2013 and 2014. July was fresher in 2012 than in the rest of the study period, whereas August showed similar temperatures in the three years studied.

In the end, the cumulative GDD between April and harvest were similar among the three years, ranging from 1758 °C in 2013 to 1805 °C in 2014. However, greater differences were observed between years when considering the period from April to August, with GDD amounting 1623, 1593 and 1737 °C in 2012, 2013 and 2014, respectively. Figure 1 also shows that rainfall concentrated in April and May during 2012 and 2013, while it was more evenly distributed over the growing season in 2014.

3.2 Evolution of soil and plant indicators

Soil water content tended to decrease in Plot 1 (rain-fed) over the 2012 growing season, whereas it remained around 0.25 m³/m³ in Plot 2 (Fig. 2). A similar trend of SWC over the growing season was observed in 2013; however, both plots were irrigated during this year and SWC never went below 0.20 m³/m³ (Fig. 2). The different amount of water applied (19 % more in Plot 1 than in Plot 2) caused significant differences in SWC between plots by the end of the growing season. Finally, in 2014, the high amount of water supplied to the hop yard (double than that supplied the former year) and the even distribution of rainfall over the season led to an increasing trend of SWC in both plots (Fig. 2). Moreover, SWC in Plot 1 was higher than that of Plot 2 despite the low difference (5 %) in irrigation amounts between both plots.

