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Effect of the optimized regulated deficit irrigation methodology on water use in garlic

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ABSTRACT

The continuing decline in water availability for agricultural uses and increased energy costs have made it necessary to improve water productivity in crops. The optimized regulated deficit irrigation (ORDI) methodology was developed to maximize the yield of annual crops under water-scarce conditions, either by reaching a specific deficit target or distributing a limited volume of irrigation water throughout the growing season (ORDIL). The objective of this study was, for a limited amount of available irrigation water, to determine the effect of ORDIL methodology on yield, agronomic and irrigation water productivity and water footprint of a purple garlic cultivar crop under semi-arid conditions. To this end, five irrigation treatments were evaluated from 2015 to 2017 on an experimental farm located in semi-arid conditions (Albacete, Spain): no deficit (ND), and four with different volumes of available irrigation water, corresponding to 100% (T100), 90% (T90), 80% (T80), and 70% (T70) of garlic net irrigation requirements for the weather conditions of the intermediate typical meteorological year (2750 m^3 ha^{-1}). Yield decreased with increasing deficit, being up to 25% less for T70 compared with ND. However, the T70 ORDIL treatment attained the greatest average irrigation water productivity (5.30, 4.32 and 2.53 kg m^{-3} for 2015, 2016 and 2017, respectively) and the lowest average water footprint (349, 416 and 631 m^3 Mg^{-1}), while ND exhibited the greatest total water footprint in the process (18%, 14% and 4% greater than T70).

1. Introduction

Irrigated agriculture is essential to ensure increasing food production needed to meet the current and future needs of the world population (Singh and Panda, 2012). Moreover, the continuous reduction in the availability of water for agricultural uses due to the priority of other uses, including environmental services, together with the decrease in resources as a result of global warming, and the continued increase in energy costs require improved efficiency in the use of water and energy in agriculture so that it can be a sustainable activity (FAO, 2016; MINETUR, 2015).

Moreover, the population's increasing concern about the environment has triggered the development of indicators able to measure the impact of productive sectors on natural resources. The water footprint (WF) (Hoekstra et al., 2009) determines the amount of water required to produce a certain good or service, and may be improved by methodologies able to increase water-use efficiency, defined as kg of crop production per volume (m^3) of water received by the crop (agronomic water productivity, WP) Fernández et al. (2020).

Worldwide, in vegetable cultivation, garlic (*Allium sativum* L.) is ranked 14th in dedicated area (FAO, 2016). In Spain, Castilla-La Mancha (CLM) is the largest producing region with 58% of the national total production (MAGRAMA, 2016). Garlic is a crop of great economic and social significance in CLM, where there is a unique purple garlic cultivar, which is promoted under the protected geographical indication "Ajo morado de Las Pedroñeras" (PGIAMP) (Fig. 1). A protected geographical indication is a quality distinction granted by the European Union that links the quality of products to their geographical location. The PGIAMP consists of approximately 350,000 ha of irrigated land distributed over 26,200 km^2, with 5500 ha $year^{-1}$ dedicated to purple garlic (IGPAMP, 2016) (Fig. 1). Purple garlic occupies 1.6% of irrigated area in CLM and generates an annual income of 75 million Euros, although the average

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yield (8990 kg ha^{-1}) is approximately half that of other varieties in CLM and Spain (MAGRAMA, 2016). In semi-arid areas like CLM, garlic requires irrigation depths of around 310 mm year^{-1}.

As with other horticultural crops with high added value and high labor needs (in production and post-harvest), the cultivation of garlic can positively contribute to the local economy of rural areas, but needs tools to help in decision-making for more efficient use of water and other means of production to make it more sustainable.

Regulated Deficit Irrigation (RDI) techniques may allow water productivity to be increased (English, 1990). This methodology is based on the different sensitivities of crops to water deficit throughout their growth stages. Thus, the effect of water stress on the yield of garlic and other crops is conditioned by both the intensity of the deficit and the stage in which it occurs. In addition, other parameters such as the size of the fruits (bulbs, berries, grains, *etc.*) or sugar concentration may be affected. (Anirudh and Zora, 2012; Fabeiro et al., 2003; Hanson et al., 2003; Marouelli et al., 2002; Martín De Santa Olalla et al., 2004; Villalobos et al., 2004).

The optimized regulated deficit irrigation (ORDI) methodology maximizes the yield of annual crops when the objective is to reach a certain deficit for the whole growing period (Domínguez et al., 2012c), or when the amount of available irrigation water is limited and lower than the requirements of the crop (ORDIL) (Leite et al., 2015b). This methodology was adapted by the model for the economic optimization of irrigation water (MOPECO) (Ortega et al., 2004), which was conceived to optimize the gross margin (GM) of irrigated farms located in water scarce areas. It distributes the available water among the different crops on the farm, by establishing the irrigation schedules for each of the crops, simulating crop yields by using the equation proposed by Stewart et al. (1977). MOPECO has been calibrated for the main extensive annual crops in CLM and other areas of the world (Carvalho et al., 2014; Domínguez et al., 2012a, 2012b, 2013; Leite et al., 2015a; Léllis et al., 2017; López-Urrea et al., 2020; Martínez-Romero et al., 2019).

The aim of this study was to evaluate the effectiveness of ORDIL methodology under real management conditions for three different limited volumes of available irrigation water, and determine its effect on yield, agronomic water productivity, and water footprint of a garlic crop under the semi-arid climatic conditions in CLM.

2. Material and methods

2.1. Description of irrigated lands in Castilla-La Mancha

Agriculture in CLM occupies an area of 3,773,029 ha, of which 557,851 ha are irrigated lands (MAPA, 2018), mainly with sprinkler and drip irrigation systems. The use of irrigation in the area is the result of low average annual precipitation from around 400 mm year^{-1} and high reference evapotranspiration of over 1100 mm year^{-1}, characterizing the area as semi-arid (Domínguez and de Juan, 2008). Approximately 70% of the irrigable area in CLM is located close to groundwater sources, given that most surface water resources are used in other bordering regions (Fig. 1). The most common crops in these areas are grapes, cereals, garlic, onion, melon, watermelon, pepper, and others such as sunflower, potato and alfalfa.

2.2. Field experiments

The field trials were conducted in 2015, 2016 and 2017 at the Integrated Center for Vocational Training in Aguas Nuevas (longitude 1° 53’ 58’’ W, latitude 38° 56’ 42’’ N, at an altitude of 695 m above sea level) (Fig. 1). The experiment was conducted using a purple garlic cultivar, namely “Ajo Morado de las Pedroñeras” (IGPAMP, 2016), with a sowing rate of 0.08 m of plant spacing and 0.50 m of row width (250, 000 plants ha^{-1}). Garlic was manually planted, and the cloves of garlic were covered by small ridges.

According to the Köppen classification, the climate is BSk (semi-arid cold climate). The average annual temperature is around 14ºC (4ºC in January and 24ºC in July), and the accumulated rainfall is between 200 and 400 mm year^{-1} which is recorded mainly in spring and autumn. The average annual reference evapotranspiration is around 1300 mm year^{-1} (Penman-Monteith FAO method), varying between 30 and 220 mm month^{-1} in January and July, respectively.

At the beginning of the initial growing season, 25 soil samples

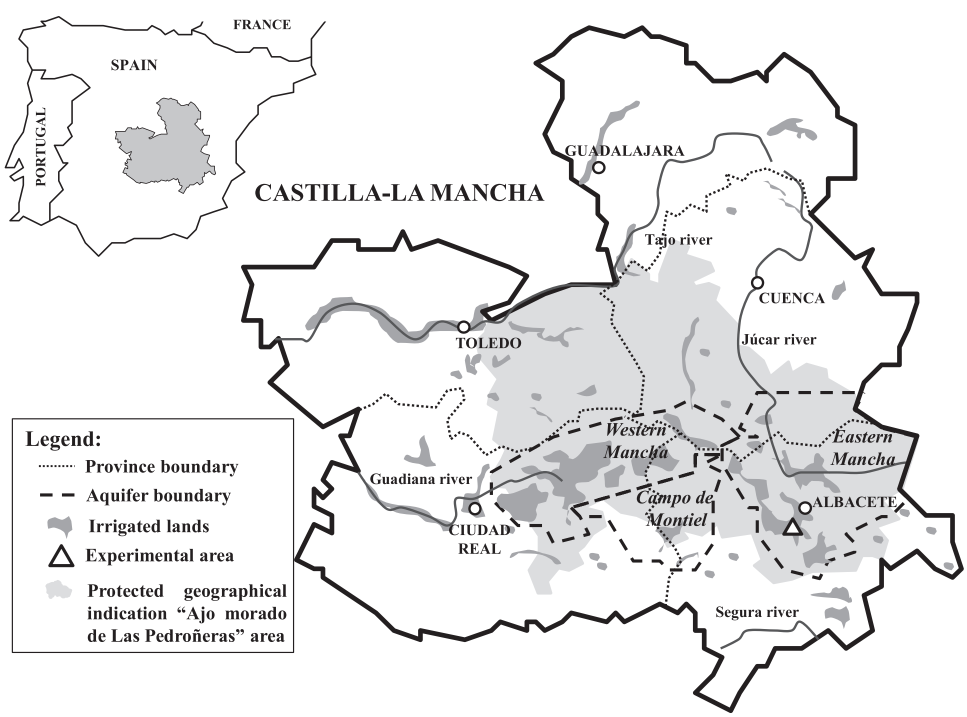

Fig. 1. Irrigated lands and groundwater resources in Castilla-La Mancha, and location of the experimental farm.

totaling approximately 5 kg were taken from the plot in a zig-zag pattern using an auger inclined about 20º. Sampling depth was 0.4 m, were a compacted layer limits the soil depth, with no observable horizonation for retrieved samples for this portion of the profile. A subsample was analyzed to determine the physicochemical properties. Soil water retention characteristics were evaluated with undisturbed samples using pressure plate apparatus (Vanderlinden et al., 2003; Carducci et al., 2012). Volumetric water contents were determined for a range of water potentials: 0.033, 0.05, 0.1, 0.2, 0.5, 0.8, 1.2 and 1.5 MPa. Field bulk density was also determined from 5 zig-zag samples (0 – 0.4 m) were taken using a 5.0 cm diameter cylinder with 98.2 cm^3 of internal volume, drying in the oven at 105 °C for 48 h and subsequently weighing to determine soil mass (Blake and Hartge, 1986). The soil is classified as Petrocalcic-Xerochrepts (USDA-NCRS, 2006) with a clay-loam texture (35% sand, 35% silt and 30% clay) above the petrocalcic horizon that has a mean depth of 0.4 m. The soil is Alkaline (pH = 8.7) with a high level of active carbonates (21.7–25.3%), a soil organic matter content of 24 g kg^{-1}, a total nitrogen content of 1.4–1.6 g kg^{-1}, and 131–145 mg kg^{-1} of extractable potassium. The bulk density, water content at field capacity and at the wilting point are 1.410 g cm^{-3}, 0.372 m^3 m^{-3} and 0.244 m^3 m^{-3} respectively.

