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Effect of the optimized regulated deficit irrigation methodology on quality, profitability and sustainability of barley in water scarce areas

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ABSTRACT

A three-year experiment (2015–2017) was conducted under the semiarid conditions of the Hydrogeological Unit Eastern Mancha (HUEM) (Spain), using the optimized regulated deficit irrigation for a limited amount of irrigation water (ORDIL) methodology on barley. Five irrigation treatments were performed during the experiment: no deficit (ND), 100% (T100), 90% (T90), 80% (T80), and 70% (T70) of barley net typical irrigation requirements (2500 m^3 ha^{-1}) in the area. The aim was to determine the effect of ORDIL: 1) on the quality of grain and malt; 2) on the profitability and use of water at farm scale; and 3) on the profitability and sustainability of the HUEM. Despite using less water, ORDIL treatments showed no significant differences in grain quality with respect to ND, while T80 achieved the highest economic water productivity (average 0.17 € m^{-3}). Thus, by using T80 instead of ND and increasing the irrigated area of barley on the farm by 14%, it is possible to save up to 31% of water with the same profitability. This amount of water could be used for more profitable crops, increasing the profitability of the farm. The use of ORDIL at basin scale, using T80 instead of ND and increasing the cultivated area by 9%, could have saved up to 55.9 hm^3 over the 3 experimental years (16% of annual extractions in the HUEM). Supplying this water to more profitable crops, the profitability of the basin could have increased by up to 44.4 M€. In the case of saving this amount of groundwater, piezometric levels would have risen, decreasing the pumping costs and improving the environmental conditions in the area. Consequently, applying ORDIL in low-profit crops, such as barley, and in water scarce areas, could improve the profitability and/or the sustainability of agricultural systems, maintaining the production.

1. Introduction

Barley (*Hordeum vulgare* L.) is the fourth most important cereal in the world in terms of both quantity produced and cultivated area (FAOSTAT, 2020). On average, the annual world harvest of barley is more than 141 Mt obtained from nearly 48 Mha (FAOSTAT, 2020).

Barley is well adapted to different global climates through its genetic evolution (Garstang et al., 2011; Ingvordsen et al., 2015), and is generally produced in temperate (winter and/or spring planting) and semiarid subtropical (winter planting) climates (Ullrich, 2011). It is used in different economic sectors, such as animal feed (70%), malting, brewing and distilling industries (21%), human food (6%), and, recently, in biofuel production (Tricase et al., 2018).

In Spain, 2.6 Mha of this species is cropped, producing around 9.2 Mt $year^{-1}$ of grain. Castilla–La Mancha (CLM) is the second largest producing region, with 28% of the national total, cultivating around 0.78 Mha, of which 12.2% is irrigated (MAPA, 2020). Around 0.9 Mt of the total production corresponds to brewing cultivars (CE, 2019).

The Spanish malting industries generate around 6000 direct jobs and invoice 175 M€ per $year^{-1}$ through the production of 485,000 t $year^{-1}$ of malt. The annual needs are about 631,000 t of malting-quality barley grains. With current national production, this demand is not covered, forcing imports of around 10% (CE, 2019). This percentage is higher during dry seasons, as occurred in 2017, where quality is more compromised and the rejection rate of national brewing barley productions exceeds 50%. Thus, when the grain quality reaches malt category, the price of the grain increases by an average of 15% (MAPAMA, 2017).

The Hydrogeological Unit Eastern Mancha (HUEM), located in the Júcar basin (Fig. 1), is one of the main irrigation areas in CLM. It has an

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extension of 8500 km^2 with 110,000 ha of irrigable lands. In HUEM, irrigation depths of around 250 mm $year^{-1}$ may triple the yield of rainfed barley (JCRMO, 2019; MAPA, 2020). Barley requires a low depth of irrigation water compared to that applied to other annual crops, such as onion, maize or alfalfa (580, 650 and 750 mm $year^{-1}$, respectively) (Pardo et al., 2020). Nevertheless, the decreasing availability of irrigation water in the area and the global rise in production costs are accentuating the need to apply techniques that enhance water use efficiency, such as Regulated Deficit Irrigation (RDI) (Chai et al., 2016; English, 1990).

The effect of water stress on barley yield is conditioned by both the intensity of the water deficit and the stage in which it occurs. Broadly speaking, water deficit during plant development and around anthesis decreases yield, due to a reduction in the potential number of kernels per unit of area (Abrha et al., 2012; Cossani et al., 2009; De Mezer et al., 2014; Fischer, 1985; Giunta et al., 1993; Marok et al., 2021; Savin and Slafer, 1991). In addition, water deficit, together with high temperatures during grain formation, reduces the mean weight of kernels (Abrha et al., 2012; Acevedo et al., 2002; Carter and Stoker, 1985; Oweis et al., 2000; Ugarte et al., 2007). Carter and Stoker (1985) and Qureshi and Neibling (2009) reported that the quality of the grain for malting is also affected by water deficit, mainly during grain formation. In addition, Hong and Zhang (2020) noted that a drought period during the grain filling stage of malting barley causes instability and deterioration of malt quality.

To address the lack of water and low profitability in the agricultural systems of CLM, the Regional Centre of Water Research (CREA) of Castilla-La Mancha University (UCLM) is developing several models, tools and methodologies to advise the productive sector on a more efficient, profitable and sustainable use of irrigation water. Thus, the optimized regulated deficit irrigation (ORDI) methodology maximizes the yield of annual crops when the objectives are either to reach a certain deficit for the whole growing period (Domínguez et al., 2012b), or to allocate a limited irrigation water amount along the crop cycle (ORDIL; Leite et al., 2015a). These methodologies were developed for the MOPECO model (Ortega et al., 2004), which was conceived to optimize the gross margin (GM) of irrigated farms located in water scarce areas. The model has been calibrated for the main annual extensive crops in CLM and others in different areas of the world (Carvalho et al., 2014; Domínguez et al., 2012a, 2012c, 2013; Leite et al., 2015b; Léllis et al., 2017; Martínez-Romero et al., 2019; López-Urrea et al., 2020). MOPECO is currently being used as part of the European project SUPROMED focused on improving the sustainability of agro-ecosystems in the Mediterranean basin (www.supromed.eu).

Considering the above, the aims of this research were: 1) to determine the effect of ORDIL on the quality parameters of barley grain and malt; 2) to determine the effect of ORDIL on the profitability of barley and its use of water at farm scale; and 3) to analyze the effect of applying ORDIL in barley on the profitability and sustainability of the HUEM agricultural system. This paper complements the study published by Pardo et al. (2020), in which the effect of ORDIL on yield, water productivity and water footprint of barley was analyzed in the area.