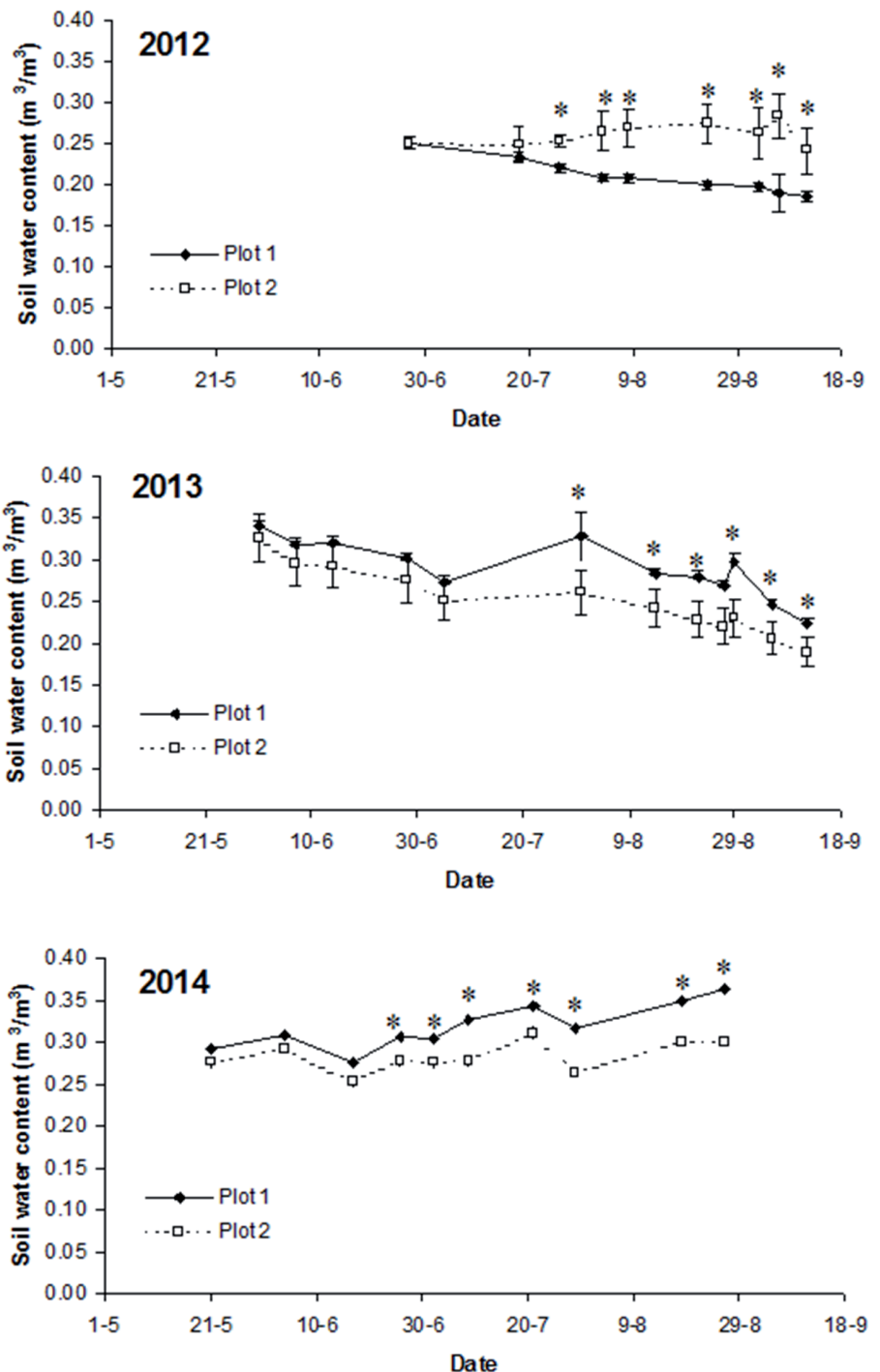


Fig. 2 Dynamics of soil water content in the studied plots over the 2012, 2013 and 2014 growing seasons. Asterisks indicate significant differences between plots for a given date according to ANOVA

Table 5 Average annual values and standard errors for leaf water potential at midday (Ψ_m), osmotic potential (Ψ_o), turgor pressure (Ψ_p) and relative water content (RWC) in each plot and year. The average yield (dry weight) per plot is also shown

| Parameter | Plot | Year | | |
|-------------------|------|----------------|------------------|-------------------|
| | | 2012 | 2013 | 2014 |
| Ψ_m (MPa) | 1 | – | -1.68 ± 0.01 | -1.61 ± 0.02 |
| | 2 | – | -1.78 ± 0.03 | -1.71 ± 0.01 |
| Ψ_o (MPa) | 1 | – | -2.54 ± 0.00 | -2.40 ± 0.01 |
| | 2 | – | -2.61 ± 0.03 | -2.46 ± 0.01 |
| Ψ_p (MPa) | 1 | – | 0.86 ± 0.00 | 0.91 ± 0.01 b |
| | 2 | – | 0.84 ± 0.00 | 0.86 ± 0.01 a |
| RWC (%) | 1 | 85.8 ± 7.8 | 82.5 ± 0.8 | 89.1 ± 1.1 b |
| | 2 | 82.9 ± 7.1 | 80.9 ± 0.7 | 84.2 ± 0.8 a |
| Yield (kg/ha) | 1 | 1258 | 1737 | 2264 |
| | 2 | 1896 | 1880 | 2572 |

For a given parameter and year, different letters indicate significant differences between plots at $P < 0.05$

The evolution of the LWSI varied depending on the year and plot considered (Table 5). In this sense, Ψ_m decreased progressively over the growing season, although no significant differences were detected between plots. Considering the average values (Table 5), hop plants from Plot 2 showed 5.9 % more negative Ψ_m values than those from Plot 1 in 2013 and 6.2 % in 2014. This reflected the lower soil water availability in Plot 2 than Plot 1 (Fig. 2).

The values of Ψ_o indicated a slightly higher salt concentration in leaves of hop plants from the 2013/14 less irrigated Plot 2 compared to those from Plot 1, 2.8 % in 2013 and 2.5 % in 2014 (Table 5). No significant differences between plots were detected, and Ψ_o tended to be more negative at the end of season. The Ψ_p indicator reflected a maintenance of hop water status over the season, with higher averages in 2014 compared to 2013 (Table 5). In 2014, Ψ_p values were significantly higher in Plot 1 than in Plot 2. In the three seasons studied, Plot 2 showed lower RWC values than Plot 1, being this difference significant in 2014 (Table 5). Moreover, the inter-year variability in the values of LWSI was small, ranging between 4 and 8 % depending on the indicator,