The experimental area of 4730 m^2 consisted of four 51 m x 18 m plots (Fig. 2). Each year, 2.5 m x 18 m subplots with 3 m buffers on either end were laid out with one of the four subdivided plots (Fig. 3).

Five irrigation treatments were implemented: no deficit "ND" (control), which was full irrigated according to calculated ET_c, and four with different volumes of available irrigation water, corresponding to 100% (T100), 90% (T90), 80% (T80), and 70% (T70) of garlic net irrigation requirements in the weather conditions of the intermediate typical meteorological year (Domínguez et al., 2013).

Given the few studies in the area, the Kc values were calibrated for the "Ajo Morado de las Pedroñeras" variety during 2015 using the water balance in the soil obtained by the soil moisture sensors and validated with the records obtained by a weighing mini lysimeter (Nicolás-Cuevas et al., 2020) whose effective dimensions were 1.00 × 0.50 × 0.40 m, installed in the middle of one of the ND treatment subplots during 2016 (Figs. 2 and 3). So, the lysimeter was fully integrated into the plot, maintaining the same plant density both inside and outside, and the distance to the four edges of the plot was 16.5 m and 34 m towards the 18 m border, and 8.5 m and 8.5 m towards the 51 m border of the plot.

All the treatments were randomized with 4 repetitions for T90, T80, T70 and 3 repetitions for T100 and ND (Fig. 3). These last two treatments should be the same under the conditions of intermediate and humid years, and only in dry years should they be different at the end of the cropping period, when the amount of irrigation water of T100 is depleted.

The water was applied by a drip irrigation system in which the spacing between drip tape was 0.5 × 0.5 m, the drip lines were located in the middle of the crop rows and it was equipped with pressure compensated drip emitters providing 3.8 L h^{-1} of nominal discharge. An irrigation evaluation was carried out at the beginning of each phenological development stage, and the distribution uniformity was 98% on average. Five high accuracy (± 2%) flowmeters (one per treatment) were used to monitor the volume of water applied in each irrigation event and for each irrigation treatment level. In this experiment, the net irrigation water was considered to be the total amount of gross irrigation water supplied by the irrigation system, as the drift and evaporation losses may be considered negligible (Ortíz et al., 2009; Tarjuelo et al., 2000).

Fertilizer application rates were determined according to the results of the analysis of the soil samples collected at the beginning of the experiment and to the expected yield simulated by MOPECO for a typical meteorological year (TMY). Fertilizers were applied twice, one as basal (in solid form, before sowing day and incorporated by tillage), which were on January 14 in 2015 and 2016, and on January 16 in 2017 and the second top dressing, injected by the drip system during the crop development growth stage (Table 1). In top dressing, each application of fertirrigation was performed 14 days apart, by applying about 17 kg N ha^{-1} per event until the full dose was reached for the calculated requirements of each treatment.

During the field trials, daily irrigation scheduling was performed, using the simplified water balance methodology in the root zone (Allen et al., 1998; Pereira and Allen, 1999), which is that used by MOPECO (Domínguez et al., 2011). The simulated soil water balance was monitored and compared with the real one provided by the soil moisture sensors until harvest. The climatic data were collected from the

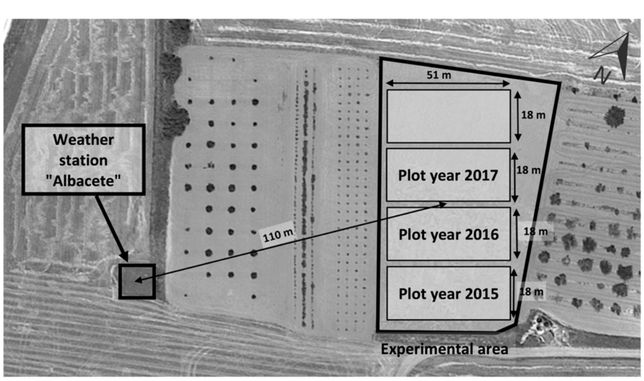

Fig. 2. Plot distribution over the three experimental years.
Source: Prepared by the authors, based on Google maps© 2018.

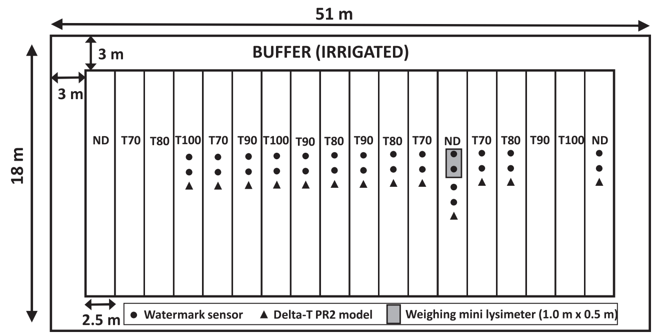

Fig. 3. Distribution of the different treatments in the experimental plot and location of the soil moisture sensors. Note: The weighing mini lysimeter was installed in the plot occupied in 2016. ND: No deficit treatment; T100, T90, T80 and T70: Treatments corresponding to 100% 90%, 80% and 70%, respectively, of garlic net irrigation requirements in the weather conditions of the intermediate typical meteorological year.

Table 1
Fertilization received by the different treatments.

Date	Dressing	Dose (kg ha^{-1})
01/09/15	Basal dressing	50.0 N – 101.8 P_2O_5 – 0.0 K_2O
03/15/15[a]	Top dressing	ND and T100: 49.6.0 N; T90: 33.6 N; T80: 17.6 N; T70: 1.5 N
01/12/16	Basal dressing	50.0 N – 101.8 P_2O_5 – 0.0 K_2O
03/07/16[a]	Top dressing	ND and T100: 49.6 N; T90: 29.5 N; T80: 14.2.0 N; T70: 0.0 N
01/13/17	Basal dressing	40.0 N – 100.5 P_2O_5 – 156.8 K_2O
03/20/17[a]	Top dressing	ND and T100: 44.0 N; T90: 24.0 N; T80: 10.0 N; T70: 0.0 N

ND: No deficit treatment; T100, T90, T80 and T70 are 100%, 90%, 80% and 70% of garlic net irrigation requirements in the weather conditions of the intermediate typical meteorological year. Basal dressing, in solid form. Top dressing injected by the drip system.

[a] Data of first application

"Albacete" weather station located at the experimental farm (Fig. 2), which belongs to the national network of the agroclimatic information system for irrigation (SIAR, 2018) managed by the Spanish Ministry of Agriculture, Fishery and Food (MAPA, Ministerio de Agricultura, Pesca y Alimentación).

In three of the four plot replicates of T90, T80 and T70, and in two of the three plot replicates of ND and T100, we installed sensors for monitoring the soil moisture content during the experiments (Fig. 3): Watermark© tensiometer sensors at 20 and 40 cm depth, and Delta-T PR2© volumetric soil water sensors at 10, 20, 30, and 40 cm depth. These sensors were placed in representative areas of the experimental plots, 20 cm from drip lines and 5 cm from the crop row, approximately.

This experiment was also used to measure different physiological parameters during the cropping season (Sánchez-Virosta et al., 2020). To determine the yield at harvest, two samples of 2 m of plants representative of the plot were harvested from each repetition (2 m x 0.5 m = 1 m^2). 36 samples in total were taken at the two central rows, which were not necessarily adjacent. After 15 days of drying at outdoor temperature, as done in commercial garlic, bulbs were weighed and final yields were estimated (kg m^{-2}).

2.3. Soil water balance

The daily water balance in the soil simulated by MOPECO to determine the irrigation schedules was validated after each irrigation event using the readings of the Watermark sensors installed in the subplots (Fig. 3). Water potentials measured using the Watermark sensors were converted to volumetric soil water content based on water desorption curves developed with disturbed soil samples (or intact soil cores) at potentials ranging from 33 to 1500 kPa using pressure plate apparatus (Léllis, 2017).

$$ET_c = Z_r \bullet (\theta_i - \theta_j) + \Delta Z_r \bullet (\theta'_j) + I_N + P_e - P_r \quad (1)$$

where: ET_c: Crop evapotranspiration accumulated from day i to j (mm); Z_r: Rooting depth (mm); $\theta_i - \theta_j$: Water content in the soil on day i to j (mm mm^{-1}); ΔZ_r: root growth (mm); θ'_j: Water content in the portion of soil incorporated in the balance after root growth; In: Irrigation accumulated (mm); Pe: Effective rainfall accumulated (mm); P_r: Percolation accumulated (mm). Effective rainfall (Pe) is the infiltrated precipitation in the soil, which was estimated using the USDA "curve number 2" methodology (SCS, 1972; NRCS, 2004). Deep percolation was estimated by the model depending on the characteristics of the soil and the root growth. In 2016, an experimental continuous weighing mini lysimeter (Figs. 3 and 4) was also used to validate the K_c values proposed for the area by Fabeiro et al. (2003), who determined these without performing soil moisture measurements. The weights record is carried out by means of 4 load cells located in the corners of the protection frame, with a maximum capacity of 150 kg each and a sensitivity of 30 g. The drainage water is controlled by another load cell connected to a 4000 ml capacity tank with a sensitivity of 10 g. Weight readings are taken every 10 s, storing averages per minute (Nicolás-Cuevas et al., 2020). The average values are determined every 30 min. These 48 values per day are taken to determine the cumulative balance values. In 2016, ET_c was determined as follows:

$$ET_c = (1/\rho_w) * (Z_r/V) * (\omega_i - \omega_j) + IN + Pe - Pr \quad (2)$$

where: ρ_w: density of water (assumed 1000 kg m^{-3}); Z_r: rooting depth (mm); V: Volume of the lysimeter; $\omega_i - \omega_j$: Variation of the weight of the lysimeter (kg); IN: Irrigation accumulated (mm); Pe: Effective rainfall accumulated (mm); Pr: Percolation accumulated (mm); ET_c: Accumulated crop evapotranspiration (mm).