2. Material and methods

2.1. Description of irrigated lands in Hydrogeological Unit Eastern Mancha

The Hydrogeological Unit "Eastern Mancha" (HUEM) supplies water for irrigation to about 20% of total irrigable land in CLM, using modern irrigation techniques (mainly drip, sprinkler and center pivot systems), and for urban consumption, including industrial demand. The average annual water draft for irrigation is about 334 hm^3, of which around 85% is groundwater (JCRMO, 2019).

The considerable development of irrigation systems between 1975 and 2000 caused a significant decrease in the piezometric levels of this

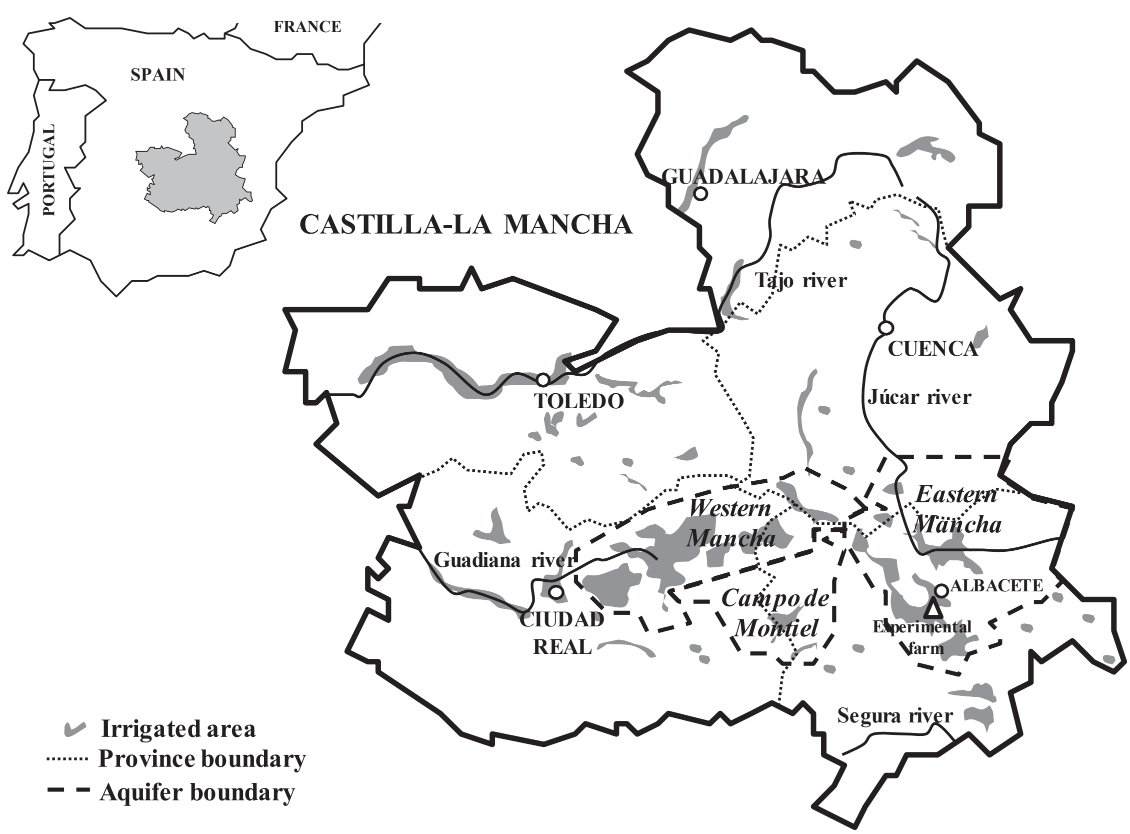

Fig. 1. Irrigated lands, groundwater resources in Castilla-La Mancha, and location of the experimental farm.

aquifer. Currently, more appropriate management of the aquifer has halted this trend, although the system is still close to overexploitation (Martín de Santa Olalla et al., 2007).

The most common crops in the area are grape, cereals, garlic, onion, broccoli, and others, such as sunflower, potato and alfalfa. Barley is the second most cultivated cereal, occupying around 15,000 ha of irrigated lands (JCRMO, 2019).

Although irrigation water is free of charge in the area, its use is administratively regulated, and farmers must pay for the energy required for pumping, as well as the amortization and maintenance of the irrigation systems. Accordingly, the average water cost in the area is 0.12 € m^{-3}, which mainly depends on the depth of the piezometric level in the farm (Carrión et al., 2016).

The way water resources are managed by the HUEM does not favor the use of deficit irrigation in annual crops. Depending on the evolution of the piezometric levels of the aquifer in the last year, the water authority, known as the "Confederación Hidrográfica del Júcar" (CHJ, Hydrogrpahic Confederation of the Júcar Basin), establishes the theoretical volume of water that can be used for irrigation in the following campaign, which is different each year to guarantee the sustainability of the HUEM. The irrigators' association, known as "Junta Central de Regantes de la Mancha Oriental" (JCRMO, General Board of Irrigation Users of Eastern La Mancha), distributes this volume among the farmers of the area, based on a series of rights and rules established by the association itself (JCRMO, 2019). In the area, the average seasonal gross irrigation water requirements have been determined for each crop (JCRMO, 2019). Thus, the area dedicated to each crop, multiplied by the theoretical average amount of gross irrigation water, cannot be higher than the volume assigned for the farm. In this sense, farmers must yearly submit a document, their "Exploitation Plan" (EP), which reports the crops to be cultivated, the total area dedicated to each crop, and the cadastral reference of the plots where crops will be cultivated. The document will be approved if the total estimated volume is lower or equal to the amount assigned for that season to the farmer in question. However, if the season is drier than average, the farmer can apply a greater volume of irrigation water to fulfill the requirements of the crop, while if the year is wetter, it is assumed the farmer will save water to reduce the energy costs. Similarly, if the farmer selects high irrigation requirement crops, a considerable percentage of the irrigable area of the farm must possibly be left as fallow or cultivated under rainfed conditions. Therefore, what is actually limited and controlled in the HUEM is the irrigated area of the farms rather than the real amount of water used in them (JCRMO, 2019).