Table 6 Regression equations between the soil and plant indicators measured in a hop yard (cv. “Nugget”) in NW Spain during the years 2013 and 2014

| Year | Variable | | Regression equation | R ² |
|---------|-----------|-------------|--------------------------------------|----------------|
| | Dependent | Independent | | |
| 2013 | Ψ_p | RWC | $\Psi_p = 0.003 \text{ RWC} + 0.589$ | 0.82 |
| | Ψ_o | Ψ_m | $\Psi_o = 0.993 \Psi_m - 0.858$ | 0.99 |
| 2014 | Ψ_p | SWC | $\Psi_p = 0.857 \text{ SWC} + 0.624$ | 0.64 |
| | Ψ_o | Ψ_m | $\Psi_o = 1.081 \Psi_m - 0.755$ | 0.97 |
| 2013-14 | Ψ_p | SWC | $\Psi_p = 0.588 \text{ SWC} + 0.703$ | 0.42 |
| | Ψ_p | RWC | $\Psi_p = 0.004 \text{ RWC} + 0.582$ | 0.41 |
| | Ψ_o | Ψ_m | $\Psi_o = 1.014 \Psi_m - 0.852$ | 0.98 |

SWC (Soil water content at 0.8 m) [m^3/m^3], Ψ_m (leaf water potential at midday) [MPa], Ψ_o (osmotic leaf water potential) [MPa], Ψ_p (turgor pressure) [MPa], RWC (relative water content) [%], R² (coefficient of determination).

showing that the water status of hop plants was similar between years.

3.3 Relations between soil and plant indicators

In 2013, no significant relationships between the LWSI and SWC were detected; however, Ψ_p and SWC were significantly related in 2014 ($R^2 = 0.64$). When considering both years, 2013 and 2014, this relation is significant but with a lower regression coefficient (Table 6). In addition, the plant water stress indicators assessed in the current study presented different levels of correlation (Table 6). For instance, Ψ_p related weakly with RWC, while Ψ_o and Ψ_m showed a strong correlation (Table 6). Evaluating each year separately, a strong relationship between Ψ_o and Ψ_m ($R^2 = 0.98$) was detected; however, Ψ_p and RWC were closely related in 2013 ($R^2 = 0.82$) but not in 2014, while the relationship between Ψ_p and SWC was strong in 2014 ($R^2 = 0.64$).

4 Discussion

4.1 Weather conditions and hop growth

Weather conditions affected hop growth cycle, since the higher rainfall and lower ET_o in 2013 might have delayed the occurrence of the different crop coefficient curve stages with respect to 2012 and 2014 (Table 4). The lower ambient and soil temperatures suggested a delay in bud break of the rhizome (perennial plant part) and the trellis formation. This fact, along with the late pruning in 2013, 35 days later than in 2014, had caused an earlier harvest, 9 days, in the last year of the study. These results suggest the relevance of rainfall and temperature for an adequate hop growth, as previously reported by several authors worldwide [3, 7, 10, 26].

4.2 Evolution of soil and plant indicators over the growing season

The values of the indicators considered in the current study seemed to indicate a moderate to severe degree of water stress in hop plants; however, some factors must be considered prior to reach this conclusion. Hence, the position of the leaves to the total height of the plant may affect the Ψ_m value [27], which becomes more negative as the height increases. Although the Ψ_m determinations are considered reliable indicators of crop water status [28], they are not useful for hops by themselves because their progressive increase (negatively) is not accompanied by an increased crop stress. Moreover, no reference values of Ψ_m are available to determine hop water status, such as they are for grapevines [29]. Therefore, complementary indicators (RWC, Ψ_p , Ψ_o) are required for establishing hop water status. For example, RWC values were within the intervals reported for other well-irrigated hop cultivars [30]. This trait was less affected by drought than other LWSI, since its values were only reduced after 22 days of exposure to water restrictions [30].

Plot 2 showed higher yields than Plot 1 in the last two years of the study (Table 5), ranging from 8.3 % in 2013 to 13.6 % in 2014., i.e. similar yields between plots due to comparable amounts of total water received (Tables 2 and 5), although it seems that the additional 40–50 mm received by Plot 1 generated a slight reduction in yield. Otherwise, the huge difference in yield between plots occurred in 2012 might be explained by the high irrigation amount applied to Plot 2, being Plot 1 rain-fed. It is interesting to highlight that applying 128 mm in two months would lead to 50 % increases in yield when compared to non-irrigated hop yards, confirming that irrigation management can be used to modulate yield, as previously reported [15, 16].

