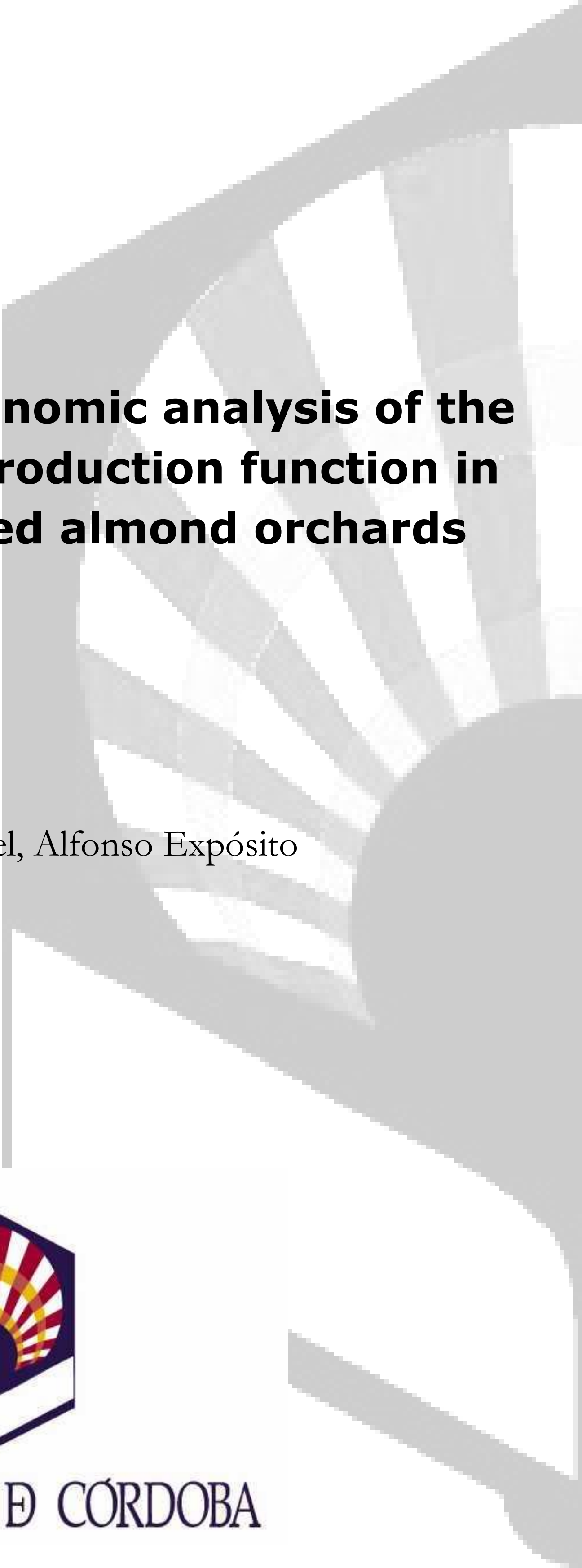
Octubre 2021

PROCEEDINGS

# Microeconomic analysis of the water-production function in irrigated almond orchards



Authors: Julio Berbel, Alfonso Expósito

Language: English

.

UNIVERSIDAD DE CÓRDOBA

Cita:

**Expósito, A.; Berbel, J**. 2021. Microeconomic analysis of the water-production function in irrigated almond orchards. XXXIV CONGRESO INTERNACIONAL DE ECONOMÍA APLICADA ASEPELT. Jaen. Oct 2021 (Spain)

# ANÁLISIS MICROECONÓMICO DE LA RELACIÓN AGUA-PRODUCCIÓN EN EL ALMENDRO DE REGADÍO

## Resumen

Este artículo ofrece un análisis microeconómico del uso del agua en el cultivo del almendro cuando el agua se considera el factor limitante. Cuando un cultivo está sujeto a limitación de agua, los principios microeconómicos detrás de las decisiones de riego se basan en la relación entre rendimiento y riego. El análisis se aplica a una función de respuesta agua-producción estimada para almendros de regadío en España. Nuestra investigación se centra en determinar la dosis óptima de riego cuando se aplica riego deficitario, como es habitual en contexto de escasez de agua. Finalmente, la situación en España se compara con la de otros países donde los derechos de agua están menos restringidos. El análisis económico de la función de producción de agua es crucial, ya que determina los ingresos de los agricultores y los ayuda a tomar decisiones de gestión adecuadas, como la asignación de agua limitada a los cultivos y la extensión del área regada. Además, las instituciones públicas necesitan esta información para garantizar una adecuada asignación de los recursos hídricos en un contexto de demanda creciente y recursos limitados.