In the case of barley, for the 2015–2017 period, the average gross irrigation requirements established by JCRMO were 2450 m^3 ha^{-1} (JCRMO, 2019), which is lower than the average endowment in the area (4000 m^3 ha^{-1}). This crop is cultivated because of its importance in the suitable rotation of horticultural crops and to compensate for the greater use of irrigation water by other crops. Nevertheless, in years with dry winters and/or dry springs, crop needs can exceed 4000 m^3 ha^{-1}, which entails a greater than expected use of groundwater in the area. This can negatively affect the profitability of the basin, given that the cultivated area of barley in HUEM is around 15,000 ha and its water profitability (0.10 € m^{-3}; Domínguez et al., 2017) is low compared with the average water profitability of crops cultivated in the Júcar river basin (0.80 € m^{-3}; CHJ, 2018).

2.2. Field experiments

A three-year experiment (2015–2017) was conducted at the Integrated Center for Vocational Training in Aguas Nuevas (longitude 1º 53' 58'' W, latitude 38º 56' 42'' N, at an altitude of 695 m above sea level) (Albacete, Spain) (Fig. 1).

Five irrigation treatments were performed during the experiment: no deficit (ND) (control), and four with different volumes of available irrigation water, which corresponded to 100% (T100), 90% (T90), 80% (T80), and 70% (T70) of barley net irrigation requirements for the weather conditions of the intermediate Typical Meteorological Year (2500 m^3 ha^{-1}; Pardo et al., 2020) (TMY) (Hall et al., 1978; Domínguez et al., 2013). The T100 volume was assumed to be sufficient to complete the crop cycle without water deficit (Pardo et al., 2020), even though the weather conditions during the crop cycle are unknown. Therefore, our initial hypothesis during the three years of the trial was that the irrigation schedule of T100 would coincide with that of ND treatment for a TMY-intermediate. If the climatic conditions were drier than those of a TMY-intermediate, T100 would stop irrigating when the available water was depleted, i.e., before the crop reached physiological maturity.

The experimental area (4730 m^2) was composed of four 51 m x 18 m plots. Each year, 18 subplots of 2.5 m x 18 m (sampling area of 2.5 m x 12 m) and another two of 3 m x 18 m (buffer) were defined. The soil is classified as Calcixerrollic-Petrocalcic-Xerochrepts (USDA-NCRS, 2006). The average soil depth is 40 cm, being classified as clay-loam texture. Four randomly distributed repetitions of each treatment were established in each plot, except in the case of no deficit and T100 treatments, for which the number of repetitions was three.

Water was applied by a square spacing drip irrigation system (0.5 ×0.5 m between pipes and emitters), equipped with self-compensating emitters providing 3.8 L h^{-1} of nominal flow. A high accuracy (2%) flowmeter per treatment was installed, as well as soil moisture sensors (volumetric and tensiometer) for the water use monitoring.

The amount of fertilization applied to each treatment was determined according to the expected yield simulated by MOPECO for a typical year.

A more detailed description of the experiment is included in Pardo et al. (2020).

2.3. Optimized Regulated Deficit Irrigation for Limited volumes of irrigation water (ORDIL)

The net irrigation requirements of a barley crop under the TMY-intermediate conditions were estimated using the MOPECO model, which was calibrated for this crop in the area by López-Urrea et al. (2020) (Table 1). The resulting amount of water was considered as the reference, and was assigned to the T100 treatment (2500 m^3 ha^{-1}). Three ORDIL strategies were then performed with three different volumes of available irrigation water, corresponding to 90% (T90), 80% (T80), and 70% (T70) of net irrigation requirements (2250, 2000 and 1750 m^3 ha^{-1} respectively). In addition, one treatment under no deficit conditions (ND) was carried out as control.

ND and 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 (2500 m^3 ha^{-1}). The irrigation schedules of the three ORDIL treatments followed the methodology established by Leite et al. (2015a). This methodology determines the deficit in terms of ET_a/ET_m to be applied to the crop at each K_y stage to maximize yield and estimates the amount of irrigation water required to reach that level of deficit, using the TMY climatic data and the MOPECO simulation model. After the end of each K_y stage, a new optimization is carried out in order to take into account the actual amount of irrigation water applied to the crop and the actual ET_a/ET_m. Therefore, at each optimization, the deficit to be reached in the following stages to maximize yield is updated according to the remaining available water. A detailed description of how ORDIL works and the deficit reached in each development stage can be found in Pardo et al. (2020). Table 2 shows the results in terms of yield, global ET_a/ET_m and amount of water received by the different treatments (Pardo et al., 2020).

2.4. Analysis of harvest

In the case of barley, the harvest price is conditioned by the quality of the grain (MAPAMA, 2017), affecting the profitability of the farm. In

Table 1
Parameters for the simulation of barley in Castilla-La Mancha region by using MOPECO.

Stage	$^{(*)}K_c$	GDD (°C)	Stage	K_y $^{(**)}$	GDD (°C)	Other parameters	Value
I	0.30	290.3	i	0.20	645.3	ET group	3
II	0.30–1.15	744.5	ii	0.55	981.2	Y_m (kg ha^{-1})	9000
III	1.15	1087.2	iii	0.30	1186.1	T_L (°C)	2
IV	1.15–0.45	1449.5	iv	0.15	1449.5	T_U (°C)	28

$^{(*)}$ K_c values based on those proposed by FAO 56 (Allen et al., 1998) and fitted to the regional conditions (López-Urrea et al., 2020); K_c: crop coefficient; K_c (I): initial; K_c (II): crop development; K_c (III): mid-season; K_c (IV): late season; GDD: accumulated growing-degree-days; 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): flowering period; K_y (iii): yield formation; K_y (iv): 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 cultivar 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; $^{(**)}$ To apply ORDIL methodology, the maximum difference between ET_a/ET_m rates of two consecutive K_y stages was established as 0.25.

Table 2
Amount of water received by the treatments and yields.

Year	Treatment	Irrigation water (m^3 ha^{-1})	Total water (m^3 ha^{-1})	Global ET_a/ET_m	Yield (kg ha^{-1})	YWP (kg m^{-3})
2015	ND	2856	3915	1.00	9199	3.22
	T100	2506	3565	0.94	8614	3.45
	T90	2251	3311	0.87	7620	3.39
	T80	2002	3061	0.82	7362	3.68
	T70	1753	2812	0.76	6404	3.66
2016	ND	3334	4373	0.96	8877	2.66
	T100	2584	3623	0.84	7973	3.09
	T90	2250	3290	0.83	7691	3.42
	T80	2004	3043	0.78	7224	3.60
	T70	1755	2795	0.73	6331	3.61
2017	ND	3679	4718	1.00	9071	2.47
	T100	2500	3539	0.85	8028	3.21
	T90	2251	3291	0.81	7621	3.39
	T80	2017	3057	0.77	7311	3.62
	T70	1748	2787	0.71	6282	3.59

Total water: Irrigation Water; + Effective rainfall; ET_a/ET_m: ratio between accumulated actual and maximum evapotranspiration; YWP: irrigation water productivity in terms of yield.

order to quantify the combined effect of ORDIL and the level of deficit on the quality of the harvest, a series of quality parameters was analyzed in the eight samples collected per treatment.