By using the ET_c values, approximate values of crop coefficient (K_c) (Eq. 3) were estimated and compared with values available in the literature.

Fig. 4. Installation of the continuous weighing mini lysimeter.

$$K_c = ET_c/ET_o \quad (3)$$

where: ET_{cij}: Crop evapotranspiration accumulated from day i to j (mm); ET_{oij}: Reference evapotranspiration accumulated from day i to j (mm) (Allen et al., 1998); and K_c: crop coefficient.

2.4. Determination of the typical meteorological years (TMYs)

A typical meteorological year (TMY) (Hall et al., 1978) represents the conditions considered "typical" over a long period and was adapted by Domínguez et al. (2013) for forecasting irrigation schedules, being used also by other authors (Martínez-Romero et al., 2019). A TMY consists of 12 months selected from individual years and concatenated to form a complete year with daily values. In this study, the TMYs (dry, intermediate, and wet) determined by Leite et al. (2015a) were used, which were calculated by using the 1951–2004 climatic series generated by the "Los Llanos" weather station located 3 km from the experimental area (Table 2) (Pardo et al., 2020).

TMY daily data and the daily growing degree days (GDD) determined by the double triangulation method proposed by Sevacherian et al. (1997) were used in order to predict the duration of garlic growth stages.

Table 2
Main values of the typical meteorological years in Albacete.

	ET_o (mm $year^{-1}$)	P (mm $year^{-1}$)
TMY-dry	1282	222
TMY-intermediate	1212	289
TMY-wet	1182	409

TMY: Typical meteorological year; ET_o: reference evapotranspiration; P: Precipitation.

2.5. Optimized regulated deficit irrigation for limited volumes of irrigation water (ORDIL)

MOPECO uses the equation proposed by Stewart et al. (1977) to estimate crop yield (Y_a) as a function of the actual *versus* maximum evapotranspiration ratio (ET_a/ET_c) in the different growth stages, the potential yield in the area (Y_m) and the crop yield response factor (K_y) by growing stage (in the case of garlic: vegetative period, yield formation, and ripening) (Doorenbos and Kassam, 1979). If the soil water content is higher than the fraction of the total available water (TAW) that a crop can extract without suffering water stress due to water deficit, then the crop is considered not to be affected by water deficit conditions and Y_a will be equal to Y_m. Under water deficit conditions, ETa is calculated according to Allen et al. (1998) (Domínguez et al., 2011) and Y_a will be lower than Y_m.

$$Y_a = Y_m \prod_{k=1}^{3} \left(1\text{-}K_{y_k}\left(1\text{-}\frac{ET_{a_k}}{ET_{c_k}}\right)\right) \quad (4)$$

MOPECO was calibrated for this crop in the area by Domínguez et al. (2013) using field tests carried out by López-Urrea et al. (2002, 2003) (Table 3). The BBCH-scale (Bleiholder et al., 2001) was used to determine the phenological growth stages of garlic. Daily ET_c was calculated by multiplying daily crop coefficient (K_c) by daily reference evapotranspiration (ET_o) values determined by the FAO-Penman Monteith method (Allen et al., 1998). Daily ET_a under water deficit conditions was calculated using the equation implemented by Domínguez et al. (2013) with the depletion fraction below which water stress occurs, *p*, as a function of ET_c evaluated using the exponential function of Danuso et al. (1995), which requires a daily balance of water in the soil (Domínguez et al., 2011).

According to Danuso et al. (1995) the value of p is a daily variable value, which depends on the type of crop and the ET_o, *p* was calculated as:

$$p = \frac{A}{1 + B\bullet} e^{(-C\bullet ET_c)}{}_m \quad (5)$$

by using crop group 1 where: A = 0.85, B = 1.585 and C = 0.405.

The net irrigation requirements of a garlic crop under the TMY-intermediate conditions were estimated by using the MOPECO model. This volume of water was considered as the reference, and was assigned to the T100 treatment. The three ORDIL strategies associated with available irrigation water volumes corresponded to 90% (T90), 80% (T80), and 70% (T70) of net irrigation requirements (T100). In addition, one treatment under no deficit conditions (ND) was implemented.

The ND and the T100 treatments received the same irrigation schedule up to harvest or until the depletion of the amount of irrigation water available for the T100 treatment in dryer years than the TMY. The irrigation schedules of the three ORDIL treatments followed the methodology established by Leite et al. (2015b) (Fig. 5). In order to maximize yield, the methodology determines the deficit in terms of ET_a/ET_c to be applied to the crop at each K_y stage and estimates the amount of irrigation water required to reach that level of deficit, using the TMY climatic data and the MOPECO simulation model (1st optimization). Domínguez et al. (2013) calibrated the K_y values in the area (Table 3). The maximum difference between ET_a/ET_c rates of two consecutive K_y stages was determined as 0.40, while minimum ET_a/ET_c rate for K_y (i') was ≥ 0.8 in order to avoid nascence and/or establishment problems during the K_c (I) stage (Domínguez et al., 2012a, 2012b, 2013). During the first K_y stage, the objective is to apply the irrigation schedule that reaches the ET_a/ET_c objective determined by the methodology for that stage under real management conditions. At the end of the first stage, the ET_a/ET_c reached by the crop (estimated by MOPECO) should be similar to the target (in the first stage, there is enough irrigation water) or higher (if the climatic conditions and/or the soil water availability do not allow that level of deficit to be generated). However, the amount of irrigation water applied to the crop will likely be different to that forecast by the model. Consequently, after the first K_y stage, the methodology determines updated ET_a/ET_c targets for the following K_y stages, considering the actual remaining irrigation water (2nd optimization). The same methodology is followed at the end of each K_y stage. During the optimizations, a portion of irrigation water is saved for the last stage "K_y (iii)" (that determined in the 2nd optimization) in order to avoid the early total depletion of irrigation water during K_y (iii). Moreover, the TMY used may be changed to the wet, intermediate or dry series, depending on the progression of the climatic conditions, in order to better fit the optimizations to the characteristics of the actual year.

2.6. Agronomic and irrigation water productivity

For each irrigation strategy (ND, T100, T90, T80 and T70), the irrigation water productivity (WP_I, yield per unit of gross irrigation water applied to the crop) was analyzed as the main factor affecting the agricultural activity in the area (Rodrigues and Pereira, 2009). Agronomic water productivity (WP, yield per unit of gross irrigation and effective rainfall) was also analyzed.

$$WP_I = \frac{Y_a}{TWG} \quad (6)$$

$$WP = \frac{Y_a}{TW} \quad (7)$$

where: WP_I: irrigation water productivity expressed as mass of crop production per unit of volume of gross irrigation water supplied to the crop (kg m^{-3}); Y_a: actual yield (kg ha^{-1}); TWG: total gross irrigation water (m^3 ha^{-1}); WP: agronomic water productivity expressed as mass of crop production per unit of volume of total water received by the crop (kg m^{-3}); TW: total water (gross irrigation water + effective rainfall) (m^3 ha^{-1}).

2.7. Water footprint

The water footprint of the process for cropping garlic ($WF_{process}$) was

Table 3
Parameters for the simulation of garlic in Castilla-La Mancha region using MOPECO.

Stage	(*)K_c	GDD±SD (°C)	Stage	K_y	GDD±SD (°C)	Other parameters	
I	0.40	468.50 ± 50.4	**i'**	0.45	468.0 ± 50.4	**ET group**	3
II	0.40–1.00	1021.50 ± 82.0	**i''**	0.45	1021.50 ± 82.0	**Y_m (kg ha^{-1})**	9.000
III	1.00	1615.20 ± 112.3	**ii**	0.75	1615.20 ± 112.3	**T_L (°C)**	2
IV	1.00–0.60	2044.00 ± 137.9	**iii**	0.30	2044.00 ± 137.9	**T_U (°C)**	28

(*) K_c values used by Fabeiro et al. (2003) based on those proposed by FAO 56 (Allen et al., 1998) and fitted to the regional conditions; K_c: crop coefficients; K_c (I): initial; K_c (II): crop development; K_c (III): mid-season; K_c (IV): late season; GDD: accumulated growing-degree-days (Domínguez et al., 2013); SD: standard deviation; K_y: crop yield response factor; K_y (i): vegetative period. This stage is divided into two substages: K_y (i) "establishment", which coincides with K_c (I), and K_y (i') "vegetative development" from the end of K_c (I) up to beginning of next K_y stage; K_y (ii): yield formation; K_y (iii): ripening; ET group, which conditions the daily value of the fraction of the total available water (TAW) that a crop can extract without suffering water stress (Danuso et al., 1995); Y_m: potential crop yield fitted to the cultivars used in this study; T_U: upper developmental threshold temperature or the temperature at and above which the rate of development begins to decrease; T_L: lower developmental threshold temperature or the temperature at and below which development stops.