*Palabras clave:* respuesta agua-producción, riego deficitario, factor limitante, almendro.

*Área Temática:* Economía Ambiental y de Recursos Naturales no relacionados con el olivar.

# MICROECONOMIC ANALYSIS OF THE WATER-PRODUCTION FUNCTION IN IRRIGATED ALMOND ORCHARDS

## Abstract

This paper offers an exploratory microeconomic analysis of water use in the cultivation of almonds orchards when water is considered as the limiting factor. When a crop is subjected to water limitation, the microeconomic principles behind irrigation decisions are based upon the water-yield relationship. The analysis is applied to an estimated water-yield response function for irrigated almond trees in Spain; our research focuses on determining the optimal irrigation dose when deficit irrigation is applied, as is usual in the context of water limitation. The situation in Spain is compared to that of other countries where water rights are less constrained. The economic analysis of the water production function is crucial, since it determines the farmers' income and helps them make appropriate management decisions, such as the allocation of limited water to crops and the extension of the irrigated area. Furthermore, public institutions need this basic information in order to assign water allocation in the context of increasing demand and limited resources.

*Key Words:* Water-yield response function, deficit irrigation, water-limiting condition, almond crop.

*Thematic Area:* Environmental and natural resources economics (not related to the olive sector).

## 1. INTRODUCTION

The present research applies the microeconomic theory of production to the study of the behaviour of farmers who have to make decisions regarding the allocation of scarce production resources, such as the extent of irrigated land and water allocated per hectare. Following a similar microeconomic approach, Expósito and Berbel [7] derived a water-response function under a scheme of deficit irrigation in olive groves and analysed farmers' perception and choice regarding the optimal irrigation dose.

The impact of water deficits on almond production has been studied by Goldhamer and Viveros (2000), Goldhamer et al. (2005), and Esparza et al. (2001) in the case of California; Girona et al. (2005) and Egea et al. (2010) in Spain; and Stevens et al. (2011) for Australia. More recently, the study by Goldhamer and Fereres (2016) has offered an estimation of a water-yield response function in the case of California where water is a limiting factor and the study by López-López et al. (2018) applied a similar analysis in the case of southern Spain. However, none of the studies offers a microeconomic analysis of the optimal allocation of water based on a contrasted economic model. A similar application of the microeconomic analysis carried out in this work can be found in Expósito and Berbel (2016), who extended and empirically tested the models of English (1990)] and of Berbel and Mateos (2014) for the case of deficit irrigation in olive groves located in southern Spain. In order to apply the proposed microeconomic analysis to irrigated almond crops, the water-yield response function estimated by López-López et al. (2018) in the case of southern Spain is applied in this work and several comments on the information available on Australia and California are then made in the Discussion section.

The selection of southern Spain as the case study is justified since the high water consumption related to the irrigation of almond trees has become controversial due to increasing water scarcity, especially in the southern and eastern regions of Spain. Moreover, the increasing frequency and length of drought periods due to climate change pose significant challenges to water management in Spain. When a crop is subjected to water limitation, the water-yield response function should guide the microeconomic principles behind the irrigation decisions. This knowledge is crucial, since it determines the farmers' income and helps them make appropriate management decisions (such as allocating limited water to various crops). Furthermore, water authorities and public administrations need this basic information in order to assign water allocation in a context of increasing demand and limited resources.

The structure of the paper is as follows. Section 2 briefly presents the microeconomic foundations of the model used in this study. Section 3 gives a brief description of the case study and of the cultivation of irrigated almonds in southern Spain under a deficit-irrigation scheme. The results are shown in Section 4, followed by a brief discussion and concluding remarks in Section 5.

## 2. METHODOLOGICAL APPROACH

The analysis of crop yield and water use to improve water management was initially proposed by Doorenbos and Kassam (1980). The extensive literature that examines the water-response functions covers a wide variety of crops (Steduto et al., 2012; Dagnino and Ward, 2012). Empirical and theoretical yield-irrigation functions are usually deduced from longitudinal field data and are based on estimated agronomic coefficients. Specifically, a recently estimated yield-irrigation function for almond trees for southern Spain (López et al., 2018) is used in this study. Commonly, yield-irrigation functions are used to obtain derived water-demand functions defined by the marginal value of irrigation water. By applying the production function y(w), marginal productivity of irrigation water (w) can be obtained from its partial derivative with respect to water "w". The marginal value of irrigation water is thus obtained from the crop price multiplied by the estimated marginal productivity.