Malting plants establish their own requirements for determining the quality of barley grains and malt (Coles et al., 1991). In this case, the criteria set by the INTERMALTA malting factory located in Albacete and belonging to MALTEUROP group (www.malteurop.com) were used (Intermalta, Personal communication). This company analyzed the malt parameters described below, following the official methodology (EBC ANALYTICA, 2019). After the analysis, the company only provided the average result for each parameter. Consequently, these data could not be statistically analyzed.

Grain parameters:

- Caliber of grains: the minimum total weight percentage of grains with a caliber higher than 2.5 mm (Fraction II) must be 90%, the maximum total weight percentage of grains with a caliber lower than 2.2 mm (Fraction IV) must be 2.5%, and the total weight percentage of broken grains must be lower than 4%. Grain calibre was measured using a "Sortimat" (Pfeuffer©) device.
- Protein content: the value must be compressed between 9.5% and 12.5%. This parameter was measured using an "Infratec Grain Analyzer" (Foss©) device.
- Moisture: the value must be lower than 12%. This parameter was measured using an "Infratec Grain Analyzer" (Foss©) device.

Malt parameters:

- Moisture: values must be compressed between 4% and 5%.
- Extract: values should be higher than 80%.
- Total protein: values must be compressed between 9.5% and 12.5%.
- Soluble protein: accepted values range from 4% to 6% depending on the type of malt sought.
- Kolbach index: values must be compressed between 35 and 45.
- Friability: values must be higher than 80%.
- Viscosity: values should be lower than 1.55 cP, although values up to 1.57 cP may be accepted.
- β-glucan content: values should be lower than 175 mg L^{-1}, although values up to 200 mg L^{-1} may be accepted.

2.5. Effect of ORDIL on the profitability of barley at farm scale

To calculate gross margin (GM), it is necessary to determine the yield of grains (12% moisture), the amount of straw, the amount of water supplied to the crop and its cost, the subsidies, and the variable costs related to the management of the crop:

$$GM = Y_a HP + Y_a{}' HP' - Cv - I_G Cw + Subs \quad (1)$$

GM: gross margin (€ ha^{-1}); Y_a: main product yield (kg ha^{-1}); HP: harvest sale price of the main product (€ kg^{-1}); Y_a': sub-product yield (kg ha^{-1}); HP': harvest sale price of the sub-product (€ kg^{-1}); Cv: variable costs (€ ha^{-1}), which were obtained in de Juan et al. (2003) and updated for this study. Different yield objectives involve different uses of production inputs and, therefore, different variable costs; I_G: gross irrigation depth applied by the irrigation system (m^3 ha^{-1}); Cw: irrigation water cost, using 0.12 € m^{-3} in this study (Carrión et al., 2016); Subs.: subsidies for farmers, using 200 € ha^{-1} in this study (Domínguez et al., 2017).

In order to analyze the irrigation methodology effects on GM, harvest prices were equal and calculated as the average of the three years for the trials, considering the main product and the sub-product at market price (182.5 € Mg^{-1} for malting grains, 158.8 € Mg^{-1} grains for animal feeding and 4.0 € Mg^{-1} for straw) (MAPAMA, 2017).

For each irrigation strategy (ND, T100, T90, T80 and T70), we analyzed the economic irrigation water productivity "EWP" (defined as the gross margin produced by the crop per unit of gross irrigation water supplied).

In order to assess the effect of the results obtained in this experiment at farm scale, the following scenarios were analyzed (FARM_S):

- The farmer was assumed to dedicate 15 ha of the total area of the farm to barley, irrigating 10 ha by ND strategy and cultivating the remaining area under rainfed conditions.
- Under the climatic conditions of the three experimental years and extrapolating the yield and economic results obtained in the trials, we calculated the increase in irrigated area of each ORDIL treatment

that would have been necessary to reach a similar profitability to that obtained by the ND treatment.

- The effect of ORDIL strategies on the total volume of water applied by the farmer was also analyzed. The difference between the total available area for barley and the area occupied by ND and ORDIL treatments was assumed to be covered by rainfed barley, with a profitability ranging between − 68 and 104 € ha^{-1}, according to the average yield obtained in the area in the study years (MAPA, 2017, 2018).
- To calculate the gross irrigation requirements, it was considered that losses due to evaporation and drift, together with the lack of uniformity of the irrigation system, generate a 12% increase in net irrigation water use (Ortiz et al., 2009).

2.6. Effect of ORDIL on the profitability of barley and on the sustainability of the HUEM agricultural system

This section aims to assess the economic and environmental impact of the most favorable ORDIL treatment (Section 2.5) on barley cultivation at HUEM scale if farmers decide to use this methodology in the entire cultivated and irrigated area of this crop.

In this scenario (HUEM_S), the ND and ORDIL T80 strategies were compared. Thus, in the case of ND, it was assumed that the irrigation water requirements of the crop in the entire cultivated area were fulfilled, given that the Exploitation Plan limits the area but not the actual amount of water supplied to the crop. In the case of ORDIL T80, we calculated the total area that could have been irrigated during the three experimental years, using the same theoretical amount of water used by ND. In the comparison, the water consumption, yield and costs of each strategy were assumed to be similar to those obtained in the experiment. However, in order to avoid overestimates of the economic impact when calculating the GM differences, we considered only 8% of the total production of both strategies reached malting quality, which corresponds to the national average data (CE, 2019).

2.7. Statistical analysis of the results

For every year, Duncan's test (Westfall and Stanley, 1993) was performed to determine whether significant differences ($p < 0.05$) existed between irrigation treatments.

