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Quantitative analysis of almond yield response to irrigation regimes in Mediterranean Spain

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ABSTRACT

Almond plantations are expanding worldwide, specifically in Spain; the new orchards are often designed under more intensive systems in comparison to the traditional rainfed orchards frequently found in the Mediterranean Sea basin. In these new areas, water is the main limiting factor, and therefore, the present research is aimed at quantitatively analyzing previous findings obtained in irrigation field trials carried out in Spain with mature almond trees. The goal was to derive applied water-production functions and compare sustained and regulated deficit irrigation strategies to provide robust information on the marginal water productivity and the preferred irrigation option to be applied under water scarcity conditions. This quantitative analysis reported a yield increase as water application increased, with the highest potential yield of about 2500 kg/ha achieved with around 1000 mm of irrigation water applied. Under severe water restrictions, similar responses were observed regardless of the deficit irrigation technique employed. In contrast, under moderate water stress, it seems more advantageous to apply a regulated deficit irrigation strategy rather than a sustained deficit strategy. The reported results are useful for deriving more sustainable irrigation protocols and highlight the need to optimize other inputs in addition to water to take full advantage of the irrigation intensification to be carried out in the new almond plantations.

1. Introduction

Global awareness of the health benefits of nuts has resulted in a rapid expansion of the nuts industry, which is expected to continue. In the case of the almond crop, the global harvested area has increased from 1776,546 ha in 2015 to 2162,263 ha in 2020, an increase of 22% in five years (FAOSTAT, 2021). Most of the new almond orchards planted in the main producing countries are intensive irrigated plantations, which would explain the 54% increase in almond production worldwide observed over the same period; from 2696,057 t of shelled almonds in 2015 to 4140,043 t in 2020 (FAOSTAT, 2021). The United States of America, Spain and Australia are the world's leading almond producers, with a share of 57%, 10% and 5% of world production in 2020, respectively (FAOSTAT, 2021).

The almond sector in Spain is undergoing a substantial transformation, with an increase in the cultivated area from 580,467 ha in 2015 (ESYRCE, 2015) to 721,796 ha in 2020 (ESYRCE, 2020). Most of the new almond plantations are being developed in traditional irrigated areas, displacing other irrigated crops (i.e., stone fruits) which have a lower profitability. As a consequence, Spain's irrigated almond area has almost tripled in five years, from 52,990 ha in 2015 to 139,399 ha in 2020 (ESYRCE, 2020, 2015). Despite this increase in irrigated areas, low-yielding rainfed almond orchards still represent 80% of the cultivated area, which explains the low average yields in Spain (0.58 t/ha of

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shelled almonds) as compared to those of the USA (4.68 t/ha of shelled almonds) (FAOSTAT, 2021), where most of the almond plantations are intensively irrigated (Goldhamer and Fereres, 2017).

One of the main threats of the new drip-irrigated almond plantations in Spain is the reduced water allocation provided by the regulatory authorities for this crop species. For instance, the Hydrographical Confederation of the Guadalquivir River Basin establishes an endowment of 250 mm for almond tree plantations in its hydrological regulatory plans (CHG, 2015). This water amount is notably lower than the irrigation requirements to meet the maximum crop evapotranspiration (ETc) of this species under Mediterranean climate conditions, which can exceed 1300 mm in California (Goldhamer and Fereres, 2017), and 800 mm in southern Spain (López-López et al., 2018). These water allocations can be further reduced in drought periods, which are expected to be more frequent due to climate change in arid and semi-arid regions.

Under these scenarios of severe water shortages, experimental works such as that by Moldero et al. (2022) demonstrate the need to continuously develop optimal irrigation management strategies to cope with both the chronic water shortages of most almond producing areas of Spain, and the extreme events caused by cycling droughts. In this regard, Moldero et al. (2022) found that almond trees grown in southern Spain that were submitted to severe water deprivation during a single season, experienced very high tree mortality (92%) when submitted to rainfed conditions after previous seasons of full irrigation application. In contrast, those receiving only 25% ETc had a 33% yield reduction as compared to fully irrigated trees, and recovered yield levels in the following years.

In the last two decades, a great research effort has been carried out in Spain to determine the physiological and agronomic responses of almond trees to irrigation strategies supplying water depths lower than those required to meet the maximum ETc, namely deficit irrigation (DI) strategies (Fereres and Soriano, 2007). Within the term DI, a distinction can be made between sustained deficit irrigation strategies (SDI), aimed at applying a certain level of water deficit throughout the growing season, and regulated deficit irrigation strategies (RDI), aimed at applying water deficit only in certain phenological periods that are less sensitive to water stress (Egea et al., 2013). RDI strategies in almond trees have mainly consisted in applying a more or less severe water deficit during the grain-filling stage, coinciding with the months of highest water demand (Egea et al., 2010; García-Tejero et al., 2019; Girona et al., 2005; López-López et al., 2018; Mañas et al., 2014). However, this has not always been the case, as moderate water deficits have also been applied in the rapid fruit growth and/or postharvest stages in some field experiments (Moldero et al., 2021; Puerto et al., 2013; Romero et al., 2004). The great range of RDI treatments tested, together with the high number of cultivars evaluated, the differing soil (i.e., deep vs shallow soils), and weather conditions (i.e., semi-arid Mediterranean, Continental, Mediterranean), complicate drawing solid and clear messages to convey to irrigation managers and farmers on the most suitable irrigation strategy for a given water allocation in drought-prone areas, such as Spain.