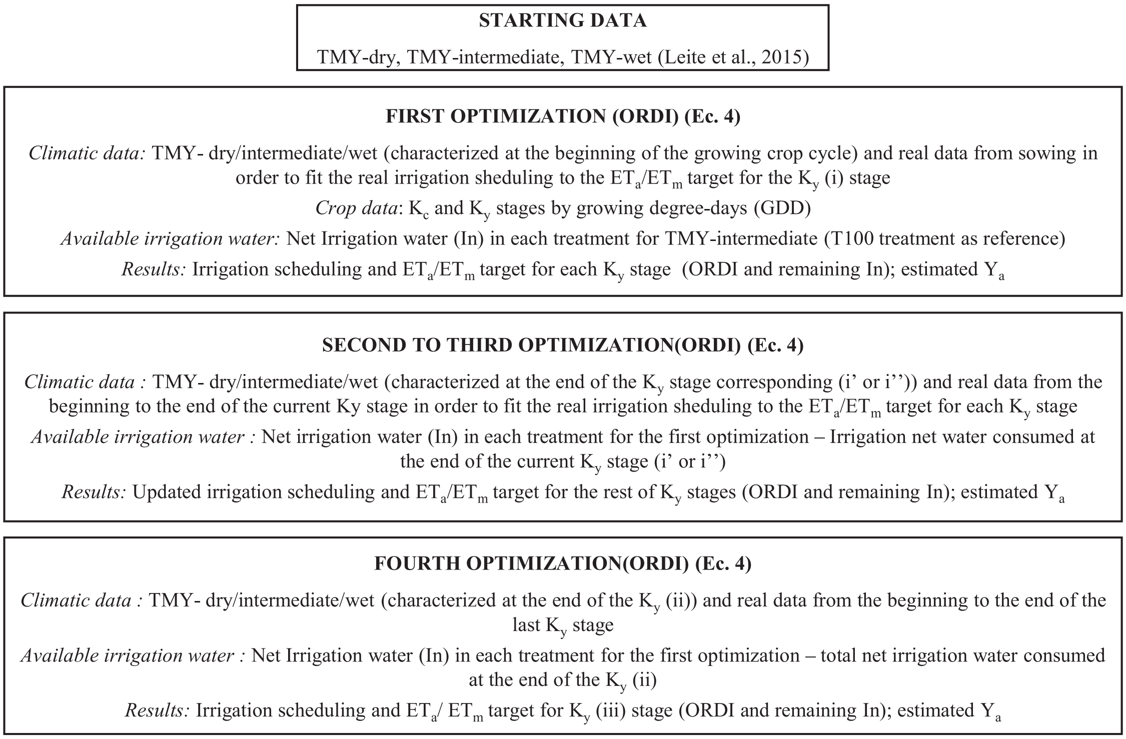

Fig. 5. Procedure for determining the optimized regulated deficit irrigation schedule for a limited volume of irrigation water. TMY: typical meteorological year; ORDIL: optimized regulated deficit irrigation for limited volumes of irrigation water; ET_a and ET_c are the actual and maximum accumulated crop evapotranspiration for the whole growing cycle; K_y is the crop yield response factor by growing stage (K_y (i) vegetative period (K_y (i') establishment, K_y (i'') vegetative development), K_y (ii) yield formation, K_y (iii) ripening; K_c: crop coefficients; K_c (I): initial; K_c (II): crop development; K_c (III): mid-season; K_c (IV): late season); Y_a the actual crop yield.

analyzed as the sum of the blue (WF_{blue}), green (WF_{green}) and grey (WF_{grey}) components. The blue water footprint (WF_{blue}) refers to consumption of blue water resources (surface and groundwater) along the supply chain of a product. "Consumption" refers to loss of water from the available ground-surface water body in a catchment area, which happens when water evaporates, returns to another catchment area or the sea, or is incorporated into a product. The green water footprint (WF_{green}) refers to consumption of green water resources (rainwater stored in the soil as soil moisture). This part of the precipitation eventually evaporates or transpires through plants. The grey water footprint (WF_{grey}) is an indicator of the degree of freshwater pollution that can be associated with the process, and is defined as the volume of fresh water required to assimilate the load of pollutants based on existing ambient water quality standards. In agriculture, it is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards (Franke et al., 2013; Hoekstra et al., 2009; Mekonnen and Hoekstra, 2010).

$$WF_{process} = WF_{blue} + WF_{green} + WF_{grey} \tag{8}$$

$$WF_{blue} = \frac{ETa_{blue}}{Y_a} \tag{9}$$

$$WF_{green} = \frac{ETa_{green}}{Y_a} \tag{10}$$

$$WF_{grey} = \frac{\frac{\alpha \quad AR}{C_{maximum} - C_{natural}}}{Y_a} \tag{11}$$

where: WF: water footprint expressed as m^3 of TW per Mg of crop production (m^3 Mg^{-1}); blue: net irrigation water (m^3 ha^{-1}); ET_a: actual evapotranspiration (m^3 ha^{-1}); Y_a: actual yield (Mg ha^{-1}); green: water in natural processes (m^3 ha^{-1}); grey: irrigation water to reduce the concentration of pollutants (m^3 ha^{-1}). The legislation in the area considers nitrates as the elements that define fresh and groundwater pollution; α: fraction of applied chemical substances reaching freshwater bodies (dimensionless), in this case 0.08 (Franke et al., 2013); AR: chemical substances applied on or in the soil (Mg ha^{-1}), with the amount of N applied to the treatments being used in this case (Table 1); $C_{maximum}$: maximum acceptable concentration (Mg m^{-3}), in this case $50 \cdot 10^{-6}$ Mg L^{-1} (CEE, 1991); $C_{natural}$: natural concentration in the receiving water body (that would occur if there were no human disturbances) (kg m^{-3}), in this case $37.6 \cdot 10^{-6}$ Mg L^{-1} (CHJ, 2017)).

2.8. Statistical analysis

Analysis of variance was carried out each study year for a completely randomized design, with year assumed to be a dependent variable. Differences were considered significant for $0.01 < p < 0.05$ or highly significant when $p < 0.01$ using the Duncan's test (Westfall and Stanley, 1993). The standard deviation (SD) and the coefficient of variation (CV) were used to analyze the variability of the collected samples within the treatments. For the relationship between observed and simulated results the root mean square error (RMSE) and the normalized root mean square error (NRMSE) were performed.

3. Results and discussion

3.1. Phenological monitoring

Length of growth stages was similar for the three years of the trial (Table 4), although slightly greater than that proposed by Domínguez et al. (2013). Accumulated GDD for the complete crop cycle by these authors was determined to be (PGIAMP) 2044 ± 137 ºC, between 5% and 11% lower than the GDD calculated for the years of the current study (Table 3). In 2016, the first two stages of K_c occurred with a lower

Table 4
Duration of K_c and K_y garlic stages in days and accumulated growing-degree-days.

Stages	2015		2016		2017	
	DFP (days)	GDD (°C)	DFP (days)	GDD (°C)	DFP (days)	GDD (°C)
K_c (I) / K_y (i')	73	470.6	54	374.2	61	444.8
K_c (II) / K_y (i'')	115	1027.8	110	931.9	111	1014.3
K_c (III) / K_y (ii)	147	1623.4	156	1716.9	144	1623.9
K_c (IV) / K_y (iii)	175	2259.1	184	2364.4	163	2122.1

K_c: crop coefficients; K_c (I): initial; K_c (II): crop development; K_c (III): mid-season; K_c (IV): late season; K_y: crop yield response factor; K_y (i): vegetative period. This stage is divided into two substages: K_y (i) "establishment", which coincides with K_c (I), and K_y (i) "vegetative development" from the end of K_c (I) up to beginning of next K_y stage; K_y (ii): yield formation; K_y (iii): ripening. DFP: Days from planting; GDD: accumulated growing-degree-days.

accumulation of GDD compared to the values proposed by Domínguez et al. (2013) and with respect to the observed GDD in 2015 and 2017. The climatic conditions of 2016 probably contributed to these observed results, given that the average temperatures were above average for the first stage, being above the threshold of optimal temperatures for the development of garlic (18–20 °C). This caused an advance in the growth of the crop in the early stages, as has been observed by other authors (del Pozo et al., 1997; del Pozo and González, 2005; Espagnacq et al., 1987; Gorini, 1977; Macêdo et al., 2006; Pooler and Simon, 1993). On the other hand, the crop cycle was lengthened in the following stages, accumulating more GDD compared with the other study years, lengthening the growth stage by 9 and 21 days in relation to 2015 and 2017, respectively. Although 2016 had the lowest amount of precipitation, it was also the one in which the crop received the greatest water depth (precipitation and irrigation) during the last stage, which could have contributed to increasing the duration of the phenological stage and prolonging attainment of physiological maturity. For the same year, no significant differences between treatments were observed on the length of the growth stages. This may be because garlic could withstand well the moderate water deficit imposed by ORDIL and recover physiological normal development, denoting that previous water limitation did not produced chronic damage (Sánchez-Virosta et al., 2020).

3.2. Soil water balance

In 2015, for the climatic conditions of the TMY-intermediate (Table 2) and using the K_c coefficients proposed by Fabeiro et al. (2003), the net growing season irrigation requirements of garlic were established as 3400 m^3 ha^{-1} (T100). However, at the beginning of the irrigation period the readings of the Watermark sensors indicated a higher moisture content than that estimated by the model, so it was considered that the K_c values were possibly overestimated and that the crop was being over-irrigated. Therefore, to achieve a deficit in the ORDIL treatments, the irrigation schedules of the ND treatments were determined using the soil water potential measured with the Watermark sensors. Irrigation was scheduled when the average readings of the sensors located in the soil profile occupied by the roots attained a water potential between − 40 and − 60 cbar. Soil water potential typically declined (became less negative) to approximately − 20 cbar after irrigation application (*i.e.*, around 28 mm during the period of higher irrigation requirements). In order to follow the ORDIL methodology as closely as possible, in 2015 the irrigation schedules of the deficit treatments were carried out by decreasing a certain percentage the amount of water supplied to ND treatment. This percentage was similar to the ET_a/ET_c objective calculated by ORDIL for the initial scenario (irrigation water availability for T100 = 3400 m^3 ha^{-1}; and K_c calibrated by Fabeiro et al., 2003).

By using the soil moisture sensor readings obtained in 2015 for the ND treatment, the K_c values for garlic were calibrated for that year (Eq. 2). These values were validated in 2016 with the soil moisture readings registered by the sensors installed in the experimental plot and those provided by one continuous weighing mini lysimeter (Eq. 1) (Fig. 6). The final K_c values were 0.25–0.95–0.40 (Table 5), which were obtained after fitting the cloud of points formed by the calculated K_c segment curve (Eq. 2) to the classical shape of the K_c progression proposed by Allen et al. (1998) (Fig. 6). Although they were obtained under non-standard climatic conditions, they are lower than those generally recommended by FAO (0.70–1.00–0.70), and those used in previous works in the area (0.40–1.00–0.60) (Fabeiro et al., 2003) (Table 3).

where: "K_c adjusted based on sensors data" line was obtained after fitting the cloud of points formed by the calculated K_c values to the classical shape of the K_c progression by using the average values of the soil moisture sensors and the lysimeter readings.