In our model, farmers with rational economic behaviour should maximise the following profit equation by taking land as the single limiting factor and water as the variable:

$$Z = p_y \cdot y(w) - c(w) \tag{1}$$

where Z represents profit, $p_y$ is crop price, y(w) is the water-yield function, and c(w) is the function of water cost. Farmers are assumed to hold a price-taking position (they cannot influence crop price with their individual production). Berbel and Mateos (2014) expanded the model originally developed by English [16] by including deficit irrigation and changes in irrigation efficiency. Therefore, water can be shared across a larger area and Equation (1) is transformed into Equation (2), where the objective is to maximise total net income by distributing both the irrigated area and the water dose.

$$Z(w) = \left[p_y \cdot y(w) - c(w)\right] \cdot A \tag{2}$$

Equation (2) considers that the irrigated area (A) is variable in the optimisation model, and the farmer decides the allocation of water "w" per area unit for maximising net income. The total volume of water ($W_T$) acts as the limiting factor and determines the irrigated area:

$$A = \frac{W_T}{w} \tag{3}$$

Thus, by satisfying Equation (1), the optimal water allocation per area unit is then defined by the value of w that optimizes Equation (2) subject to Equation (3).

$$- A \times \frac{\partial Z(w)}{\partial w} = Z(w) \times \frac{\partial A}{\partial w} \tag{4}$$

It is frequent to find quadratic water-yield response functions in the agronomic literature, and by following Reference [3], we use y(w) and a cost function c(w) composed of a fixed cost ($c_f$) and a variable water cost ($c_w$) as follows:

$$y(w) = a_0 + a_1 w + a_2 w^2 \tag{5}$$

$$c(w) = c_f + c_w w \tag{6}$$

If the proposed optimisation model was applied to the above functions, then one possible solution would be based on the conventional assumption that considers land (or irrigated area) as a limiting production factor (with water as a variable factor). This solution is denoted as the "maximum return to land" equilibrium ($W_l$) and the solution is straightforward:

$$W_l = \frac{c_w - P_y \cdot a_1}{2\,P_y \cdot a_2} \tag{7}$$

In the case of a quadratic production function, the optimal solution to Equation (4) implies the following:

$$\mathrm{Z(w)} = \left[\mathrm{p_y(a_0 + a_1 w + a_2 w^2) - (c_f + c_w w)}\right] \frac{\mathrm{W_T}}{\mathrm{w}} = \mathrm{W_T} \left[\frac{\mathrm{p_y \cdot a_0}}{\mathrm{w}} + \mathrm{p_y} \cdot \mathrm{a_1} + \mathrm{p_y} \cdot \mathrm{a_2\, w} - \frac{\mathrm{c_f}}{\mathrm{w}} - \mathrm{c_w}\right] \tag{8}$$

By setting the derivative to zero, the level of "w" that maximises overall profit can be obtained from the following:

$$\frac{\partial Z(w)}{\partial w} = W_T \left[\frac{-p_y \cdot a_0}{w^2} + p_y \cdot a_2 + \frac{c_f}{w^2}\right] = 0 \tag{9}$$

Hence, the solution denoted as the "maximum return to water" equilibrium ($W_w$) can be expressed by the following:

$$W_w = \left( \frac{P_y \cdot a_o - c_f}{P_y \cdot a_2} \right)^{1/2} \tag{10}$$

Finally, farmers may be interested in the maximum achievable yield per area, which can be computed when the marginal product equals zero. This solution is widely used in the field of agronomics to determine the maximum irrigation requirements. In our proposed model, the maximum yield point is achieved at the value represented by Wy:

$$W_y = \frac{-b_1}{2\, c_1} \tag{11}$$

Although this last solution is relevant for agronomic analysis, from an economic point of view, it requires that the marginal cost of water equals zero. This solution is only useful under the condition that the maximisation of total food production is the priority. English [2] included all variable costs that can be linked to yield (fertilizer, harvesting, etc.) in the price of irrigation water ($c_w$). In our model, all inputs except water are included in the parameter of fixed costs.

## 3. CASE STUDY

Spain is the third greatest almond-producing country in the world, after Australia and USA, and represents 5% of total world production, with a productive area of about 560,000 ha and an annual average production of 63,600 Mg (International Nut and Dried Fruit, 2020). Although most of the area is devoted to traditional rainfed production that is mainly located in the southern and eastern regions, new intensified plantations of almond groves have been put into production which use high-efficiency irrigation methods and obtain higher crop productivities. This has led to an increase of 24.8% in the cultivated area and of 73.2% in production during the period 2014–2018 (MAPA, 2018). The average productivity of almond groves is significantly higher in the case of irrigated crops: 1600–1800 kg/ha vs. 400 kg/ha for rainfed crops (MAPA, 2018). Deficit-irrigation techniques are used in order to maximise irrigated cultivated area in a context of limited water resources (Fereres and Soriano, 2006).