In addition to RDI, SDI irrigation strategies (Egea et al., 2010; García-Tejero et al., 2020; Girona et al., 2005; Gutiérrez-Gordillo et al., 2020; Lipan et al., 2020; López-López et al., 2018; Mañas et al., 2014; Moldero et al., 2021) with different degrees of water deficit ranging from 75% ETc (García-Tejero et al., 2020; López-López et al., 2018) to 25% ETc (Mañas et al., 2014) have also been evaluated in the different almond field trials conducted in Spain. In an experiment carried out in California with almond trees, Goldhamer et al. (2006) found that RDI trees had greater yields than SDI trees when similar amounts of water were applied. However, no clear differential patterns among RDI and SDI strategies were observed in the almond experiments conducted in Spain (Egea et al., 2013; Girona et al., 2005; López-López et al., 2018; Mañas et al., 2014; Moldero et al., 2021). In this sense, a meta-analysis of all the data collected in the experiments conducted so far in Spain on the response of almond trees to deficit irrigation, would help to unravel some questions on the management of deficit irrigation in almond orchards under the soil and climatic conditions found in Spain. For this reason, this work tries to answer the following questions: (1) for a given water allocation below the total crop requirements, what would be the most appropriate irrigation strategy for almond trees grown in Spain?; (2) for a given water allocation, what yield loss can be expected versus that of a well-watered orchard?; (3) under the edaphoclimatic conditions of Spain, is the productive response of almond trees to deficit irrigation conditioned by the timing at which the water stress is applied, or does it depend mainly on the percentage of ETc supplied annually?

2. Materials and methods

2.1. Preparation of the database

Data were collected from studies performed in Spain in which almond trees were subjected to different irrigation regimes. To obtain these data, research groups from all over Spain were contacted and asked to provide the data from their published works. Articles were restricted to those in which a full irrigation control was compared to either a regulated or sustained deficit treatment. Ideally, the three irrigation modalities (namely, full, regulated, and sustained) were investigated within the same study. Whenever possible, a rain-fed treatment was also considered. The criteria for incorporating a work into the final analysis were the following: 1) the experimental characteristics should indicate both in-season (or annual) rainfall and the amount of irrigation applied to each treatment, 2) the articles had to report yields for each treatment, and 3) the almond trees should be, at least, five years old. In the end, the database contained 15 articles for a total of 173 observations, mainly located in Southern and Eastern Spain (Table 1). Data from the selected articles included some years in which the trees were four years old, thus not meeting one of the criteria for selection. Therefore, data were filtered to select only those which referred to adult trees (at least five years after their plantation). Moreover, a treatment with over-irrigated trees was removed from the analysis, except for the calculation of the production function and marginal water productivity, where these data were included (see below). In the end, the database for adult almond trees consisted of 144 observations.

A database was created by listing the irrigation regimes in each study. Yield data were arranged as paired observations in which deficit irrigation treatments were compared to a full irrigation control. The treatments classified as moderate water-stress were those that received annual irrigation volumes above 55% of those received by the control treatments, whereas those that received annual irrigation depths below 55% of maximum crop water requirements were considered severe water-stressed treatments. The stress coefficient threshold value of 55% was chosen based on the production function obtained by Moldero et al. (2021), who observed in their trials carried out in Southern Spain, that reduced yield losses (≈15%) were expected for 45% irrigation shortages, and that kernel yield was impaired more significantly with water shortages higher than 45% of maximum crop water requirements. Other data referred to the experimental conditions, including location, irrigation system design, cultivar, rootstock, spacings, tree density, and age, and external factors such as rainfall received (per year and growing season), and clipped grass reference evapotranspiration (ET_o) were included in the database. Relevant moderators are shown in Table 2. All studies used conventional management practices, so this was not included in the list of moderators. The meta-analysis cannot be performed on continuous variables; hence, the moderators were sub-divided into categories (Mitchell-McCallister et al., 2020). New drip-irrigated almond plantations in Spain (including recently developed varieties, high density planting systems, and regions where almond is newly introduced) would have different water needs, but the research on these new plantations is scarce and, consequently, we did not consider them for the quantitative analysis carried out, focusing on the more traditional almond orchards.

Table 1
Published studies included in the database for the meta-analysis of the use of deficit irrigation in Spanish almond orchards.

Publication	N obs	Irrigation treatments	Cultivar	Age	Spacings	N years	Region
Egea et al. (2010)	10	FI; RDI; SDI	Marta	5	7 × 6	2	Murcia
Egea et al. (2013)	4	FI; RDI; SDI	Marta	5	7 × 6	1	Murcia
García-Tejero et al. (2019)	9	FI; RDI	Guara	5	7 × 6	3	Andalucía
García-Tejero et al. (2020)	9	FI; SDI	Guara, Lauranne, Marta	7	8 × 6	1	Andalucía
Girona et al. (1997)	15	FI; RDI	Marcona	16	5 × 5	3	Cataluña
Girona et al. (2005)	12	FI; RDI; SDI	Ferragnès	6	5 × 6	3	Cataluña
Gutiérrez-Gordillo et al. (2019b)	6	FI; SDI	Guara, Lauranne, Marta	6	8 × 6	2	Andalucía
Gutiérrez-Gordillo et al. (2019a)	18	FI; RDI	Guara, Lauranne, Marta	10	8 × 6	1	Andalucía
Gutiérrez-Gordillo et al. (2020)	9	FI; SDI	Guara, Lauranne, Marta	6	8 × 6	1	Andalucía
Lipan et al. (2020)	4	FI; RDI; SDI	Vairo	8	7 × 6	1	Andalucía
López-López et al. (2018)	9	FI; RDI; SDI	Guara	5	7 × 6	2	Andalucía
Mañas et al. (2014)	24	FI; RDI; SDI	Ferragnès	9	7 × 5	4	Castilla La Mancha
Moldero et al. (2021)	12	FI; RDI; SDI	Guara	8	7 × 6	3	Andalucía
Puerto et al. (2013)	8	FI; RDI	Guara	12	6 × 6	2	Murcia
Romero et al. (2004)	5	FI; RDI	Cartagenera	15	7 × 5	1	Murcia

Included is the number of observations (N obs), irrigation treatments applied, almond cultivars, tree age and spacings, number of years from which data were extracted (N years), and region. Full Irrigation (FI), Regulated Deficit Irrigation (RDI), Sustained Deficit Irrigation (SDI).