3. Results

3.1. Effect of ORDIL on the quality parameters of grain and malt

Although the global ET_a/ET_m covered a wide range of values (from 0.71 to 1.00; Table 2), the 2015 and 2017 seasons obtained a very similar distribution of calibers. However, the calibers obtained during 2016 were significantly lower in the main fractions (Fraction I and II around 16% and 6% less respectively; Table 3). Nonetheless, the size of more than 90% in weight of the harvested grains was greater than 2.5 mm for all treatments and years (Table 3). Analyzing the distribution of calibers for fraction I (>2.8 mm), the T100 treatment obtained the worst values in the three years (between 67% and 80%), with the T90 and T80 treatments generally being the ones that achieved the highest percentages (83% and 82%, respectively; Table 3). For Fraction II (> 2.5 mm), the average intra-year values were very similar, and significant differences only appeared between T80 (highest values) and T70 in 2015. For the rest of the fractions, T100 was the treatment with the poorest results for all the years (Table 3).

As with the calibers, during the three years, and in all the treatments, the protein content requirements were met, since they did not exceed

Table 4
Grain protein and moisture content in the three experimental years.

Year	Treatment	Global ET_a/ET_m	Protein (%)	Moisture (%)
2015	ND	1.00	11.03a	10.08b
	T100	0.94	11.19a	9.86ab
	T90	0.87	11.62a	10.11b
	T80	0.82	11.56a	9.97b
	T70	0.76	11.50a	9.64a
	p valor		ns	*
2016	ND	0.96	11.63a	10.40a
	T100	0.84	11.94a	10.32a
	T90	0.83	11.90a	10.37a
	T80	0.78	11.62a	10.38a
	T70	0.73	11.85a	10.43a
	p valor		ns	ns
2017	ND	1.00	11.50a	10.57b
	T100	0.85	12.05a	10.33a
	T90	0.81	11.80a	10.55b
	T80	0.77	11.75a	10.43ab
	T70	0.71	11.60a	10.43ab
	p valor		ns	*

ET_a: actual evapotranspiration; ET_m: maximum evapotranspiration; ns: not significant; *: $p < 0.05$. Duncań's test.

Table 3
Grain size obtained by the different treatments in the three experimental years.

Year	Treatment	Global ET_a/ET_m	Fraction I (> 2.8 mm) (%)	Fraction II (> 2.5 mm) (%)	Fraction III (2.2–2.5 mm) (%)	Fraction IV (<2.2 mm) (%)
2015	ND	1.00	82.18 bc	97.75ab	1.55a	0.42a
	T100	0.94	76.98d	96.99ab	2.18b	0.66a
	T90	0.87	87.97a	97.71ab	1.24a	0.64a
	T80	0.82	86.57ab	97.97a	1.31a	0.44a
	T70	0.76	81.54c	96.80b	1.78ab	0.50a
	p valor		*	*	*	ns
2016	ND	0.96	72.48a	91.62a	6.10a	2.28a
	T100	0.84	67.04a	90.42a	7.16a	2.42a
	T90	0.83	71.63a	91.53a	6.65a	1.82a
	T80	0.78	70.48a	91.38a	6.32a	2.30a
	T70	0.73	70.92a	91.78a	6.08a	2.14a
	p valor		ns	ns	ns	ns
2017	ND	1.00	88.85a	97.50a	2.05a	0.40a
	T100	0.85	79.97b	97.07a	2.50a	0.40a
	T90	0.81	89.73a	97.15a	2.45a	0.43a
	T80	0.77	89.58a	97.23a	2.30a	0.48a
	T70	0.71	86.63a	97.23a	2.18a	0.40a
	p valor		*	ns	ns	ns

ET_a: actual evapotranspiration; ET_m: máximum evapotranspiration; ns: not significant; *: $p < 0.05$. Duncań's test.

the 12.5% threshold established by the industry (Intermalta, Personal communication) (Table 4). No significant differences in grain protein were found between treatments, with the 2015 treatments being those with the lowest percentage of protein (between 11.0% and 11.6%), thanks to both the distribution of rainfall and temperatures, together with the lower levels of water deficit achieved (Table 4). While, in 2015, the T100 treatment showed the second lowest percentage of protein (11.2%), in 2016 and 2017, it presented the highest content (around 12.0%; Table 4).

Grain moisture in all treatments in the three seasons was below the threshold (12%; Table 4). There were slight differences between treatments, with the lower content of T100 being justified by the early depletion of the irrigation water. On the other hand, the water deficit caused by ORDIL did not negatively affect the quality of the malt, since all the parameters were within the ranges required by the malting plant in the three seasons (Table 5). Finally, as observed with grain size, the climatic conditions of year 2016 negatively affected the results, although they all fulfilled the requirements of the malting plant. Comparing ORDIL treatments with ND, similar values were obtained for the majority of the parameters, with some, such as Kolbach Index (only in 2015), friability, and viscosity, even improving (Table 5).

3.2. Effect of ORDIL on the profitability of farms

In the three years of the study, the cost of irrigation water represented between 22% for T70 and 27% of the total cost for T100 treatments, reaching 33% in ND treatments (Table 6). The maximum GM per unit of area was obtained by ND in 2015 (507.2 € ha^{-1}), when irrigation requirements were lower, decreasing by 19% and 23% in 2016 and 2017, respectively (Table 6). For the same treatment, the interannual differences were more pronounced in the non-optimized treatments (around 19%) than in the ORDIL ones (around 3%). Thus, the maximum difference for ND was 23% (2015 and 2017) and 18% for T100 (2015 and 2016), while in the ORDIL treatments it was 11% for T70 in 2016 and 2017 years, being 3% for T80 and T90 for 2015 and 2016.

Economic irrigation water productivity (EWP) increased with the water deficit, reaching the maximum in the T80 treatment. Comparing T80 with ND, the improvement in EWP was 10.4%, 53.3% and 79.9%, in 2015, 2016 and 2017, respectively (Table 7). As in the case of GM, the optimized treatments presented a lower interannual EWP variability.

The irrigated barley area that a farmer should dedicate to each ORDIL treatment under the premises of the FARM_S scenario is shown in Table 8. The area increased with water deficit, being around 45% greater in the case of T70. In addition to reaching the same profitability as ND for the total barley area, ORDIL strategies would have used a lower amount of irrigation water, saving between 11.4% and 37.6% of total irrigation water supplied to barley, depending on the year and ORDIL treatment. Thus, the T80 strategy was the most successful for the 3 years studied, saving, on average, 30.6% of irrigation water by increasing the irrigated area of barley 14% (Table 8).