This study uses the water-yield response function developed by López-López et al. (2018) based on an agronomic experiment carried out in Cordoba (southern Spain) in the period 2014–16. This location enjoys a typical Mediterranean climate, with hot and dry summers, mild winters, and an average annual rainfall of around 590 mm. These climate characteristics are shared across the whole Guadalquivir river basin, where the experiment was located. This river basin registers increasing variability in its rainfall as well as periodic and persistent periods of drought (Berbel and Esteban, 2019). Additionally, the Guadalquivir river basin has become a closed basin, meaning that all available water resources are allocated and that no significant future augmentation in supply is expected. This context translates into increasing conflicts among alternative water users (Expósito and Berbel, 2017). The agronomic experiment compared water-yield responses given regarding almond trees of the Guara variety under alternative irrigation schemes. Details of the experiment are extensively described in López-López et al. (2018) with a quadratic production function described by Equation (12):

$$Y(Y(w) = 243 + 4.87 \cdot w - 0.0025 \cdot w2 \tag{12}$$

with a fit adjustment measured by R2 = 0.72 (p-value = 0.0001) (López et al., 2018). Regarding production costs, fixed costs account for all costs associated with production factors other than that of water. According to the reviewed literature, production costs of irrigated almond groves in Spain are reported to be approximately 2000 EUR·ha-1 with a range from 1800 EUR (García et al., 2005) to 2500 EUR (Novello, 2019), excluding the variable water cost. In our optimisation exercise, the cost of 2000 EUR is considered, although sensitivity analysis in the range 1800–2500 EUR·ha-1 induces no serious change. Nevertheless, a sensitivity analysis of the optimal solution under deficit irrigation shows that the optimum would be stable within this range of costs. With respect to variable cost, the irrigation water price is set at 0.12 EUR per cubic metre that is estimated as a weighted average of abstraction cost according to the Spanish Ministry of Environment (MIMAN, 2007). The cost function is represented by Equation (13):

$$C(w) = 2{,}000 + 0.12 \cdot w \quad (13)$$

Finally, crop price ($p_y$) has been set at 5.0 EUR/kg. Nevertheless, due to price instabilities in the Spanish almond exchange market (MAPA, 2019), this study carries out a sensitivity analysis that considers the variability of prices between 4 and 6 EUR/kg.

## 4. RESULTS

### 4.1. Alternative Water—Use Optimum

Application of the proposed model in the previous section offers three possible solutions. Table 1 shows these solutions together with relevant information in order to understand the economic behaviour analysed by the proposed optimisation model. Firstly, the solution (Wy = 975 mm) represents the maximum achievable yield (Equation (11)). This solution is illustrated in Figure 1 by the irrigation dose (w) that yields the maximum production and, thus, the maximum value of crop production. In this case, the value of the marginal product (VMP) of irrigation water is zero (as also shown by Figure 2), and this solution may be explained either because the famer's goal is to maximise yield regardless of water cost or because the marginal cost of water for the farmer is close to zero. The average income (AI) and average profit (AP) per cubic metre of irrigation water are 13.41 and 10.16 EUR, respectively.

The profit-maximising solution that corresponds to the maximum return to land ($W_l$ = 927 mm), as defined by Equation (7), requires a lower irrigation dose than does the maximum yield, which represents 95% of water use for full irrigation. In this case, the estimated VMP is 1.20 EUR/m$^3$ and the AI and AB are 14.07 and 10.72 EUR/m$^3$, respectively.

Finally, according to Equation (10), the maximum return to water (which assumes that water is the limiting production factor) would imply an irrigation use of $W_w$ = 251 mm, which is 26% of the maximum yield requirements. The estimated VMP would be 18.10 EUR/m$^3$, which is significantly above the values achieved by the previous solutions. Similarly, AI and AB would be maximum values (26.05 and 16.89 EUR/m$^3$, respectively, as shown in Table 1). For the sake of clarification, Figure 1 shows the graphical representation of these three optimisation solutions.