Table 2
List of moderators for almond yield recorded from field experiments conducted in Spain from 1990 to 2019.

Moderator	Description
Almond cultivar	Cartagenera, Ferragnès, Guara, Lauranne, Marcona, Marta, Vairo
Irrigation strategy	FI, RDI, SDI
Water deficit	Control, Moderate, Severe
Soil depth	Shallow (< 80 cm), Deep (> 80 cm)

Full Irrigation (FI), Regulated Deficit Irrigation (RDI), Sustained Deficit Irrigation (SDI). Water deficit is computed as the ratio between the irrigation dose applied to the control treatment and that applied to the deficit treatments: Moderate (ratio between 0.55 and 0.99), Severe (ratio < 0.55).

2.2. Relative yield and water production

To reduce the variability in the results from the studies considered, which involved different almond cultivars, irrigation amounts, soil types, and rainfall regimes, yields were relativized to the yield observed in the full-irrigation control corresponding to each study. With this, data from all the studies could be easily compared.

Moreover, applied water production functions for each irrigation strategy (either FI, RDI, or SDI, and for all of them combined) were calculated by plotting the mean yield response to the water applied, and fitting a second-order polynomial expression (Goldhamer and Fereres, 2017). The marginal water productivity was computed as the derivative of the water productivity function and plotted against the applied water (Goldhamer and Fereres, 2017).

2.3. Data analysis

An exploratory analysis, including descriptive statistics, boxplots, and scatterplots for relating different variables and external factors, was first conducted. Generalized linear models between yield (both total and relative) and water received (both rainfall and irrigation) were performed, and regression coefficients were computed. Shapiro-Wilks and Bartlett tests were used for assessing the normality of yield data among water deficit treatments, to carry out an ANOVA for evaluating the effect of watering types and regimes on almond yield. Means were separated using Tukey's test.

A meta-analysis was performed to aggregate the results from the individual studies and, thus, obtain greater statistical power. Meta-analysis is a research process used to systematically synthesize and merge the findings of single, independent studies, using statistical methods to calculate an overall or 'absolute' effect (Egger and Smith, 1997; Shorten and Shorten, 2013). This technique uses well recognised, systematic methods to account for differences in sample size, variability (heterogeneity) in study approach and findings (treatment effects) and test how sensitive their results are (Egger and Smith, 1997; Borenstein et al., 2009). This technique has provided further insights into the impacts of agricultural practices on crop yield and water use efficiency (Fan et al., 2018; Mitchell-McCallister et al., 2020). The meta-analysis was conducted using the "meta" and "metasens" packages (Balduzzi et al., 2019; Schwarzer, 2007; Schwarzer et al., 2015) under the R statistical environment (R Core Team, 2021). A random effects model was considered to assess yield under deficit irrigation, as we assumed that the true effect varied across studies (Borenstein et al., 2009). Moreover, a fixed effects model was also considered.

Cochran's Q statistic was used to assess heterogeneity, testing the null hypothesis that all the studies share a common effect size. This statistic follows a chi-square distribution with the number of studies minus one degree of freedom. The percentage of variation across studies due to heterogeneity rather than chance was assessed through the I^2 statistic, which is computed as:

$$I^2 = (Q - df) / Q \times 100 \tag{1}$$

where Q is the Cochran's heterogeneity statistic, and df means degrees of freedom. Values of I^2 range from 0% to 100%, where values of 25%, 50%, and 75% represent low, medium, and high heterogeneity (Borenstein et al., 2009; Higgins et al., 2003).

Graphical and statistical methods were used for determining publication bias, which is the most significant source of Type I errors in a meta-analysis (Harrison, 2011). Funnel plots were used to present the effect size plotted against the standard error, placing the effect sizes of small studies at the bottom of the funnel and larger studies concentrated at the top. Funnel plots are symmetrical in the absence of bias (Sterne et al., 2006).

3. Results

3.1. Description of the dataset

Table 3 summarises the number of data, mean, maximum and minimum values for each variable, as well as the number of missing data. Yield and irrigation applied data were present in the 144 observations (Table 3), whereas the rest of the variables showed missing data. Yield in these studies showed a wide spectrum of values, ranging from 352 to 3329 kg/ha (Table 3), while irrigation applied varied from 7 to 985 mm (Table 3).

A categorical variable representing the ratio between the irrigation applied to a given deficit treatment, over the irrigation applied to the

Table 3
Minimum, maximum, and average values for the variables included in the dataset of deficit irrigation studies in Spain.

Variable	N	Minimum	Maximum	Average	No data
Annual rainfall (mm)	129	230	802	453	15
Rainfall over the growing season (mm)	96	116	391	220	48
Irrigation applied (mm)	144	7	985	408	0
Annual rainfall + irrigation (mm)	129	277	1958	1042	15
Reference evapotranspiration (mm)	120	855	1400	1165	24
Yield (kg/ha)	144	352	3329	1684	0
Relative yield (%)	144	30	128	87	0
Number of fruits per tree	111	2308	13280	6312	33
Kernel weight (g)	111	0.9	1.7	1.3	33

control treatment, allowed for classifying the deficit irrigation treatments into moderate (ratio between 0.55 and 0.99) and severe (ratio < 0.55). Fig. 1 shows the boxplots of yields and relative yields for the different watering regimes considered (the combinations of stress level and irrigation strategy).

Both yield and relative yield data met the normality and homoscedasticity assumptions according to Shapiro-Wilks and Bartlett's tests (p-values > 0.05), so an ANOVA was performed to assess the significance of the effects of both irrigation strategy and water stress level (Fig. 1). Yields from severe deficit treatments were significantly lower than those from the control and moderate deficit treatments, independently of the irrigation strategy (Fig. 1a). However, a moderate SDI treatment significantly reduced the relative yield with respect to the control treatment, but the RDI strategy did not (Fig. 1b).