3.3. Effect of ORDIL on the profitability and sustainability at HUEM scale

During the 3 experimental years, an average of 345 hm^3 year^{-1} of water was theoretically supplied to crops cultivated in the HUEM, with 15,000 ha year^{-1} (around 14% of the total) being the average area dedicated to irrigated barley (JCRMO, 2019) (Table 9). According to the irrigation requirements of barley established by the Exploitation Plan, the theoretical volume of water supplied to barley in the area would have reached 110.2 hm^3. The T80 strategy, instead of ND during the 3 experimental years, equaled the volume estimated by JCRMO by increasing the irrigated barley area by 9% (Table 10). In addition, extrapolating the observed irrigation requirements (Table 6) to the total cultivated area of the HUEM, the actual water consumption would have reached 166.1 hm^3. This represents around 55.9 hm^3 more than the theoretical value for the three campaigns (Table 9). The GM of the HUEM would have enhanced by up to 0.8 million euros in the 2016 and 2017 campaigns. However, it would have decreased by up to 0.30 million euros (2%) in all three years (Table 10). Nonetheless, the EWP of barley would have improved by 47% on average.

4. Discussion

4.1. Effect of ORDIL on the quality parameters of grain and malt

In general, although no minimum value is assigned to Fraction I (> 2.8 mm) by the malting industry, it is considered the most interesting fraction, since large grains usually have a higher starch content and thus produce a higher extract yield (Cozzolino et al., 2021). Nevertheless, the Fraction II results for all treatments are similar to those obtained by Martínez-Romero et al. (2017) with a "Scarlett" cultivar in CLM (90–96%), and higher than those observed by Pržulj et al. (2014) in Serbia with eight malting cultivars (79–91%). Similarly, Pettersson and Eckersten (2007), for two malting cultivars under different nitrogen fertilization doses in Sweden (82–91%), Högy et al. (2013), in Germany with the "Quench" cultivar (73–81%), and Marconi et al. (2011), in Italy with six different cultivars (47–84%), achieved lower percentages in this fraction. The lower caliber values obtained during 2016 can be justified because the amount of nitrogen fertilizer applied that year was significantly higher compared to the other two. Thus, the amount was increased (10%) to reduce the risk of great nitrogen leaching losses caused by large forecast precipitations for the days after the application,

Table 5
Malt quality parameters.

Year	Treatment	Moisture (%)	Soluble Protein (%)	Total protein (%)	Extract (%)	Kolbach index	β-glucan content (mg L^{-1})	Friabi-lity (%)	Viscosi- ty (cP)
2015	ND	4.7	4.6	10.2	83.9	45	131	91	1.51
	T100	4.9	4.7	11.2	82.9	41	133	90	1.49
	T90	4.6	5.7	11.4	80.0	50	86	91	1.46
	T80	4.8	5.0	11.1	83.3	45	135	90	1.49
	T70	4.8	6.0	11.7	84.3	52	81	94	1.48
2016	ND	5.2	4.2	10.9	81.3	39	97	86	1.48
	T100	5.4	4.5	11.3	81.8	40	56	89	1.45
	T90	5.4	4.1	11.3	80.8	38	*	89	1.46
	T80	5.3	4.1	10.8	81.0	38	138	85	1.50
	T70	5.3	4.2	10.9	81.0	39	133	83	1.49
2017	ND	5.8	4.4	11.3	82.3	39	50	92	1.47
	T100	5.9	4.4	12.1	81.1	36	61	84	1.49
	T90	5.8	4.2	11.7	81.7	36	117	86	1.53
	T80	5.9	4.0	11.1	82.0	36	110	82	1.51
	T70	5.8	4.2	11.6	81.7	36	71	89	1.49

* could not be carried out due to lack of sample, as the analyzes had to be repeated twice due to changes in the micromalting software

Table 6
Yields, irrigation water and economic data for calculating the gross margin.

Treatment	Y_a (kg ha^{-1})	Y_a' (kg ha^{-1})	Cv (€ ha^{-1})	I_G (m^3 ha^{-1})	Total Income+Subs (€ ha^{-1})	Total costs (€ ha^{-1})	GM (€ ha^{-1})
Year 2015							
ND	9199	8845	1017.0	3250	1914.2	1407.0	507.2
T100	8614	8283	982.1	2841	1805.2	1323.0	482.2
T90	7620	7523	922.8	2557	1620.7	1229.6	391.1
T80	7362	7079	907.4	2273	1571.9	1180.2	391.7
T70	6404	6158	850.3	1989	1393.4	1089.0	304.4
Rainfed*	1289	1418	478.0	0	410.4	478.0	-67.6
Year 2016							
ND	8877	10,436	997.8	3788	1861.8	1452.3	409.5
T100	7973	8674	943.9	2936	1689.8	1296.2	393.5
T90	7691	8491	927.1	2557	1637.6	1233.9	403.7
T80	7224	7853	899.2	2278	1549.8	1172.5	377.3
T70	6516	7464	857.0	1995	1419.0	1096.4	322.6
Rainfed*	2457	2703	496.5	0	601.0	496.5	104.4
Year 2017							
ND	9071	11,614	1009.3	4181	1901.9	1511.0	390.9
T100	8028	7817	947.2	2841	1696.4	1288.1	408.3
T90	7621	9003	922.9	2558	1626.8	1229.9	397.0
T80	7311	7712	904.4	2293	1565.1	1179.5	385.6
T70	6282	5722	843.1	1987	1369.4	1081.4	287.9
Rainfed*	1764	1940	485.5	0	487.9	485.5	2.4

GM: gross margin; Ya: grain yield; Ya': straw yield; Cv: variable costs; I_G: gross irrigation depth applied by the irrigation system; Subs.: subsidies for farmers = 200 € ha^{-1} (Domínguez et al., 2017); Irrigation water cost = 0.12 € m^{-3}; Grain price (malting quality) = 182.5 € Mg^{-1}; Grain price (animal feeding) = 158.8 € Mg^{-1}, it was considered rainfed barley do not reach malting quality; Straw price = 4.0 € Mg^{-1}; *Data from Ministry of Agriculture, Fishery and Food (MAPA, 2017, 2018)

Table 7
Economic water productivity.