**Table 1.** Solutions to the optimisation model: $W_y$ (maximum yield), $W_l$ (maximum return to land), $W_w$ (maximum return to water).

| Solution | Irrigation water (w) (mm) | Relative irrigation supply (%) | Irrigated area (ha) with total volume of water ($W_T$) = 975mm | Value Marg. Product (EUR/m$^3$) | Average Income (EUR/m$^3$) | Average Profit (EUR/m$^3$) |
|---|---|---|---|---|---|---|
| $W_y$ | 975 | 100% | 1.00 | 0.00 | 13.41 | 10.16 |
| $W_l$ | 927 | 95% | 1.05 | 1.20 | 14.07 | 10.72 |
| $W_w$ | 251 | 26% | 3.88 | 18.10 | 26.05 | 16.89 |

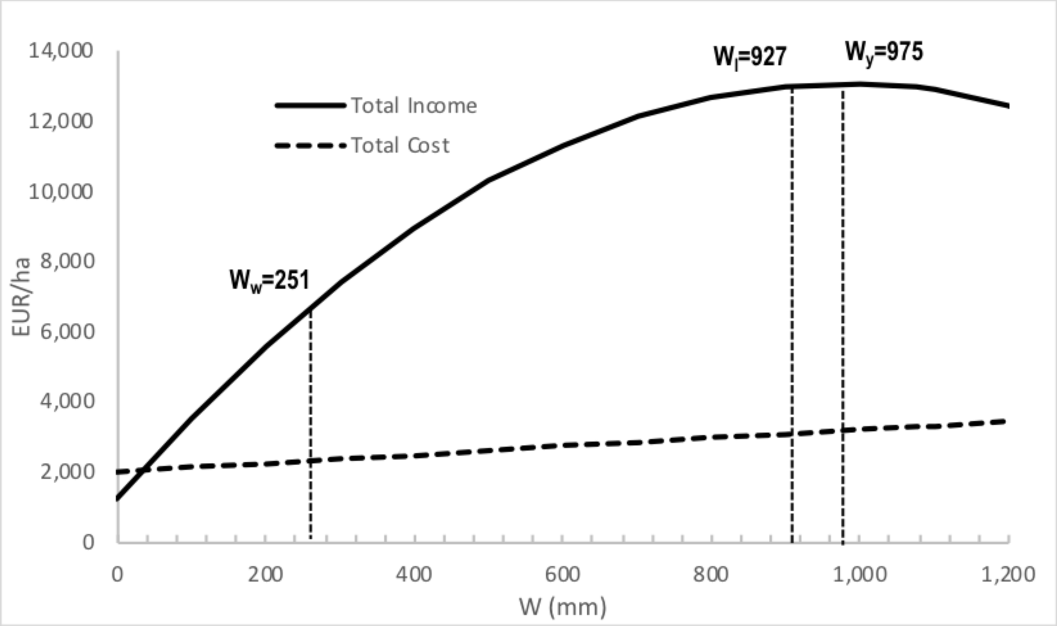


**Figure 1.** Graphical representation of optimisation solutions: $W_y$ (maximum yield), $W_l$ (maximum return to land), $W_w$ (maximum return to water).

As commented above, the VMP of irrigation water decreases as the irrigation dose (w) increases, since the income function grows at a decreasing rate while the cost function increases at a constant rate. This explains why the slope of the VMP function (as shown in Figure 2) is negative, and it therefore registers a zero value when maximum income (maximum yield) is reached, that is, when the irrigation dose is Wy = 975 mm.

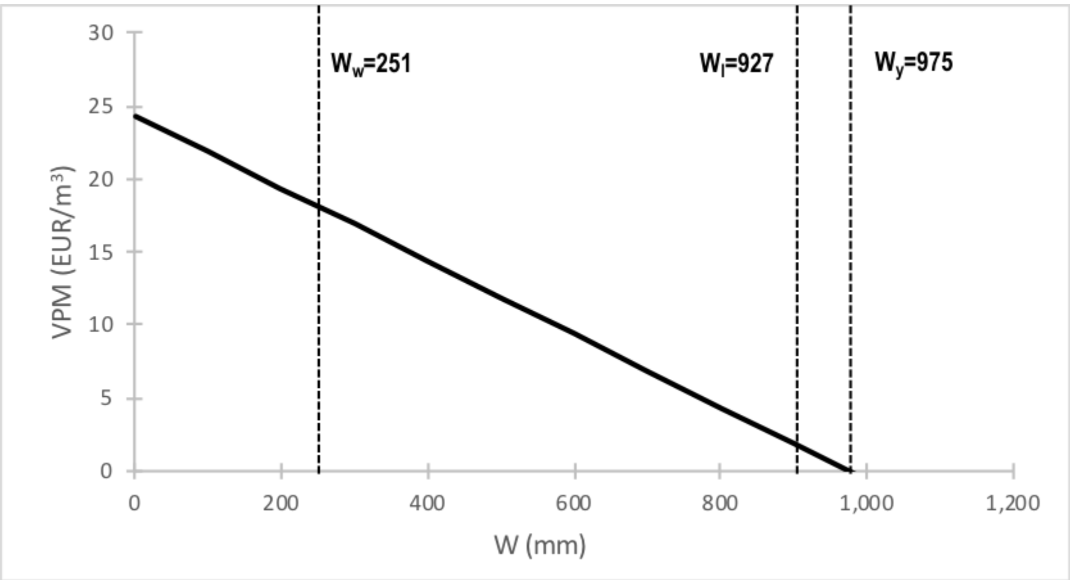


**Figure 2.** Value of marginal product (VMP) vs. irrigation water (W). Optimisation solutions: $W_y$ (maximum yield), $W_l$ (maximum return to land), $W_w$ (maximum return to water).