A positive and significant correlation between the water received (rainfall + irrigation) by the almond trees and their yield was observed (Fig. 2a). This relationship can be expressed as yield $= -0.0009 \times (\text{Rainfall} + \text{irrigation})^2 + 3.3433 \times (\text{Rainfall} + \text{irrigation}) - 489.55$, and its coefficient of determination (R^2) was 0.5761 (p-value < 0.01). According to this equation, an amount around 1100 mm of water per year would be needed to obtain 2000 kg/ha of almonds. In terms of irrigation supply, the dataset suggests that the maximum yield would be obtained with 800 mm of irrigation water per year (Fig. S1). Moreover, when the yield and the water received were relativized to the corresponding full irrigation control (Fig. 2b), the dataset suggests that no yield reduction could be expected if the water received is more than 85% that of the control.

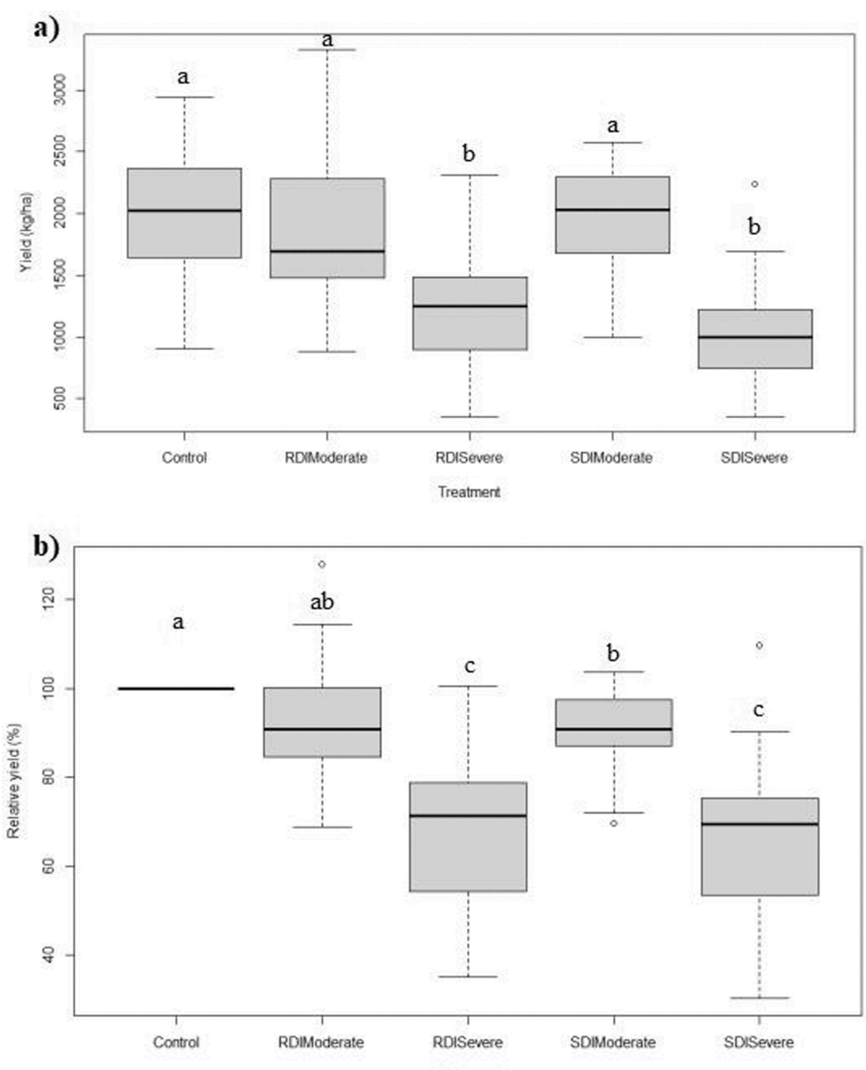

Fig. 1. Boxplots of (a) yield and (b) the relative yield (percentage of yield of a given deficit irrigation treatment over the yield in the control) as a function of the watering regime and stress level. Different letters on the boxes indicate significant differences among treatments according to the Tukey's test ($p < 0.05$). RDI = Regulated deficit irrigation, SDI = Sustained deficit irrigation.