When combining the information provided by plant indicators (Table 5) and SWC measurements (Fig. 2), it seems that hop plants in both plots did not suffer from severe water restrictions, although a weak to moderate level of water stress occurred in Plot 2. In fact, SWC values in Plot 2 were close to the permanent wilting point by the end of the 2013 season (Fig. 2), which corresponded to values of around -2.4 MPa for Ψ_m , -3.3 MPa for Ψ_o , 0.85 MPa for Ψ_p and approximately 81 % for RWC. Ideally, the assessment of these four LWSI, along with SWC, would provide reliable information for the determination of hop water status. Taking into account that RWC measurement is time consuming and less sensitive to water restrictions than other indicators [30], it seems unsuitable for the commercial management of irrigation in hop yards. Similarly, Ψ_o determination is time consuming and therefore also unsuitable for commercial use. Therefore, from the results of the current study, SWC, Ψ_m and Ψ_p seem to be more practical indicators for determining hop water status. Nevertheless, SWC can be considered as the reference variable for irrigation scheduling because it does not require destructing plant material. Moreover, SWC does not need complex methods for its implementation, such as Ψ_m and Ψ_p , which require labour and are time-consuming.

4.3 Relations between soil and plant indicators

Relationships between LWSI and soil properties have been reported for other crops [31, 32, 33]. In hops, Gloser et al. [34] reported a weak relationship ($R^2 = 0.38$) between Ψ_m and SWC; however, these authors used different methodologies than the ones employed in the current study for determining those variables: pressure chamber for Ψ_m and Theta probe for SWC. This difference might have been one of the causes for the variability between the results from the present work with those reported previously [34].

As expected, water use exerted a large im-

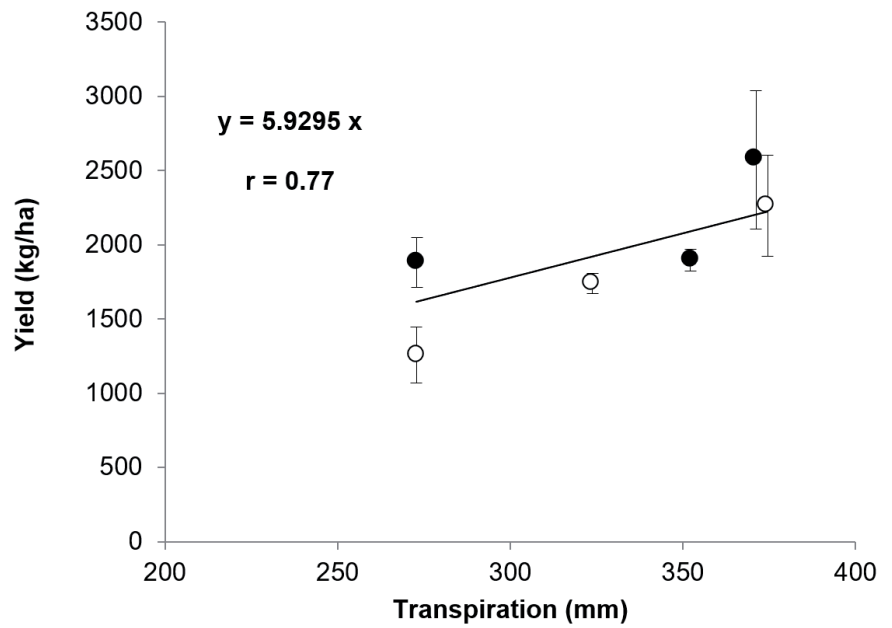


Fig. 3 Linear regression between yield (dry matter) and hop transpiration. Empty points represent Plot 1 and filled points Plot 2. Error bars are the standard deviation

pact on hop cone yield and a positive linear relationship between yield and hop transpiration was detected (Fig. 3), confirming that transpiration favours hop yield [11, 12, 15, 16].

4.4 Tools for managing irrigation in hop yards

Water management in hop yards is extremely relevant for maximizing yield and hop cone quality [11, 16, 35]. In the current study, an easy-to-implement approach for irrigation management in commercial hop yards is described. Although the results presented here are adapted to the local conditions of Galicia, they might be adapted to other regions worldwide. In order to facilitate the daily irrigation management, the single K_c for each main hop developmental stage was calculated (Fig. 4).