## 4.2. Impact of Chosen Solution in Production Costs

Figure 3 helps to describe the rational behaviour of the solution given by the maximum return to water. Specifically, an irrigation dose of $W_w$ = 251 mm represents the solution where crop price (5 EUR/kg) equals the marginal cost of production (as shown by point "E" in the graph). This means that marginal income (crop price) equals marginal cost, which is the condition to maximise benefit for the farmer. This equilibrium point should be understood as the optimal irrigation dose to maximise the benefit by the farmer under a constrained irrigation water supply. The representation of the average crop cost function shows that the marginal cost function crosses the average cost function at its minimum value, as the microeconomic theory predicts.

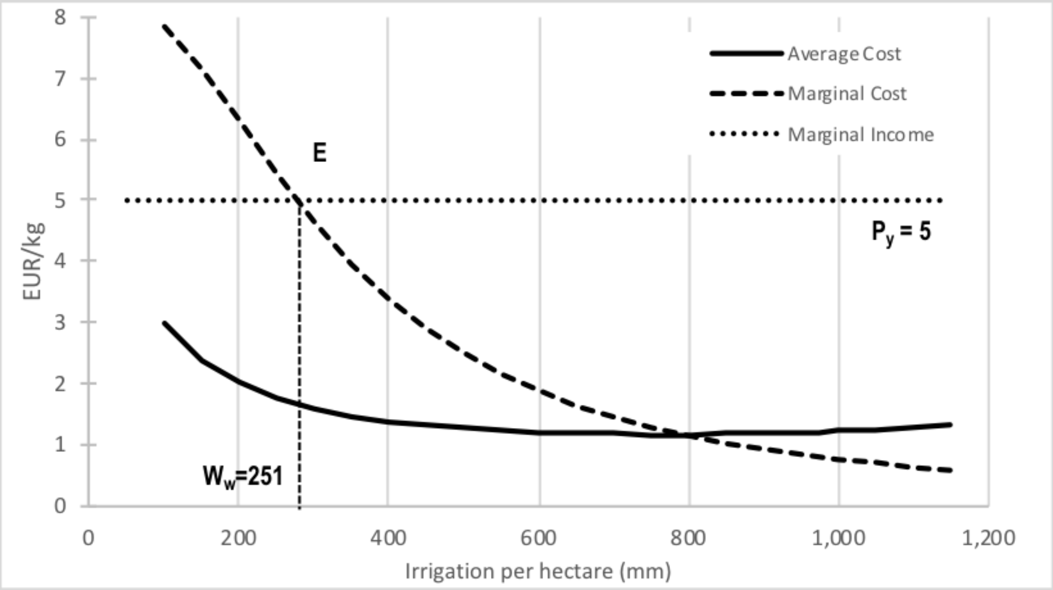


**Figure 3.** Graphical representation of average and marginal costs vs. water use. $W_w$ (maximum return to water), $P_y$ (crop price).

The economic interpretation of the $W_w$ solution (maximum return to water as the limiting factor) can also be described in terms of production cost per almond or cost of production (EUR/kg). Figure 4 illustrates the production achievable with an irrigation dose of 975 mm/ha (Wy) when increasing the irrigated area and decreasing the irrigation dose ($w = W_T/A$, see Equation (3)), which corresponds to our three optimum solutions: a) $W_y$, maximum yield (A = 1.00 ha, w = 975 mm); b) $W_l$, maximum return to land (A = 1.05 ha, w = 927 mm); and c) $W_w$, maximum return to water (A = 3.88 ha, w= 251 mm).