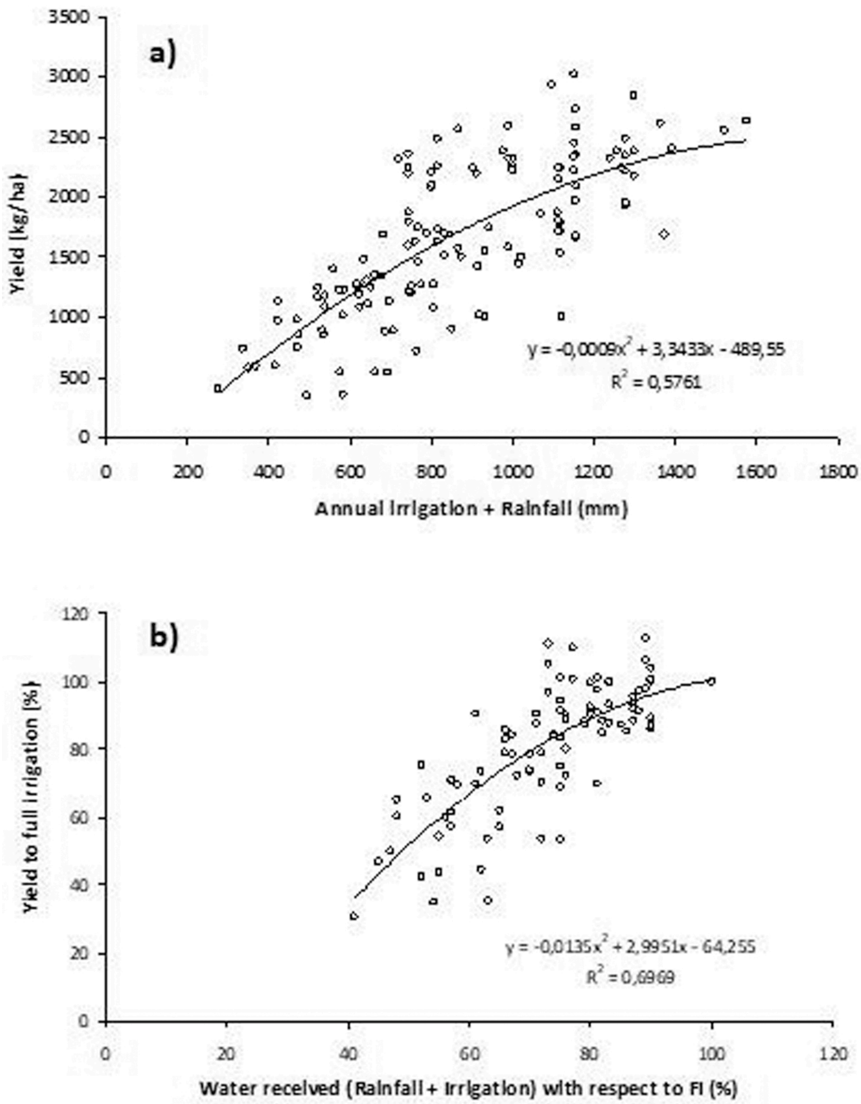

Fig. 2. Relationships between the water received (rainfall + irrigation) and almond yield (a) and between the water received and almond yield with respect to yields obtained in the corresponding full irrigation (FI) control (b).

The variation in yield among studies was not only dependent on the water received, but also on the almond cultivar (Fig. 3). In this dataset, "Guara" and "Lauranne" showed the highest yields, whereas "Ferragnès" showed the lowest yields. However, a high variability was observed, likely caused by the different conditions (agrometeorological, soil) and fertigation practices among studies (Fig. 3).

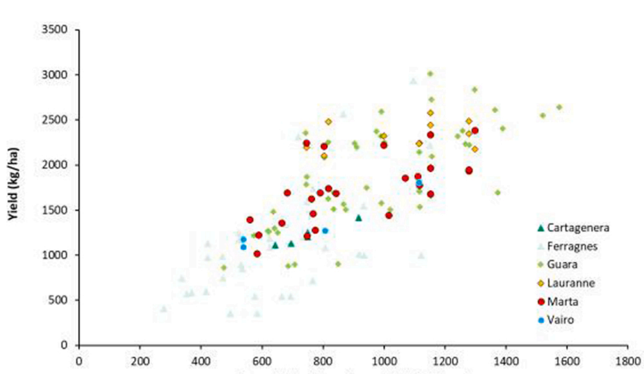

Fig. 3. Relationship between the amount of water received (annual rainfall + annual irrigation) and almond yield as a function of the cultivar.

To better understand this situation, generalized linear models were built separately for each cultivar to describe the relationship between water received (rainfall + irrigation) and yield (Table 4). Except for the cultivars "Marcona", for which there were no rainfall data available, and "Lauranne", the slopes of the fitted models were significantly different from zero (Table 4). The intercept was not significant for "Ferragnès" and "Vairo". In addition, the regression coefficients were lower than 0.6, except for "Vairo" and "Cartagenera" (Table 4). Therefore, a

Table 4
Parameters of the models fitted to the relationships between water received (rainfall + irrigation) and yield for each almond cultivar considered in the dataset.

Cultivar	Intercept	p-value	Slope	p-value	R^2
Cartagenera	346.5588	0.03978	1.1675	0.00299	0.9513
Ferragnes	-2.5163	0.9925	1.7115	0.000103	0.37
Guara	508.1408	0.0285	1.4036	< 0.0001	0.4522
Lauranne	2093.5514	< 0.0001	0.2199	0.358	-0.0066
Marcona	Rainfall data are not available				
Marta	809.9124	0.002042	1.0033	0.000459	0.3817
Vairo	490.7189	0.1237	1.1265	0.0434	0.8726

heterogeneity in the yield response to water received was observed among cultivars, although this effect was negligible for “Lauranne”. This can be due to the magnitude of the yields observed in the dataset (very high in “Lauranne” when compared to the rest of the cultivars).

When plotted as a function of the irrigation strategy, the highest yields corresponded to the control treatments and, in some cases, to the moderate deficit treatments (both RDI and SDI), whereas the lowest yields always corresponded to the treatments that imposed a severe water deficit (Fig. 4).

3.2. *Water production function and water productivity*

The yield response to applied irrigation (AI) for the treatments included within this dataset is shown in Fig. 5. Yields increased from about 500 kg/ha with AI of 50 mm to nearly 2700 kg/ha with the 1050 mm of applied irrigation, and then it seemed to stabilize. Kernel yield did not decline within the limits of applied irrigation considered in the current study (Fig. 5). To quantify water productivity levels as a function of applied irrigation, a second-order polynomial expression was fitted to the mean yield versus AI (Fig. 5), and its derivative, the marginal water productivity, was computed and plotted against AI (Fig. 6). Water productivity reached a maximum value of 0.34 kg/m^3 when no irrigation was applied, and decreased to zero at 1260 mm, becoming negative as AI increased (Fig. 6). The yield response to AI and the marginal water productivities for regulated and sustained deficit irrigation strategies are shown in the Supplementary Material (Figs. S1 and S2, respectively).

3.3. *Meta-analysis*

The effect of water deficit (combining RDI with SDI treatments for all deficit levels) on yield (kg/ha) was assessed by means of a forest plot combining the 15 studies included in the database (Fig. 7). This graph indicates that deficit treatments yielded 84–87% of what their respective well-irrigated controls yielded. The confidence interval is quite narrow, varying between 0.85 and 0.89 in the case of a fixed effects model, and between 0.79 and 0.89 in the case of a random effects model (Fig. 7). Finally, the heterogeneity indicators showed a large variability between studies ($I^2 = 77\%$). Cochran’s Q indicator took a value of 61.54 (*p-value* < 0.0001), indicating that the effect size differed among studies. The funnel plot revealed the presence of a certain publication bias (Fig. S3); however, a regression test of funnel plot asymmetry provided an intercept of -0.1164 with a *p-value* of 0.2519, suggesting that the estimated effects were robust.