Although strictly speaking the climatic and management conditions were not the same., other authors (Ayars, 2008; Bryla et al., 2010; Villalobos et al., 2004; Pereira et al., 2021) proposed as maximum K_c values those ranging from 1.00 to 1.20 in semi-arid areas of California (USA) and Córdoba (Spain). Although the values in Table 5 are lower than those proposed by FAO under standard climatic conditions (0.40 and 0.70 for initial and final stages, respectively) (Allen et al., 1998; Pereira et al., 2021), Bryla et al. (2010) also stated low values in late season (0.16). So, Pereira et al. (2021) indicated that discrepancies in the K_c values at the end-season of certain crops as garlic, may be caused by the crop management, the crop cultivar, and environmental conditions prior to harvesting, which influence on the duration of senescence. The lower values determined in this study may have been partially affected by the irrigation system used (drip irrigation, and not sprinkling), by reducing the evaporative fraction of ET_o, especially in the stages of establishment and vegetative development. In any event, the values obtained are better adjusted to the test conditions than to the values indicated by FAO for garlic. By using the proposed K_c values (Table 5), MOPECO simulated the evolution of the water content in the soil similarly to the values estimated by the Watermark sensors. As an example, Fig. 7 shows these values for the ND treatment in 2016.

The Watermark sensors were installed on Julian day 26, 12 days after planting, and during the first days they marked high water contents values since they were installed, saturating the soil in contact with them. In the following days, the soil water contents using sensor measurements based on MOPECO simulations exhibited the same trend and showed similar values. On day 150, due to a fault in the pumping system, it was not possible to irrigate for a week and the crop was stressed due to water deficit, as shown by both representations of soil moisture as the available water line of the soil is below 1-p, which indicates that the fraction of total available water (TAW) had been exhausted, so theoretically the crop entered into stress due to water deficit (Allen et al., 1998). One week before the harvest, irrigation was terminated to facilitate the drying of the bulbs, which is reflected in the decrease in soil moisture at the end of the cycle.

3.3. Management of irrigation water

For the climatic conditions of the TMY-intermediate (Table 2) and using the crop parameters in Table 3 and corrected K_c values (Table 5), the calculated reference net seasonal irrigation requirements of garlic (T100) were 2750 m^3 ha^{-1}. This value was used to calculate the amount of irrigation water available for the ORDIL strategies: T90 = 2475 m^3 ha^{-1}; T80 = 2200 m^3 ha^{-1}; and T70 = 1925 m^3 ha^{-1} in 2016 and 2017 (Table 6).

For the three study years, accumulated ET_o at the end of the growing season was greater than that corresponding to TMY-intermediate (between 10% and 15%) (Fig. 8). This outcome was also observed by Pardo

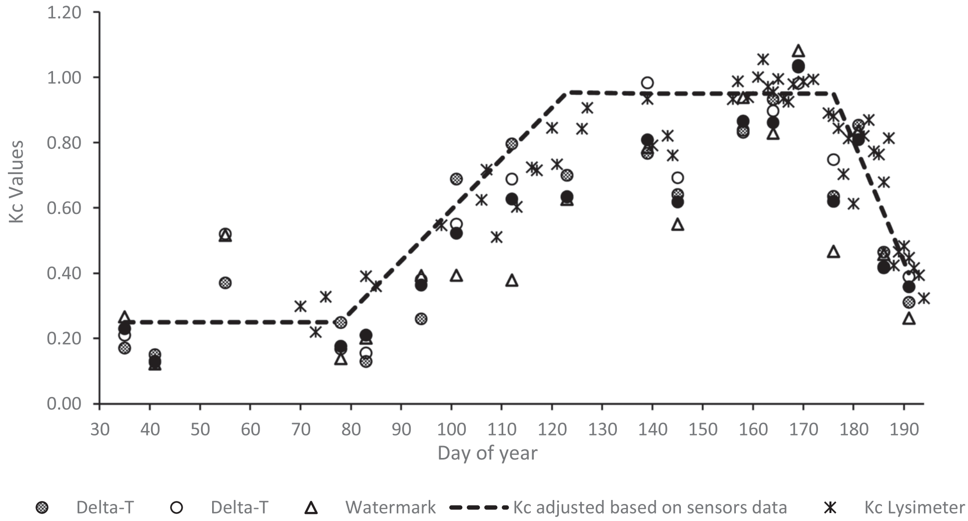

Fig. 6. Crop coefficients (K_c) values calculated from the records of the soil moisture sensors (in no deficit treatments) and the weighing mini lysimeter. Year 2016.

Table 5
Crop coefficient (K_c) values under the weather conditions of Albacete using drip irrigation.

	Initial stage	Crop development	Mid-season	Late season
Crop coefficients (K_c)	0.25	0.25–0.95	0.95	0.95–0.40

et al. (2020) during the same years for barley. The accumulated rainfall in 2017 was slightly (5%) greater than that approximated by the TMY-intermediate. Nevertheless, accumulated precipitation between 71 and 73 Julian days in 2017 was 58 mm, which resulted in the deep percolation of a considerable proportion of the rainfall that could not be used by the crop (41 mm in the ND treatment according to the simulations of MOPECO). On the other hand, cumulative precipitation in 2015 and 2016 was lower than the TMY-intermediate projections, starting with the middle of the growing cycle in 2015, and for the entire growing season in 2016, which was the driest year with a 21% less rainfall compared with TMY-intermediate projections.

Consequently, the weather conditioned the ET_a/ET_c objectives for each stage as well as the amount of irrigation water applied at each K_y stage. The three experimental years were adverse in terms of irrigation water requirements because initially the climatology was similar (2015 and 2016) or even better (2017) than the reference conditions (TMY-intermediate), but the three seasons progressed to drier than normal conditions (Table 7). Therefore, the crop was under a greater water deficit than projected in all the treatments during the final growth stage except for ND (Fig. 9) and was therefore considerably complex with regards to the application of the ORDIL methodology. As a consequence, irrigation requirements of garlic (ND) were greater compared with that projected for a TMY-intermediate year (14.2%, 33.4% and 47.2% for 2015, 2016 and 2017, respectively). Nonetheless, the methodology allowed the limited volumes of water to be managed and reduced the

Table 6
Available volume of net irrigation water for each treatment (m^3 ha^{-1}).

ND	T100	T90	T80	T70
Irrigation requirements (2015)[a]	3400	3060	2720	2380
Irrigation requirements (2016, 2017)	2750	2475	2200	1925

ND: No deficit treatment, garlic net irrigation requirements in the weather conditions of the actual year; Treatments T100, T90, T80 and T70: 100%, 90%, 80% and 70% of garlic net irrigation requirements in the weather conditions of the intermediate typical meteorological year

[a] by using crop coefficients (K_c values) proposed by Fabeiro et al. (2003)

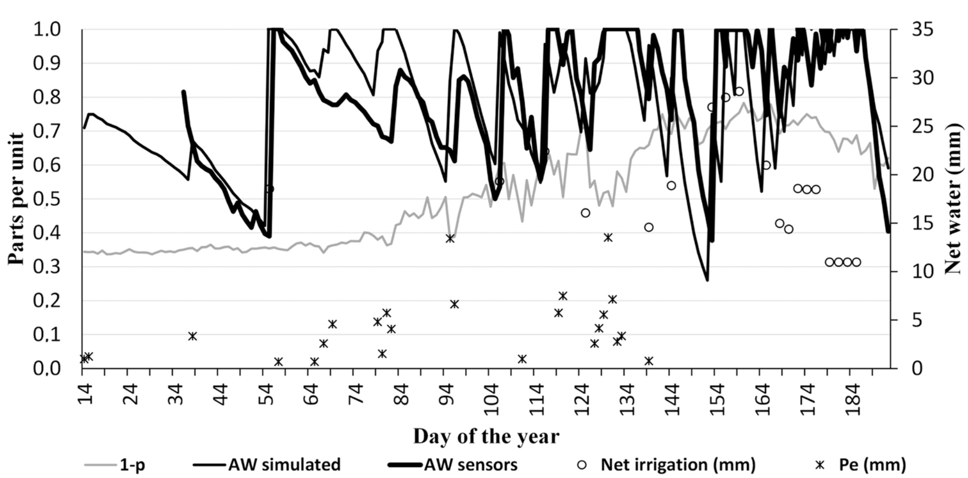

Fig. 7. Comparison between simulated (MOPECO) and measured (potential sensors) available soil moisture content progression in the ND treatment (2016). p: fraction of total available water that a crop can extract without suffering water stress (main Y-axis); AW: available water (main Y-axis); Pe: effective precipitation (secondary Y-axis); net irrigation (secondary Y-axis).

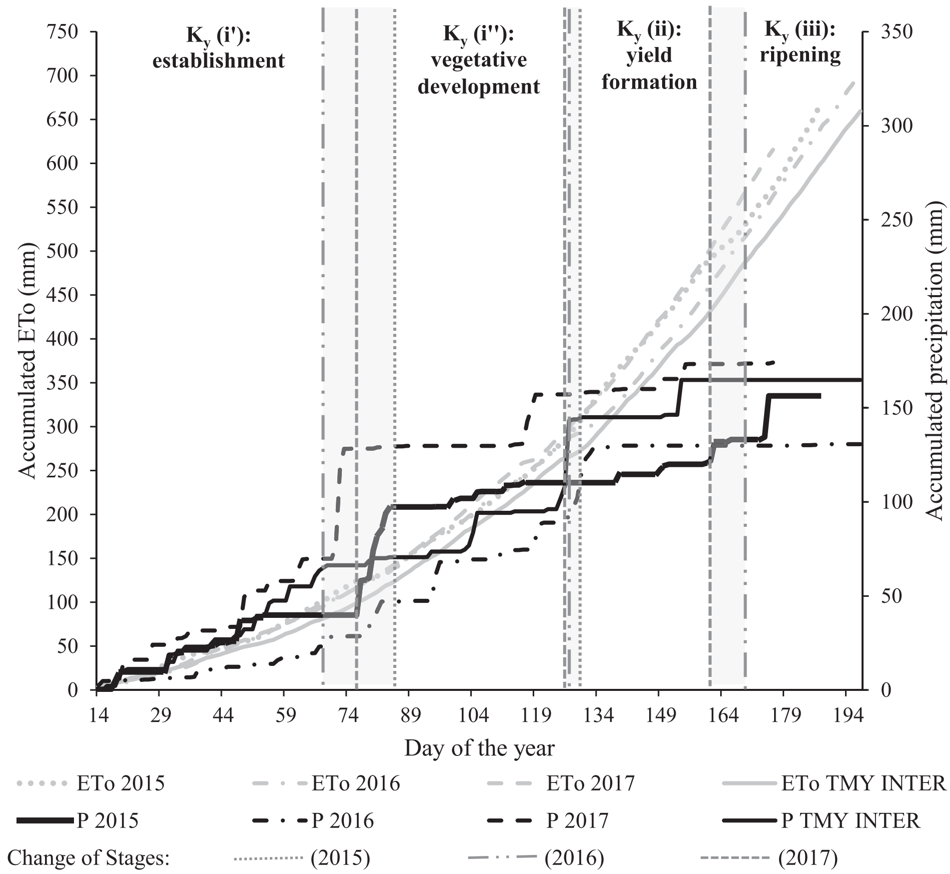

Fig. 8. Accumulated daily progression of precipitation and reference evapotranspiration for the experimental years (2015, 2016 and 2017) and the intermediate typical meteorological year during the growing period of garlic. Note: Grey vertical bars indicate the date interval when the crop reached the next K_y stage, which varied for the 3 experimental years (Table 4). ET_o: reference evapotranspiration; P: Precipitation; TMY INTER: intermediate typical meteorological year;.