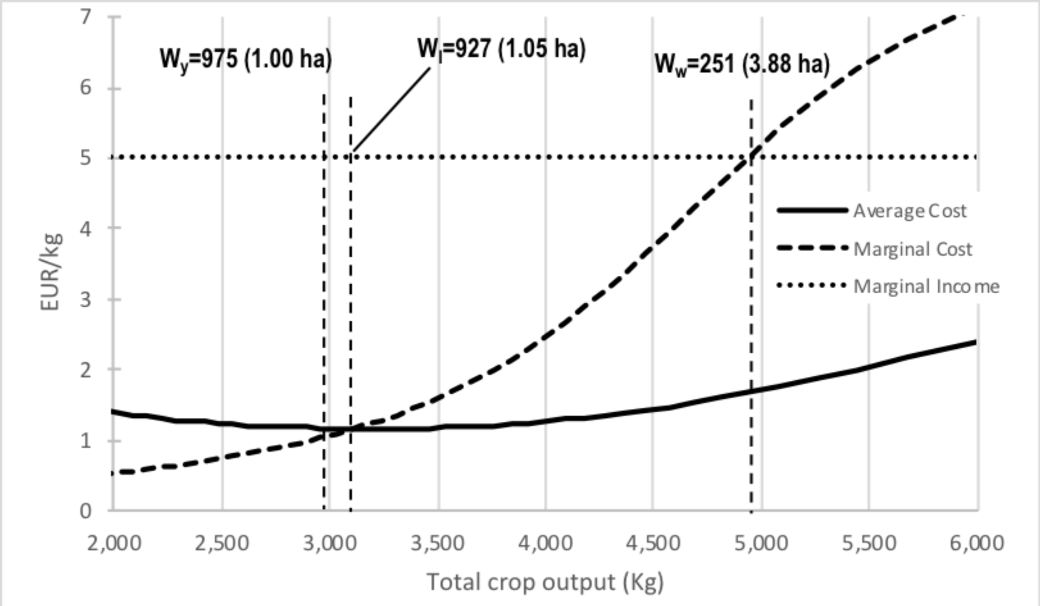


**Figure 4.** Graphical representation of average and marginal costs vs. total output. Optimisation solutions: $W_y$ (maximum yield), $W_l$ (maximum return to land), $W_w$ (maximum return to water).

## 5. DISCUSSION AND CONCLUDING REMARKS

This paper offers an exploratory microeconomic analysis of water use in almond groves when water is considered the limiting production factor. In this context, deficit-irrigation techniques are usually applied. The study of Molden et al. (2010) argues that practices, such as deficit irrigation and precision irrigation, can significantly improve water productivity. Based on estimated water-yield response functions available in the literature (Doorenbos and Kassam, 1980), our research focuses on determining the optimal irrigation dose in a context of water limitation following the microeconomic model developed by English (1990) and is extended by the study of English and Raja (1996). Our results offer significant implications in the field of economics of irrigation management, which are valuable for irrigators and decision-makers in the water management sector at various scales, ranging from irrigation districts to river basin management.

Mediterranean crops, such as almond crops, are adapted to long and dry summers with high temperatures and no rain, which greatly limit agricultural productivity in those climates (Jacobsen et al., 2012); irrigation provides an adaptation to this seasonal aridity. The system increases productivity when supplementary or full irrigation is applied, especially since the mild and wet winters allow adapted crops to maximise the use of soil water in winter and spring before climatic conditions become adverse. Almond cultivation is well adapted to the Mediterranean climate. It is considered a drought-tolerant crop because it exhibits xeromorphic characteristics (Romero et al., 2004). The analysis conducted here is valid for southern Spain with a precipitation in the range of 400 to 600 mm; in these conditions, the crop can partly take advantage of the soil water derived from seasonal rain.

The application of the model described in this paper to the production function obtained by Goldhamer and Fereres (2016) in Kern County (southern California) fails to provide a real solution for Equation (10). In Kern County, almonds are grown in extreme arid conditions (average rainfall of 118 mm), and the low precipitation leads to the need for higher water doses than those in the southern Spain case (average rainfall of 590 mm). This is illustrated by the fact that maximum yield is found in southern California for an irrigation dose of approximately 1250 mm compared to 975 mm in the Spanish case. In California, the almond industry is currently subject to criticism that was initiated during the last drought (2011–2017), in which growers were forced to reduce water use by 25%. Full irrigation aimed at maximising yield remains the generalized strategy. According to Goldhamer and Fereres (2016), the productivity at economic optimum in California (around 1100 m) entails an average water productivity of 0.32 kg/m$^3$.

In Australia (second greatest almond producer worldwide after California), the strategic approach to almond irrigation is similar to that in California and involves the application of full irrigation to achieve maximum production. A report published on the almond orchards in Victoria state (334 mm average rainfall) suggests either the application of full irrigation or the application of a limited deficit (85% of full irrigation dose) to guarantee minimal yield impact (Monks et al., 2017). This strategy produces productivity ranging from 0.19 kg/m$^3$ (full irrigation) to 0.22 kg/m$^3$ (deficit irrigation).