Fig. 7 clearly shows that the control treatment favoured almond yield over deficit irrigation regardless of soil depth. However, the rate at which this yield increase occurred was different in deep (Random effects

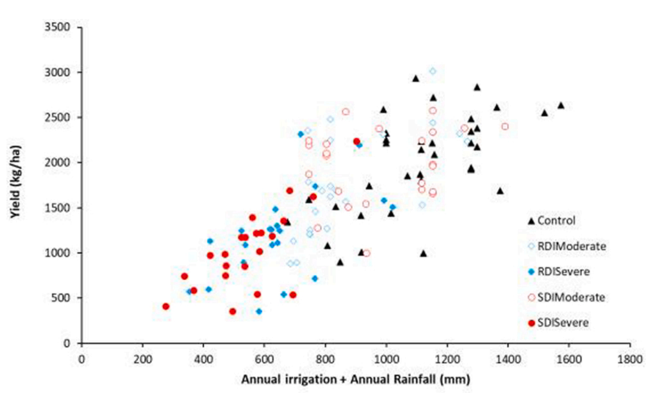

Fig. 4. Relationship between the amount of water received (annual rainfall + annual irrigation) and almond yield as a function of the watering regime and severity of water stress.

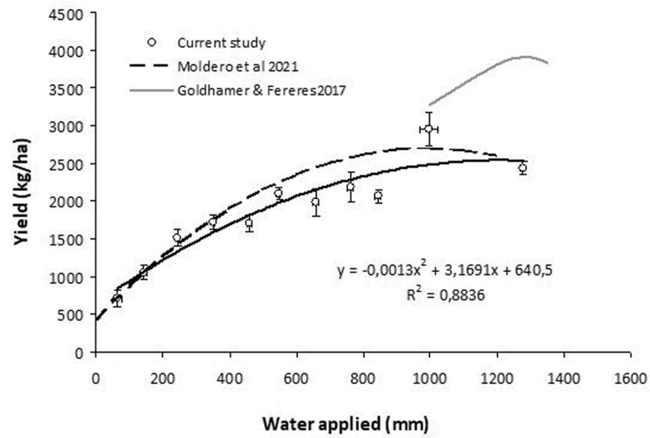

Fig. 5. Kernel yield versus applied water with the best-fit second order polynomial expression. The symbols represent mean almond yields by irrigation intervals, represented by their average value. The vertical and horizontal error bars represent the standard deviation of the means. The yield-water response functions derived by Moldero et al. (2021) and Goldhamer and Fereres (2017) have also been plotted for comparison purposes.

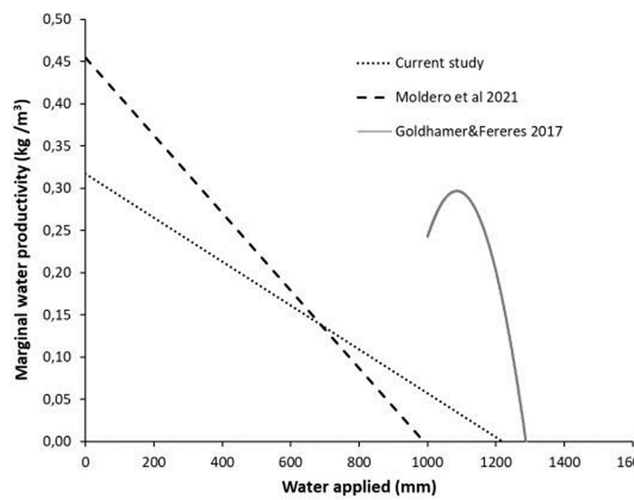

Fig. 6. Water productivity versus applied water calculated as the derivative of a best-fit second order polynomial expression fitted to the average yield from the treatments included in the dataset. The marginal productivity-water functions derived by Moldero et al. (2021) and Goldhamer and Fereres (2017) have also been plotted for comparison purposes.

model = 0.84) than in shallow soils (Random effects model = 0.76). This suggests that deficit irrigation in shallow soils decreases yield to a greater extent than in the case of deeper soils (the exact soil depth in each study incorporated within this meta-analysis is unknown), although the low number of studies carried out on shallow soils does not allow for drawing sound conclusions.

When RDI was compared against SDI, regardless of the severity of the water stress applied, the number of studies was reduced, and conclusions were not clear (Fig. 8). In fact, if a fixed effects model is considered, SDI led to a 3% higher yield compared to RDI. However, using a random effects model, the result was the opposite (Fig. 8). The variability between the studies was very high ($I^2 = 73\%$). Cochran’s Q indicator obtained a value of 26.07 (*p-value* = 0.0005), indicating that the effect size differed among studies. The funnel plot did not reveal the presence of publication bias (Fig. S4). In addition, almond yield benefited slightly under RDI in both deep and shallow soils. The rate at which this increase in yield occurred was similar in deep (Random