Table 7
Progression of the climatic characterization during the growing season: accumulated from September 1st and for the specific growing stage (between brackets).

Stages	2015	2016	2017
Pre-sowing	Intermediate	Intermediate	Wet
K_y (i')	Intermediate (Wet)	Dry (Dry)	Wet (Wet)
K_y (i'')	Intermediate (Dry)	Intermediate (Wet)	Wet (Dry)
K_y (ii)	Dry (Dry)	Dry (Dry)	Intermediate (Dry)
K_y (iii)	Dry (Intermediate)	Dry (Dry)	Intermediate (Dry)

Pre-planting: from September 1st (beginning of hydrological year) to last day before planting; K_y (i): vegetative period. This stage is divided in two substages: K_y (i) "establishment", which coincides with K_c (I) and K_y (i) "vegetative development" from the end of K_c (I) up to beginning of next K_y stage; K_y (ii): yield formation; K_y (iv): ripening.

effects of adverse weather conditions by redistributing the irrigation water for the most sensitive stages.

The methodology assumed a theoretical optimal distribution of deficit at the beginning of the irrigation season according to the projected precipitation and ET_o and the available irrigation water (Fig. 9). The ORDIL methodology suggests maintaining stage K_y (ii) with the least possible water deficit (Fig. 9), since this is the bulbification stage, in which the greatest impact on yield occurs under a water deficit stress (Table 3). Consequently, the most restrictive target ET_a/ET_c values corresponded to vegetative development "K_y (i'')" and ripening "K_y (iii)". This distribution of the water deficit proposed by ORDIL takes into account the different sensitivities to water deficit during the growth stages, and corresponds to the recommendations published by other authors (Domínguez et al., 2013; Fabeiro et al., 2003; Lipinski and Gaviola, 2011; Sadaria et al., 1997).

The deficit objectives proposed for each treatment conditioned the irrigation schedules applied. Only in 2015 were the ND and T100 treatments the same, so the global (for the whole growth cycle) ET_a/ET_c ratio, that is, the ratio over the complete crop cycle, was 0.90 in both treatments (Fig. 9), by applying 3% less of the total water planned for irrigation at the end of the season (Table 8). For the other treatments in 2015, the total water applied was between 17% and 19% lower than the projected volume as reference consumption (Table 6) in 2016 and 2017. This was partially caused by a failure in the pumping system and by the need to readjust the Kc values in order to avoid over-watering. In 2016 and 2017, scheduling irrigation using the known K_c (Table 5), the final applied volume ranged between 0% and 5% higher than that projected using the intermediate TMY, depending on the treatment and year considered (Table 8). Therefore, the ORDIL methodology was able to accommodate the planned irrigation scheduling for the volume of available water in each treatment. However, slight adjustments in proposed irrigation applications were necessary to account for small deviations between planned and applied irrigation based on measured volumes with the flowmeters. Although the volumes of irrigation applied in each treatment were similar in 2016 and 2017, the global ET_a/ET_c ratios actually achieved differed between 2% and 5% (from 0.85 to 0.90, from 0.85 to 0.88, from 0.79 to 0.83 and from 0.74 to 0.76 in the ET_a/ET_c relationships for treatments T100, T90, T80 and T70 respectively) (Fig. 9). So, the weather conditions, and especially the distribution of rainfall, determined different levels of stress due to water deficit, with equal irrigation volumes.

Applying similar volumes of irrigation water, the weather conditions

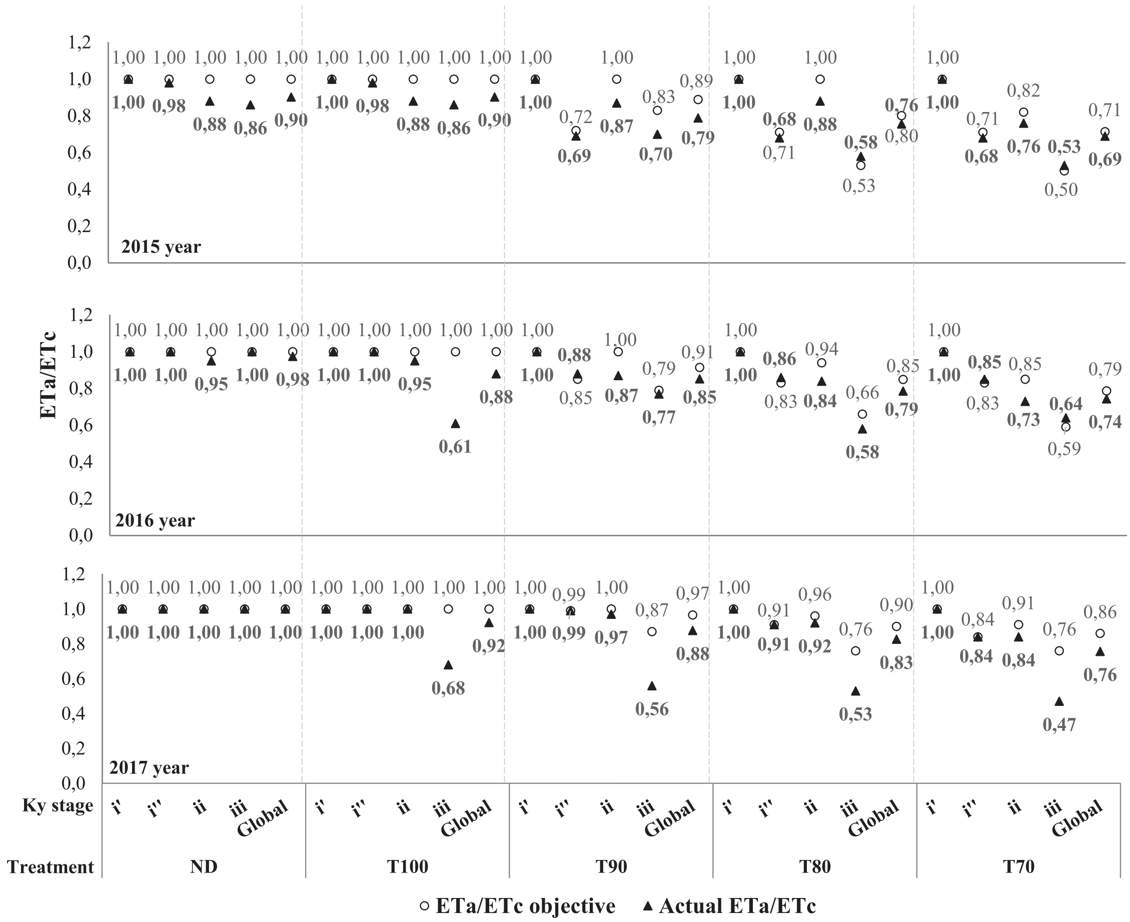

Fig. 9. ET_a/ET_c objectives proposed by Optimized Regulated Deficit Irrigation for a Limited volume of irrigation water (ORDIL) methodology at the beginning of the K_y stage and the actual value reached at the end of the stage. ET_a/ET_c: ratio between actual and maximum evapotranspiration; Irrigation treatments: ND, No deficit; T100, T90, T80 and T70 are 100%, 90%, 80% and 70% of garlic net irrigation requirements in the weather conditions of the intermediate typical meteorological year. K_y stage: growing stage related to crop yield response factor; K_y (i') “establishment”; K_y (i'') “vegetative development”; K_y (ii): yield formation; K_y (iii): ripening; Global ET_a/ET_c: ratio between total actual and maximum evapotranspiration for the whole growth cycle.

Table 8
Amount of rainfall and irrigation water received (mm) by the treatments.