Year	Treatment	EWP (€ m^{-3})
2015	ND	0.16a
	T100	0.17a
	T90	0.15a
	T80	0.17a
	T70	0.15a
2016	ND	0.11c
	T100	0.13 bc
	T90	0.16ab
	T80	0.17a
	T70	0.16ab
2017	ND	0.09c
	T100	0.14b
	T90	0.16ab
	T80	0.17a
	T70	0.14b

EWP: Economic Water Productivity; $P < 0.05$. Duncan's test.

events that did not occur. Furthermore, during the grain filling period, all the treatments were subjected to a severe water deficit due to an 8-day failure in the pumping system. In this regard, in Holland, and with the "Prisma" cultivar, Grashoff, d'Antuono (1997) observed that the greater the nitrogenous fertilization, the higher was the number of grains per m^2, reducing the weight and size of the grains. Similarly, Qi et al. (2006) in China, for the "Logan" and "Thompson" cultivars, and Albrizio et al. (2010), for the "Ponente" cultivar in Italy, reported the same response. On the other hand, water deficit from anthesis to maturity accelerates leaf senescence, reduces the duration and filling rate of the grain (Albrizio et al., 2010). Additionally, it decreases the time of translocation of carbohydrate reserves to the grain (Oweis et al., 2000), and reduces the average weight and size of the grain (Acevedo et al., 2002). This explains why T100 obtained the worst Fraction I (> 2.8 mm) results, since this treatment suffered severe stress during the last stages of development when the volume of irrigation water for this treatment was exhausted. In any event, the values obtained by this treatment (67–90%) were higher than those documented by Högy et al. (2013) (32–33%) for this fraction.

High T100 protein content in 2016 and 2017 was caused by the early water depletion, together with the high temperatures achieved during the grain filling stage. This result coincides with the findings of several authors (Morgan and Riggs, 1981; Varvel and Severson, 1987; Grant et al., 1991; Weston et al., 1993; Eagles et al., 1995; Savin and Nicolas,

Table 9
Differences between average and actual irrigation requirements of barley for the climatic conditions of the 3 experimental years in the HUEM.

Year	Barley area (ha)	Volume for irrigating HUEM area (hm^3)	Barley irrigation (hm^3)	
			Volume estimated by JCRMO	Estimated Full irrigation requirements
2015	17,412	338.2	42.7	56.7
2016	14,971	342.5	36.7	56.7
2017	12,584	353.4	30.8	52.6
Total	44,967	1034.1	110.2	166.1

Table 8
Economic analysis at farm level for the premises of FARM_S scenario.

Treat-ment	Irri-gated area (ha)	Rain-fed area (ha)	GM (irrigated + rainfed area)				Water saved vs ND			
			2015 (€)	2016 (€)	2017 (€)	Total (€)	2015 (%)	2016 (%)	2017 (%)	Total (%)
ND	10.0	5.0	4734	4617	3921	13,272	0.0	0.0	0.0	0.0
T90	11.0	4.0	4034	4860	4378	13,272	13.4	25.7	32.7	24.7
T80	11.4	3.6	4209	4669	4393	13,272	20.5	31.6	37.6	30.6
T70	14.5	0.5	4374	4727	4171	13,272	11.4	23.7	31.2	22.9

ND: no deficit strategy; T90, T80 and T70: ORDIL strategies; GM: Gross Margin;

Table 10
Economic analysis at basin level for the premises of FARM_S scenario.

Year	Barley area (ha)		Yield (Mg)		GM (€ ha^{-1})		Barley GM in HUEM (M€)		Irrigation water saved by T80 (hm^3)
	ND	T80	ND	T80	ND	T80	ND	T80	
2015	17,412	18,770	160.2	138.2	350.66	266.41	6.11	5.00	14.1
2016	14,971	16,139	132.9	116.6	258.37	254.32	3.87	4.10	20.0
2017	12,584	13,566	114.1	99.2	236.5	261.17	2.98	3.54	21.8
Total	44,967	48,474	407.2	353.9	–	–	12.95	12.65	55.9

ND: no deficit strategy; T80: ORDI T80 strategy; GM: Gross Margin; HUEM: Hydrogeological Unit "Eastern Mancha"

1996; Birch et al., 1997). Despite some authors, such as Coles et al. (1991) or Macnicol et al. (1993), observing that, in the "Triumph" and "Schooner" cultivars, water deficit reduced the protein content for the same fertilizer level, subsequent works reported contrasting findings. Wu et al. (2015) detected differences of more than four percentage points in the protein content in favor of the deficit treatments; Martínez-Romero et al. (2017) identified significant differences with the same fertilizer level for a 30% deficit level; while Albrizio et al. (2010) exceeded the limits established by the malting plants in the deficit treatments. A comparison between the ND and T100 treatments shows that, for the same amount of fertilizer, the water deficit increased the percentage of protein (Table 4). However, ORDIL treatments reached suitable protein contents likely thanks to the amount of water reserved for the last stage (Leite et al., 2015a), avoiding great deficits at any stage, together with a nitrogen fertilization dose fitted to the expected yields. The fact that no significant differences appeared between ORDIL treatments validates this methodology.

Although no relationships between malt quality parameters were found in our study, Wang et al. (2004) reported relationships between β-glucans and viscosity, extract, Kolbach index, and diastatic power. In addition, no relationships were found, either, between these parameters and water deficit, as was reported by Jansen et al. (2013) with the β-glucans. The former authors detected greater β-glucan content in the treatments subjected to higher water deficit. In contrast, Coles et al. (1991) and Wu et al. (2015) revealed that β-glucans decreased as water deficit increased. Finally, Henry (1985) and Jansen et al. (2013) found a positive relationship between grain protein and β-glucan content. The malt quality parameters obtained in this experiment were better than those documented by Nielsen, Munck (2003) in European Brewery Convention (EBC) trials with 25 cultivars in Denmark (extract ranging between 79% and 83%, Kolbach index ranging between 32% and 39%, friability ranging between 46% and 84%, viscosity ranging between 1.61 and 1.91 cP, and β-glucans ranging between 267 and 853 mg L^{-1}). They were also better than those observed by Marconi et al. (2011) with 6 cultivars in Italy (moisture ranging between 4.2% and 4.8%, extract ranging between 78% and 80%, friability ranging between 55% and 78%, viscosity ranging between 1.52 and 1.68 cP and β-glucans ranging between 245 and 452 mg L^{-1}), and similar or slightly better than those achieved by Pržulj et al. (2014) in Serbia for 8 different cultivars (extract ranging between 76% and 80%, Kolbach's index between 33% and 43%, viscosity between 1.44 and 1.61 cP).