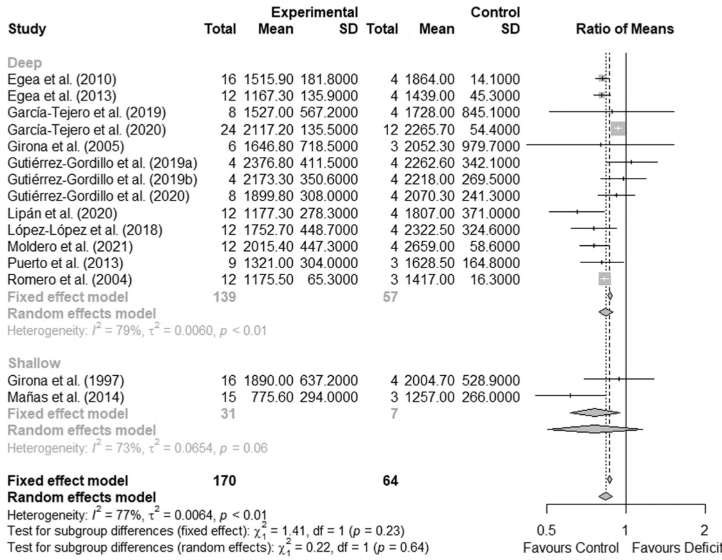

Fig. 7. Summary effect sizes of treatment (well-watered control against deficit irrigation) for the considered dataset of studies. The moderator "soil depth" is considered for separating the studies. Horizontal bars represent 95% confidence intervals (CI), which are also shown between brackets. Vertical solid line represents a null effect. Ratio of means (ROM) indicates the ratio of the average yield on the deficit treatment to that of the control treatment. Weights indicate the relevance of each study to the fixed or random effects model. Favours control and Favours deficit zones in the graph indicate when the yield from a given study were higher for the control or the deficit irrigation treatment, respectively. SD = standard deviation; df = degrees of freedom.

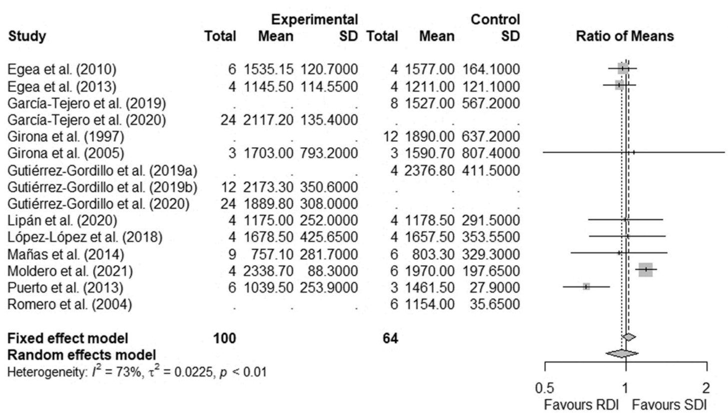

Fig. 8. Summary effect sizes of treatment (regulated deficit irrigation, RDI, versus sustained deficit irrigation, SDI) for the considered dataset of studies. Horizontal bars represent 95% confidence intervals (CI), which are also shown between brackets. Vertical solid line represents a null effect. Ratio of means (ROM) indicates the ratio of the average yield on the deficit treatment to that of the control treatment. Weights indicate the relevance of each study to the fixed or random effects model. Favours RDI and Favours SDI zones in the graph indicate when the yield from a given study were higher for the Regulated Deficit Irrigation (RDI) or the Sustained Deficit Irrigation (SDI) treatment, respectively. SD = standard deviation; df = degrees of freedom.

effects model = 0.97) and in shallow soils (Random effects model = 0.94). Considering only a moderate water deficit, the differences between applying this deficit in a sustained manner throughout the season, or in certain phases of the crop cycle, were practically nil (Fig. S5). This may be because the analysis only considered the stress for the whole season, which could be masking some other effects. However, when considering severe water stress, the meta-analysis seemed to indicate that it is more advisable to apply RDI, as yield would be less affected (Fig. S6). However, it should be noted that the latter two analyses include fewer studies.

4. Discussion

The quantitative analysis performed to evaluate the agronomic response of adult almond plantations grown in Spain to different levels of water stress revealed a wide range of almond yields (352–3329 kg/ha) for a wide range of irrigation volumes applied (7–985 mm) (Table 3). This variability was partly because the relationship between applied water and yield was not straightforward. It was affected by the soil type, the soil water content at the beginning of the season, and the prevailing evaporative demand, which can vary significantly among regions. Evapotranspiration was the pertinent indicator for this analysis, but unfortunately, it was seldom measured, so the applied water was used here as a proxy for the actual water used by the almond trees.

The comparison of these results with those obtained in field experiments conducted in California, the main almond producing area in the world, showed that the maximum yields obtained in the field trials carried out in Spain coincided with the minimum average yields obtained by Goldhamer and Fereres (2017) in a 5-year trial carried out in an adult almond orchard subjected to 10 irrigation levels. In this sense, it is important to highlight that the maximum irrigation volumes applied in the experiments carried out in Spain were close to the minimum volumes used in the study performed by Goldhamer and Fereres (2017), where up to 1350 mm of irrigation depths were applied and maximum (5-year mean) yields close to 4000 kg/ha of almonds were obtained. The incorporation of an irrigation treatment with over-irrigation in the production function obtained in this study (Fig. 5) did not lead to any increase in kernel yield, suggesting that the volumes of water applied in control (well-irrigated) treatments were suitable for reaching potential yields for the plant material, crop management, and agroclimatic conditions prevailing in Spain.

The high almond yields achieved in California (~4000 kg/ha) resulted from decades of crop intensification (Goldhamer and Fereres, 2017); with a similar situation in Australia, the second greatest almond producer worldwide, whose almond growing sector employs the cultivars and cultural practices used in California (Thorp et al., 2021). Conversely, in Spain, these levels of crop intensification with irrigation inputs that can exceed 1300 mm per year (Goldhamer and Fereres, 2017) are not expected due to the reduced availability of irrigation water in most of the inland areas into which almond plantations are expanding. In this sense, irrigation water allocations commonly range between 250 mm and 600 mm per year (Moldero et al., 2021), well below the water requirements needed for intensive adult almond plantations. Under the premises of irrigating almond orchards with deficit allocations, the results obtained in the current study confirmed the good productive performance of almond trees under conditions of moderate water deficit, as very low yield penalties (7–9%) were observed when compared with the control treatments (Fig. 1). An important aspect of deficit irrigation management in almond orchards that continues to generate uncertainty is the convenience of using regulated (RDI) versus sustained (SDI) deficit irrigation strategies. The results obtained in this work suggest, although not definitely, a certain advantage of using RDI strategies over SDI in almond trees. In absolute terms, the mean kernel yield between RDI and SDI treatments did not differ significantly regardless of the level of water deficit applied (Fig. 1). However, when relative yields were analyzed, SDI differed from the control for both levels of water deficit (moderate and severe). In contrast, the RDI treatment only differed from the control when the water deficit was severe (Fig. 1). Despite being significant, the reduction in yield for a moderate water deficit applied through SDI was only 9% with respect to the control; therefore, the analysis performed could not robustly confirm that this irrigation strategy causes an appreciable decrease in almond yield. The meta-analysis (Fig. 8) suggested a certain production advantage for RDI over SDI, when simultaneously considering both moderate and severe water deficit. Therefore, the current study cannot provide a definite answer for the first question raised about which irrigation strategy is more appropriate for a given water allocation below the total almond water requirements, as the current study only suggests slight yield improvements for RDI.