Year	Stage		Irrigation Treatment				
		Pe	ND	T100	T90	T80	T70
2015	K_y (i')	82.0	0.0	0.0	0.0	0.0	0.0
	K_y (i'')	7.5	92.4	92.4	41.4	37.6	38.7
	K_y (ii)	6.4	123.9	123.9	142.2	142.1	120.7
	K_y (iii)	29.1	50.9	50.9	17.1	0.0	0.0
	Total	125.0	267.2	267.2	200.7	179.7	159.4
	Irrigation ratio (Actual/TMY reference)	–	–	0.97	0.81	0.82	0.83
2016	K_y (i')	9.6	18.6	19.3	16.0	17.4	15.7
	K_y (i'')	55.1	41.8	41.8	13.7	9.9	8.3
	K_y (ii)	40.0	176.5	176.5	160.6	157.7	124.3
	K_y (iii)	0.0	106.6	37.2	60.0	37.4	38.7
	Total	104.7	343.5	274.8	250.2	222.4	187.1
	Irrigation ratio (Actual/TMY reference)	–	–	1.00	1.01	1.01	0.97
2017	K_y (i')	104.1	0.0	0.0	0.0	0.0	0.0
	K_y (i'')	25.8	66.9	71.3	63.6	52.1	33.0
	K_y (ii)	12.6	179.3	175.3	170.1	148.0	145.7
	K_y (iii)	0.0	92.0	31.9	22.5	30.0	22.5
	Total	142.4	338.2	278.5	256.1	230.1	201.2
	Irrigation ratio (Actual/TMY reference)	–	–	1.01	1.03	1.05	1.05

Pe: effective rainfall; ND, No deficit; T100, T90, T80 and T70 are 100%, 90%, 80% and 70% of garlic net irrigation requirements in the weather conditions of the intermediate typical meteorological year. Ky (i): vegetative period. This stage is divided in two substages: Ky (i') “establishment”, which coincides with Kc (I) and Ky (i'') “vegetative development” from the end of Kc (I) up to beginning of next Ky stage; Ky (ii): yield formation; Ky (iv): ripening; TMY: Typical Meteorological Year.

caused the T100 treatments to be deficient in the three years, so that, in general, the target ET_a/ET_c values proposed by the model at the beginning of the cycle were greater than those actually attained. It is also important to note that, even under unfavorable weather conditions, the model reserved an amount of water for the last stage of crop development. (Fig. 9) (Leite et al., 2015b). This highlights the potential of this methodology when managing limited volumes of water even under adverse weather conditions so as not to cause high water deficits at any stage of the crop, exceeding in all cases the minimum value of ET_a/ET_c= 0.5, considered for this methodology. (Allen et al., 1998; Domínguez et al., 2013). Although the model favors water application in the most sensitive crop stages, the distribution of the irrigation varies according to the years (Table 8). Thus, stage K_y (ii), the one with the greatest water requirements (Villalobos et al., 2004), received the greatest amount of irrigation water (between 60% and 80% of the total in deficit treatments, with increasing percentages with lower water availability, being approximately 50% in the ND treatments), while during the establishment stage (K_y (i`)) it was unnecessary to apply irrigation in years 2015 and 2017 (Table 8; Fig. 9).

The total water applied in the treatments with no deficit was between 450 and 480 mm, similar to the values recorded by Fabeiro et al. (2003), with 490 mm. Hanson et al. (2003) applied 430–450 mm of seasonal irrigation for garlic in a semi-arid area of California (USA), with total rainfall less than 23 mm from establishment to harvest. They observed significant yield differences between treatments receiving lower applied irrigation levels.

3.4. Effect of ORDIL on yield

As expected, the yield was reduced by decreasing the supply of irrigation water applied to each treatment, normally with significant differences between treatments within the same year (Table 9). In all years, the highest yields were achieved in the no deficit treatments, and in 2016, it was significantly different from T100. T70 treatments achieved the lowest yields, with no significant differences compared with the T80. In 2015, the maximum amount of irrigation water set for a TMY-Intermediate year was not achieved, due to a failure in the pumping system between days 138 and 145 after sowing, so the maximum global ET_a/ET_c was 0.90 (Fig. 9 and Table 9). In 2016, which was predominantly a dry growing season (Table 7) the water assigned for T100 was not sufficient to cover the real needs during the year ($ET_a/ET_c = 0.88$), thus causing water stress which was more noticeable in the later growth stages. Consequently, significantly lower yield was observed for the ND treatment ($ET_a/ET_c = 0.98$) and that achieved in the previous year in T100 ($ET_a/ET_c = 0.90$). T80 treatments (ET_a/ET_c = 0.76–0.82) and T70 (ET_a/ET_c = 0.69–0.76) showed no significant differences between each other within each year, although the mean yields were always greater for T80 (Table 9).

Although the global ET_a/ET_c ratios were relatively similar for the same treatments in the different years, the yields were statistically different in most cases (Table 9). This was especially noticeable in 2017, when, in all treatments, the yields were statistically lower than the rest of the equivalent treatments in 2015 and 2016. Initially, 2017 was characterized as TMY-Wet with high precipitation (Table 7, Fig. 8), but the climatic conditions during the cycle changed to TMY-Dry. In addition, during the crop development cycle, temperatures were higher than usual, causing early development of the aerial part. Consequently, the performance of all the treatments in this year was negatively affected by the climatic characteristics. In 2017, performance in the ND, T100 and T90 treatments fell approximately 30%, compared to the same treatments in the years 2015 and 2016, while in T80 and T70 the loss of yields reached 42%. This is an example of how the year-on-year yield in horticultural crops such as garlic can be strongly influenced by climatic conditions, in addition to hydric conditions. In the same experiment, Sánchez-Virosta et al. (2020) in 2017 found different correlations on physiology parameters, such as net assimilation rates and stomatal conductance, with higher temperatures, when vapour pressure deficit (VPD) and mean temperature impacted negatively on stomatal conductance values (gs), unlike the 2016 year. The effect of the increase in temperature and long photoperiods favors, in general, the growth of the garlic bulb. However, if the temperatures are very high during its development (above 25 °C) bulb size decreases, and consequently causes a lower production. Considering that the increase in temperatures shortens the ripening stage, it can have a negative effect on growth (Wu et al., 2014). In addition, for garlic, night temperatures during the rest of the growing stages (including the storage of the garlic clove for planting) could affect the yield (Wu et al., 2016b, 2016a). For the same limited volume of water, an influence of the climatic conditions of each year (Fig. 8) on the yields was expected. ET_a/ET_c ratios indicates differences (Table 9), which indicates that the yields may be different for the same treatment.

In 2015 and 2016, for which maximum yields were similar, the differences between ranges in yield might be related to the global ET_a/ET_c ratios. In 2015, a 7% reduction in total water applied (T90 *vs.* T80) involved yield losses of 4% (0.34 t ha^{-1}) and a decrease in global ET_a/ET_c of 0.79–0.76. The same reduction in total water applied between

Table 9
Amount of water received by the treatments, yields and irrigation water productivity.

Year	Treatment	Global ET_a/ET_c	Yield (kg ha^{-1})	SD (kg)	CV (%)	Irrigation water (m^3 ha^{-1})	WP_I (kg m^{-3})	Total water (m^3 ha^{-1})	WP (kg m^{-3})
2015	ND	0.90	9928a A	318	3.20	2672	3.72d D	3922	2.53c C
	T100	0.90	9928a A	318	3.20	2672	3.72d D	3922	2.53c C
	T90	0.79	8894b B	691	7.77	2007	4.43c C	3257	2.73b B
	T80	0.76	8554bc C	591	6.91	1797	4.76b B	3047	2.81b B
	T70	0.69	8444bc C	473	5.60	1594	5.30a A	2844	2.97a A
2016	ND	0.98	10163a A	244	2.40	3435	2.96e F	4482	2.27d E
	T100	0.88	9066b B	424	4.68	2748	3.30d E	3795	2.39c D
	T90	0.85	8899b B	490	5.46	2502	3.56c D	3549	2.51b C
	T80	0.79	8270c CD	539	6.38	2224	3.72b D	3271	2.53b C
	T70	0.75	8090c D	516	6.71	1871	4.32a C	2918	2.77a B
2017	ND	1.00	6793a E	100	1.47	3382	2.01d I	4806	1.41c G
	T100	0.92	6700a E	197	2.94	2785	2.41c GH	4209	1.59 bc F
	T90	0.88	5742b F	202	3.52	2561	2.24c H	3985	1.44 bc G
	T80	0.82	5236c G	222	4.23	2301	2.28b H	3725	1.41b G
	T70	0.76	5083c G	267	5.28	2012	2.53a G	3436	1.48a G

WP_I: irrigation water productivity expressed as mass of crop production per unit of volume of gross irrigation water supplied to the crop (kg m^{-3}); WP: agronomic water productivity expressed as mass of crop production per unit of volume of total water received by the crop (kg m^{-3}); Total water: Irrigation Water + Effective rainfall; Global ET_a/ET_c: ratio between total actual and maximum evapotranspiration for the whole growth cycle; SD: standard deviation; CV: Coefficient of variation; Significance level ($p < 0.05$). Duncan test, small letter for intra-annual data and capital letter for interannual data. ND, No deficit treatment; T100, T90, T80 and T70 treatments: 100%, 90%, 80% and 70%, respectively, of garlic net irrigation requirements in the weather conditions of the intermediate typical meteorological year.

treatments T70 and T80, involved yield losses of 2% (0.10 t ha^{-1}) with a more noticeable difference in the global ET_a/ET_c ratio (de 0,76 a 0,69) (Table 9). The results in 2016 were similar, an 8% reduction in total water applied (T90 *vs*. T80) involved yield losses of 7% (0.67 t ha^{-1}) and a decrease in global ET_a/ET_c of 0.06 (0.85–0.79). For T70 and T80, the yield losses were as in 2015, of 2% (0.67 t ha^{-1}), with 11% less total water applied and global ET_a/ET_c ratios that fell from 0.79 to 0.75. On the other hand, in 2017, both the percentage losses of yield (9% and 3% when comparing the treatments T90 *vs*. T80 and T80 *vs*. T70) and the percentage reductions of total water supplied (7% and 8% when comparing the treatments T90 *vs*. T80 and T80 *vs*. T70) were similar to those observed in the previous two years, but the total yields were lower than those obtained in 2015 and 2016. In 2017, ET_a/ET_c ratios for each treatment were similar or slightly higher than the previous two years, so the crop was no longer stressed due to water deficit. In addition, the total amounts of water received by the crop in each of the treatments were greater compared with 2015 and 2016 (between 15% and 22% for deficit treatments, and between 11% and 7% for T100, respectively). This is likely a result of weather conditions in 2017, since, although the precipitation recorded was high, it was poorly distributed and therefore less effective, since 91% was recorded in the early stages of development (Table 8, Fig. 7).