The K_c values for hop obtained for an average year are the fol-

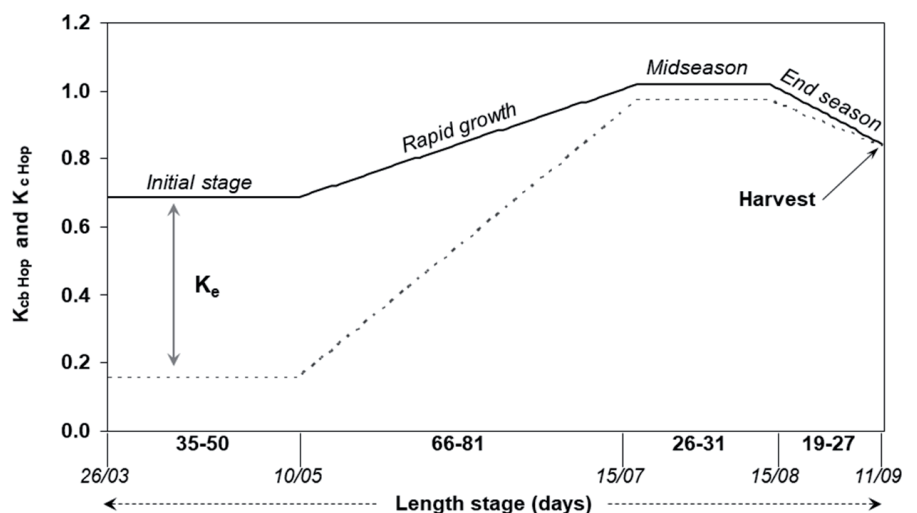


Fig. 4 Evolution of basal [K_{cbHop} ----] and single [K_{cHop} -] crop coefficients, and length of crop stages for cv. "Nugget" in Galicia. K_e : evaporation coefficient

lowing: $K_{c\text{ Hop ini}} = 0.69$; $K_{c\text{ Hop mid}} = 1.02$ and $K_{c\text{ Hop end}} = 0.84$ (Fig. 4). These coefficients are in agreement with those proposed by Allen et al. [18], except for $K_{c\text{ Hop ini}}$, which is 56 % higher than the 0.3 value reported in the literature [18]. The high value of $K_{c\text{ Hop ini}}$ is due to soil evaporation, related with the rainfall events and a high percentage of bare soil during the initial crop growth stage. Figure 4 includes the length interval of crop coefficient-curve stages adjusted to Galician conditions for the Nugget cultivar. The combined use of the proposed K_c with SWC measurements would allow for determining soil water status and, therefore, the moment to either trigger or stop irrigation, while the water amount required would be defined by daily crop evapotranspiration, calculated as the product between ET_0 and K_c . By employing this information, hop growers would be able to manage their water resources efficiently, and maximize production and quality, taking into account the occurrence of phenological stages. The proposed $K_{c\text{ Hop ini}}$ is adequate for Galician conditions; however, if active ground cover is adopted, the K_c values have to be increased by 0.05–0.20 in the initial stage, 0.05–0.10 during mid-season and up to 0.20 at end-season, depending on the inter-row management selected.

5 Conclusions/Summary

The evaluation of hop water status through the combined use of several LWSI (Ψ_m , Ψ_o , Ψ_p and RWC) and soil measurements (SWC) provided a significant contribution for designing efficient irrigation strategies. The determination of SWC provided interesting information because it enabled to observe significant differences between plots during all the studied years. Even though the LWSI (Ψ_m , Ψ_o , Ψ_p and RWC) are highly correlated between each other, they are not easy to determine and therefore might have no practical use for hop growers. Nevertheless, the correlation between SWC and LWSI might be used to estimate plant water stress by hop growers, since it is easy to determine, the correlation coefficient is still on a sufficient level, and it showed clear differences between the irrigation regimes tested.

Furthermore, the single K_c for each main coefficient-curve stage of hops was estimated and a curve of K_c was constructed for an average growing season. This will enable growers to manage irrigation more efficiently under the conditions of hop cultivation in Galicia and can be adapted to other regions by combining the information displayed on the curve with the SWC measured in each stage of crop development. Future work should consider the cumulative effect of water stress on hop growth and yield, taking into account the soil properties and the influence of groundwater.

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