RDI strategies in almond trees have mostly consisted of applying a certain level of water deficit during the kernel-filling stage, considered the most drought-resistant phenological stage in almond trees (Girona et al., 2005). However, some studies observed yield reductions when water deficit was applied during this stage (Egea et al., 2013; Goldhamer et al., 2006; Goldhamer and Viveros, 2000; Hutmacher et al., 1994), while in other studies, yield was unaffected by water deficits applied during kernel-filling (Egea et al., 2010, 2009; Goldhamer and Fereres, 2004; Puerto et al., 2013). These controversial results seem to be related to the level of water stress reached by trees during this period, as stem water potential values lower than − 2 MPa during kernel-filling have been suggested to cause yield losses (García-Tejero et al., 2018) due to variations in kernel weight (Girona et al., 2005). Despite this evidence, the analysis conducted in this work indicates that applying water shortages only during the grain filling stage rather than spreading it proportionally throughout the crop cycle is not clearly justified.

This leads to the second question about what yield loss can be expected for a given water allocation when compared to a well-watered orchard. The results obtained in the current study are not conclusive on whether the cultivars evaluated differed in their productive response to deficit irrigation. Although some differences were observed in the relationships between water input and yield of each cultivar, the variability in the ranges of water applied among the different experiments made it difficult to obtain sound conclusions regarding the tolerance of the cultivars to water stress. On the other hand, although it has sometimes been considered that shallow soils are better for the application of RDI strategies in woody crops, due to the adequate timing of water stress application that is needed in an RDI strategy (Girona et al., 2003), in almond trees it seems that the crop response to RDI strategies is poorer in shallow soils compared to deeper soils. However, the low number of studies developed on shallow soils does not allow for obtaining sound conclusions (Fig. 7). Nevertheless, the current study indicated that, for a moderate water deficit, 7–9% yield reductions can be expected with respect to a well-watered orchard, while for a severe water deficit, yield decrease could be up to 33%.

The applied irrigation-yield response function obtained in this analysis comprising multiple cultivars, irrigation treatments, and experimental conditions (Fig. 5) was similar to that obtained by Moldero et al. (2021) in a 6-year trial carried out in southern Spain on almond trees cv. "Guara". By comparing both production functions, it can be deduced that Spanish cultivars have a similar productive response to irrigation under the agroclimatic and management conditions of the Spanish almond orchards, with maximum kernel yields obtained with irrigation water allocations of about 1000 mm per growth cycle. However, when these production functions were compared with that obtained in California (Goldhamer and Fereres, 2017), it was observed that Californian almond plantations continued to increase kernel yields above 1000 mm of irrigation water applied, reaching maximum yields close to 4000 kg/ha with irrigation inputs of about 1250 mm per growth cycle.

The marginal productivity of irrigation water decreased continuously with any irrigation water input, both in the relationship obtained by Moldero et al. (2021) and in the one obtained in this analysis (Fig. 6). This pattern has also been observed in previous studies conducted with other cultivars (e.g. cv. "Marta") (Egea et al., 2010). While the almonds cv. "Guara" needed irrigation inputs close to 1000 mm for marginal water productivity to be zero, in the meta-analysis carried out in this study, irrigation inputs close to 1200 mm were needed for marginal irrigation productivity to be zero. In any case, the comparison with the irrigation water productivities obtained in California shows the low productivity of irrigation inputs in Spain above 800 mm/year, lower than 0.1 kg/m^3, while maximum marginal productivities of irrigation water of around 0.3 kg/m^3 were observed for irrigation inputs of 1100 mm/year in California (Goldhamer and Fereres, 2017). From these data, it can be concluded that higher irrigation water productivities than those observed in the Spanish trials are possible for high irrigation water allocations. Therefore, it seems that almond productive response depends mainly on the percentage of ETc supplied annually, answering the third question raised in the introduction of the current study. However, as irrigation water allocations above 700–800 mm are not expected in Spain and over the Mediterranean Sea Basin, the scientific and technological challenge for almond cultivation is to increase the marginal productivity for moderate irrigation allocations to the levels observed in Californian almond orchards for notably higher irrigation water allocations. This could be achieved not only by means of improved irrigation technologies and scheduling, but also by optimizing the overall agronomic management with particular attention to fertilization regimes and pruning operations. The challenge of increasing marginal productivity should also consider the sustainability component for minimizing contamination risks, ensuring soil conservation, and considering the common trend of increasing organic farming cultivation.

5. Final considerations and recommendations

Despite the large variability observed in the pooled data set (because of the wide range of studied conditions such as soil types, cultivars, climatic conditions, or tree sizes, among others), the quantitative analysis conducted allowed us to derive some general trends:

- In Spain, under semi-arid Mediterranean conditions, almond yield increases with irrigation water application with an expected yield of about 2500 kg/ha for around 1000 mm of irrigation water applied.
- The yield reduction observed when water allocation decreased in comparison to fully irrigated trees was mostly due to the severity of the water stress suffered by trees, and to a lesser extent due to the irrigation strategy implemented.
- The application of a regulated deficit irrigation strategy, rather than a sustained deficit one, only showed some advantage when water stress was moderate.

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.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108208.

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