In test fields, average yields in 2015 and 2016 were slightly higher than the average for the area (9.0 t ha^{-1}) corroborating a general loss of performance in the area in 2017 (MAGRAMA, 2016; COOPAMAN, 2017). These results show that this crop is sensitive to high temperatures, at least during the early stages of development. The potential yield of 11.2 t ha^{-1} proposed by Fabeiro et al. (2003) and used by Domínguez et al. (2013) to calibrate K_y coefficients was not attained in any of the years, reaching a maximum in 2016 at 10.2 t ha^{-1}. The potential yield of other garlic varieties is thus greater; Hanson et al. (2003) reported a yield of 19.2 t ha^{-1} with the white garlic variety "California Early", applying an irrigation volume of 363 mm with a constant deficit of $ET_a/ET_c = 0.8$ during all growth stages. However, according to the results of Hanson et al. (2003) similar reductions in the ET_a/ET_c ratios to those studied in the present work with respect to the ND treatments likewise caused comparable reductions in yield. The yields obtained in the present work were slightly lower than those obtained by Lipinski and Gaviola (2011) in a purple garlic cultivar (Lican INTA) and clearly lower in two white garlic cultivars (Snow INTA and Unión) (between 10,800 and 17,150 kg ha^{-1}). These works were carried out in the San Carlos region (Mendoza, Argentina) with plant densities 30% greater than those of the present work. On the other hand, yield responses reported by Marouelli et al. (2002) diverged from the above reported results of the other authors. For an irrigation depth of 323 mm, which corresponds to 80% of the net irrigation requirements of the crop, and using constant regulated deficit irrigation techniques throughout the crop cycle, they observed a 63% reduction in yield compared to the treatments with no deficit. In the present study, for similar deficits, the yields fell by a maximum of 35% (year 2017). For the most restrictive treatment (T70), the yield declines with respect to ND were 15%, 20% and 25% in 2015, 2016 y 2017, respectively. The reduction in water applied for these years was 27%, 35% and 29%, and, the reduction in global ET_a/ET_c ratios was 21%, 19% and 24%, respectively. These results show that the ORDIL methodology limited the yield declines despite the different internal weather conditions. This result coincides with those obtained by other authors in the management of regulated deficit irrigation for this and other crops (Hanson et al., 2003; Domínguez et al., 2012a; Forey et al., 2016; Martín De Santa Olalla et al., 2004; Phogat et al., 2017).

3.5. Effect of ORDIL on agronomic and irrigation water productivity

Both, agronomic (WP) and irrigation (WP_I) water productivity, was greatly influenced by yields (Eqs. 6 and 7) because water volumes were similar across years. Thus, WP was lowest in 2017 compared with other years (Table 9). In all years, WP was increased by reducing the applied water, normally showing significant differences between treatments, with this being more marked in the WP_I. In this sense, and in this same experiment, Sánchez-Virosta et al. (2020) found a higher intrinsic water use efficiency (ratio between net CO_2 assimilation and leaf stomatal conductance) in higher deficit treatments, and mainly in yield formation stage.

In T70, WP increased by 5% in 2017 and 20% on average in 2015 and 2016, relative to ND. For these same treatments, WP_I increased 26% in 2017 and 44% on average in 2015 and 2016. Except for the year 2017, with adverse and atypical climatic conditions for the development of the crop, and in semi-arid climates such as that of the test area, the stress conditions due to water deficit increased the WP and especially WP_I, with an increase of 26% in 2017 and 44% on average in 2015 and 2016 between extreme treatments (Table 9). In the same area, for barley, Pardo et al. (2020) obtained slightly lower increases (32% and 10% in the irrigation and WP, respectively).

In areas with a semi-arid climate, where the main limiting yield factor is water available for irrigation, the increase in WP would allow a higher total yield for the entire farm if the same amount of irrigation water was applied to a larger cultivable area (when possible, *i.e.*, if part of the farm is not irrigated due to insufficient irrigation water), which could generate a higher income for the farmer. However, because input costs for garlic production are high, it would be necessary to carry out an economic analysis to check whether this option is profitable. In addition, several quality factors affecting final prices obtained by farmers (size and color of the bulbs, *e.g.*) may be negatively affected by deficit irrigation.

For several crops under RDI techniques, similar trends have been observed, whereby WP increases with increasing water deficits when the methodology takes into account the sensitivity of the yield to the deficit at different stages of development: 1.8–2.5 kg m^{-3} for garlic (Mandefro and Shoeb, 2015; Fabeiro et al., 2003), from 2.2 to 3.4 kg m^{-3} for maize (Domínguez et al., 2012a), from 2.1 to 2.7 kg m^{-3} for carrot (Carvalho et al., 2014; Léllis et al., 2017), although in other crops with very high yields, the values are clearly higher, varying from 10.4 to 12.0 kg m^{-3} for onion (Domínguez et al., 2012b), from 5.0 to 12.0 kg m^{-3} for melon (Leite et al., 2015a) and from 17 to 40, from 23 to 32, from 24 to 39 and from 35 to 53 kg m^{-3} for four different potato varieties (Martínez-Romero et al., 2019).

3.6. Effect of ORDIL on the water footprint

The lower the availability of irrigation water, the greater was the value of the green water footprint (WF_{green}) (Table 10). After each irrigation event, high deficit treatments recharged a lower percentage of TAW than ND or low deficit treatments. Therefore, in the case of abundant precipitation, the percentage of rainwater retained in the root

Table 10
Water footprint (WF) for garlic in the three experimental years.

Year	Treatment	WF_{green} (m^3 Mg^{-1})	WF_{blue} (m^3 Mg^{-1})	WF_{grey} (m^3 Mg^{-1})	$WF_{process}$ (m^3 Mg^{-1})
2015	**ND**	94	253	65	412
	T100	94	253	65	412
	T90	113	226	61	399
	T80	116	210	51	377
	T70	121	189	39	349
2016	**ND**	98	314	63	475
	T100	126	279	71	476
	T90	136	276	58	469
	T80	148	256	50	454
	T70	149	227	40	416
2017	**ND**	84	491	80	655
	T100	119	409	81	609
	T90	152	446	72	676
	T80	174	439	62	675
	T70	185	396	51	631

zone increased and reduced or avoided percolation. This is an advantage of the ORDIL methodology. Thus, WF_{green} depends on the local climate and weather conditions, mainly precipitation depth and its seasonal distribution, and the water storage capacity of the soil. WF_{green} varied between 84 and 185 $m^3 Mg^{-1}$ across all treatments, with the lowest and greatest values observed for the ND and T70 treatments, respectively. These results are consistent with those obtained for barley during the same years and in the same field by Pardo et al. (2020), who obtained increases in WF_{green} between 50% and 80%. In this study, increases in WF_{green} for garlic varied between approximately 28% and 120%, which is possibly explained by the distribution of rainfall as discussed earlier.

Mekonnen and Hoekstra (2010) indicated that in humid climate areas WF_{green} of garlic may reach values of up to 337 $m^3 Mg^{-1}$. Such a high green water footprint could not be achieved for semi-arid conditions and shallow soils characteristic of this study area. Therefore, the comparison of this indicator across areas with different climatology must be performed with caution (Fernández et al., 2020; Pardo et al., 2020). However, it can be useful to compare the environmental impact on water of different treatments carried out in the same area or in areas with similar characteristics. As expected, WF_{blue} decreased with WP, being greater in the ND treatments and in the drier years (Table 8). In addition, for a rainier year (2015), WF_{blue} was lower than for a drier one (2016) in the case of deficit treatments, although it may be strongly influenced by the distribution of rainfall, and percolation. Thus, in 2017, these values were considerably greater due to the concentration of rain in a few days in March that was ineffective in elevating yield that year. Mekonnen and Hoekstra (2010) determined an average worldwide value of 81 $m^3 Mg^{-1}$ for garlic which is clearly lower than that obtained in this study. As in the case of WF_{green}, climate greatly influences the magnitude of WF_{blue}, because in areas where rainfall supplies all or the major part of the water requirements of the crop, this indicator should tend to zero. WF_{blue} is directly related to the carbon footprint in those cases where pressurized irrigation systems require conventional energy, as in most of the irrigated lands in CLM and other semi-arid areas. Consequently, reducing this indicator implies a lower impact of irrigated agriculture on global warming (Pardo et al., 2020). The main feature of WF_{grey} is reducing the concentration of dissolved nitrogen in the percolated water. In the optimized treatments (T70, T80 and T90), the indicator decreased with deficit (Table 10). Thus, ORDIL, together with a suitable fertilization based on the expected yield (lower for more deficit treatments), allowed this value to be lowered. Broadly speaking, T100 treatments reached the highest values, since the nitrogenous fertilization was the same as in the ND treatment but the final yield was lower. The values for this treatment were 60% lower than those established by Mekonnen and Hoekstra (2010) (average 170 $m^3 Mg^{-1}$).

Finally, the estimated total water footprint of the process ($WF_{process}$) ranged between approximately 350 $m^3 Mg^{-1}$ and 475 $m^3 Mg^{-1}$, being the smallest for the deficit treatments. These values are lower than those estimated by Mekonnen and Hoekstra (2010) (589 $m^3 Mg^{-1}$), due to the dependence of WF_{green} on the magnitude of precipitation.

In 2017, $WF_{process}$ with values ranging between 631 and 655 $m^3 Mg^{-1}$ was considerably greater compared with the other years (because of the relatively lower yields combined with poorly distributed precipitation in that year.

In this sense, the ORDIL methodology allows the impact of the water footprint in the environment to be reduced by increasing both the effectiveness of precipitation use and WP, and by decreasing the percolation losses and the corresponding risks of contamination of groundwater resources. This finding could represent a commercial advantage in the future if consumers and markets set a value on the sustainability of agricultural practices.

4. Conclusions

For shallow soils and in areas where standard lysimetric stations are not available, mini-lysimeters may be a suitable option for measuring a good approximation of crop evapotranspiration and determining relatively accurate K_c coefficients for herbaceous crops such as garlic. Moreover a lower manufacturing and installation price, its smaller size offers a higher versatility and portability.

Although the ND treatment achieved the highest yields and T70 the lowest (average 19% yield loss), the application of the ORDIL methodology permitted the attainment of increased irrigation water productivity with T70 being the treatment achieving the greatest WP (average 38% and 15% higher than ND for WP_I and WP, respectively). Thus, from the environmental point of view, application of the ORDIL methodology resulted in a decrease in the water footprint by up to 30% (T70) and increased the use of green water up to 120%. Nevertheless, an economic analysis is required to analyze if ORDIL would be advisable in terms of profitability.

Consequently, this study demonstrates ORDIL can be used under real management conditions of a garlic crop, when the availability of water is limited and lower than the crop water requirements. Combining this methodology with models such as MOPECO, may help farmers improve the efficiency of resource use and reduce the impact on the environment under water-scarce conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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