4.2. Effect of ORDIL on the profitability of farms

The costs of irrigation water in all treatments were in a similar range to those obtained by Domínguez et al. (2017) for this crop in the area (between 21% and 26%), which is a considerable percentage compared to other crops, such as garlic (between 4% and 6%; Domínguez et al., 2013) or onion (between 10% and 12%; Domínguez et al., 2017), and similar to maize (between 25% and 28%, Domínguez et al., 2017, 2011). Due to the harvest price being low, the efficient management of water in barley is essential to reach suitable profitability. The ORDIL treatments decreased income variability as a result of a lower impact on the gross margin of the amount of irrigation water applied to the crop, and reasonably stable yields (Table 6). In addition, the year-to-year differences in gross margin of the ND and T100 treatments can be explained by the yield drop in the T100 treatment, caused by the water deficit at the end of the cycle, and the increased irrigation requirements in the dry years for ND. Despite ND achieving the highest yield, this strategy did not always generate the highest GM for the total cultivated area of barley, including under rainfed conditions (Table 8). Thus, in 2016 and 2017, the higher yield obtained by ND did not compensate for the drop of EWP caused by higher irrigation water requirements (Table 7), being T90 and T80 the most profitable strategies, respectively (Table 8).

4.3. Effect of ORDIL on the profitability and sustainability at HUEM scale

Extrapolating the results of this trial, the irrigation needs of barley were found to have been much higher than those considered by the water management authority (JCRMO) in the area (51% higher). Applying the T80 strategy instead of ND during the 3 experimental years, up to 55.9 hm^3 of water could have been saved in the HUEM by increasing the irrigated area by 9%. In addition, in dry years, like 2016 and 2017, the GM would have improved by up to 20% (Table 10), although in other years under less severe climatic conditions, such as 2015, the GM would have been significantly lower (18%).

On the other hand, if the 55.9 hm^3 of water had been used for irrigating other more profitable crops from the Júcar system, where the average EWP equals 0.8 € m^{-3} (CHJ, 2018), the income of this area could have increased by up to 44.4 million € more. Another option could be to use this volume of water to recover the piezometric levels of the Eastern Mancha aquifer, which, despite having been stabilized in recent years, thanks to adequate management by the CHJ and the JCRMO, are still below their reference levels. This solution would mean an environmental improvement in the ecosystems of the area, as well as a decrease in the costs of pumping irrigation water since it would be located at a lower depth. Moreover, a decrease in the CO_2 footprint would be generated when using a conventional source of energy.

Under real conditions, the amount of water saved would probably not have been as large as that considered in Tables 9 and 10, due to the low profitability of barley leading many farmers to apply deficit irrigation to reduce costs. Furthermore, many pumping systems are unable to provide enough water during the peak demand period of the farm due to the high irrigation requirements of the total crops cultivated at the same time. In this sense, Garrido-Rubio et al. (2020), using remote sensing techniques in the HUEM, estimated an average decrease of 38% (ranging between 24% and 56%) in the total amount of irrigation water supplied to this crop with respect to the potential requirements for year 2012. Similarly, Nascimento (2018) stated an average 18% reduction (ranging between 0% and 49%) in the monitoring of 6 commercial plots in the same area during the 2015 and 2016 campaigns. These results confirm that farmers decrease the amount of water supplied to this crop to reduce costs and save water for other crops. Consequently, yields for the whole aquifer will also be lower than those considered for the whole aquifer for ND strategy (Table 10). In this sense, the average yield of irrigated barley for the three study years was 6333 kg ha^{-1} (MAPA, 2017, 2018), well below the around 9000 kg ha^{-1} considered for the HUEM_S scenario. Therefore, the profitability of ND barley in the zone is also lower than that considered in Table 10, although the profitability assigned to T80, as well as the consumption, could be closer to reality under appropriate management conditions. In addition, it is necessary to take into account that the way farmers apply deficit to barley is based on their own criteria, or is forced by the circumstances. Moreover, it is usually carried out during the highest demand period of the year (May and beginning of June), which coincides with the formation and filling of the grains (Nascimento, 2018). These stages are highly sensitive to water deficit (Abrha et al., 2012; Acevedo et al., 2002; Carter and Stoker, 1985; Oweis et al., 2000; Ugarte et al., 2007), with it being more advisable to generate deficit to save water during the vegetative development and/or ripening stage in order to avoid a significant drop in the final yield and the irrigation water productivity, as proposed by the ORDIL methodology (Pardo et al., 2020).

5. Conclusions

Despite using a lower amount of irrigation water, the ORDIL treatments showed no significant differences in the quality parameters of grains with respect to the no deficit and the T100 treatments. The caliber was higher than 2.5 mm for 90% of the grains in weight, and the protein and moisture content was lower than 12%. The quality parameters of malt were also within the requirements of the malting plant in all the cases. In this sense, the ORDIL treatments improved some parameters, such as the Kolbach index, friability and viscosity, compared to the no deficit and the T100 treatments. Therefore, the irrigation water allocation proposed by ORDIL, combined with a suitable fertilization amount fitted to the yield forecasted by the MOPECO model, allowed the malt category to be reached in all the treatments and studied years. Thus, the ORDIL methodology can distribute a volume of water lower than the crop needs, throughout the crop cycle, without knowing in which climatic conditions the crop will develop, allowing suitable yields to be reached without compromising quality. Consequently, ORDIL avoids supplying excessive amounts of irrigation water to low profitable crops as barley. The amount of water saved could be used by more profitable crops or sectors to reduce the pressure on natural sources, improve natural habitats, increase the piezometric levels of aquifers and reduce the energy cost and the CO_2 footprint; in other words, to enhance profitability and sustainability at farm and basin level.

In the case of a typical farm of the area, with a large non-irrigated area due to low availability of irrigation water, using the ORDIL T80 strategy (the one that achieved the highest profitability) instead of full irrigation (ND), the same profitability could be reached with barley, saving up to 31% of water by increasing the irrigable barley area by around 14%. This remaining water could be used to irrigate other more profitable crops, thus increasing the total income of the farm. Moreover, ORDIL decreases the impact of water cost and yield variability on the final profitability of barley at farm level.

In the case of the HUEM, during the three experimental years, which were drier than the average, the amount of water saved by ORDIL in barley would have reached 55.9 hm^3 (16% of the total amount of water used every year in the area). This volume could have increased the income of the Júcar system by up to 44.4 million euros, in the case of supplying that water to other more profitable crops.

Tools such as ORDIL are essential to advise farmers in the management of available irrigation water and in controlling the deficit level of their crops. This aspect is critical in dry years when actual irrigation needs are much higher than those set by regulators. Thus, inappropriate allocation of water during the growing period can negatively affect the profitability of their farms.

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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