Administrative conditions in Spain regarding water rights are more severe regarding water use since water is a public resource and the assignment of water rights are subject to hydrological basin plans. The average water rights for farmers in Andalucía are close to 3200 m$^3$/ha (CHG, 2016), although many farmers apply 6000 to 7000 m$^3$/ha to their almond orchards when they either attain access to water entitlements of a more generous nature or they manage this by internal in-farm reallocation (by leaving a portion of the farm to be rainfed). Consequently, various public administrations encourage a deficit-irrigation strategy, as is the case of the regional governments of Andalusia and Extremadura. This approach increases the average productivity of irrigation water from 0.27 kg/m$^3$ reached in the maximum yield solution (with an irrigation dose of 975 mm) to 0.52 kg/m$^3$ in the optimum deficit irrigation (251 mm).

The consequences at the microeconomic scale result in a greater economic value of water and greater profits at the farm level. Specifically, this work shows how farmers might be maximising the return to water, thereby considering that water acts as a limiting production factor and that land acts as a variable, instead of the traditionally considered maximum return to land, which considers the economic optimum with water as the variable input and land as the limiting production factor. This behaviour is consistent in those locations (or river basins) where water resources are depleted and constitute a limiting factor for agricultural production.

When the results of the microeconomic model of individual farmer decision-making are aggregated at the regional scale, then the general adoption of a deficit-irrigation strategy implies an increase in regional agricultural output, thereby maximising the global return to water. In Andalusia, the irrigated area covers 27% of total cultivated area and the demand for water has reached a limit since there are no more available resources and the different basins in Andalusia have reached a "closed" status (Expósito and Berbel, 2017a). However, the increased productivity of water triggers additional pressures on water use, as illustrated in the case of olive irrigation in the Guadalquivir river basin.

The findings of this study show that deficit irrigation is a strategy for the adaptation to water scarcity that farmers may use in the context of limited water supply in order to maximise farm profits. Deficit-irrigation strategies are also employed to achieve a more sustainable use of water in those areas with water scarcity. Regional governments may promote the implementation of deficit-irrigation techniques with the aim of maximising regional farm value when water is the limiting production factor. The model used here is a first approximation, and strategies of reducing fixed costs by means of either lowering the density of tree plantation or by simplifying irrigation systems may lower fixed costs and increase the area irrigated, thereby increasing water productivity (Expósito and Berbel, 2017b). Tree plantation density in terms of trees per hectare in the experimental design used herein as the basis for our model ranges from 214 (California) to 238 (Spain) and to 296 (Australia). Tree plantation densities may well vary when the application of deficit irrigation is decided before planting, since it implies lowering the densities which in turn leads to a revised production function that takes into consideration said lower densities. Furthermore, kernel size has not been considered in our model, and therefore, future developments should also take kernel size into consideration in the optimisation model.

Finally, future research should consider the potential effects of this strategy on the resiliency of the systems and of the consequences of this behaviour at the river basin level by taking other factors into account, such as CO2 capture, quantity and quality of return flows, and any other relevant environmental or social variables.

## REFERENCES

BERBEL, J.; ESTEBAN, E. (2019): Droughts as a catalyst for water policy change. Analysis of Spain, Australia (MDB), and California. Glob. Environ. Chang., 58, 101969, doi:10.1016/j.gloenvcha.2019.101969.

BERBEL, J.; MATEOS, L. (2014): Does investment in irrigation technology necessarily generate rebound effects? A simulation analysis based on an agro-economic model. *Agric. Syst*., 128, 25–34, doi:10.1016/j.agsy.2014.04.002.

CONFEDERACIÓN HIDROGRÁFICA DEL GUADALQUIVIR (CHG) (2016): Plan Hidrológico de la Demarcación del Guadalquivir 2015–2021, R. D. 1/2016; Confederación Hidrográfica del Guadalquivir: Sevilla, Spain, 2016.

DAGNINO, M.; WARD, F.A. (2012): Economics of Agricultural Water Conservation: Empirical Analysis and Policy Implications. *Int. J. Water Resour. Dev*., 28, 577–600, doi:10.1080/07900627.2012.665801.

DOORENBOS, J.; KASSAM, A. (1980): Yield Response to Water. *Irrig. Agric. Dev.*, 33, 257–280, doi:10.1016/b978-0-08-025675-7.50021-2.

EGEA, G.; NORTES, P.; GONZÁLEZ-REAL, M.M.; BAILLE, A.; DOMINGO, R. (2019): Agronomic response, and water productivity of almond trees under contrasted deficit irrigation regimes. *Agric. Water Manag*., 97, 171–181, doi:10.1016/j.agwat.2009.09.006.

ENGLISH, M. (1990): Deficit Irrigation. I: Analytical Framework. *J. Irrig. Drain. Eng*., 116, 399–412, doi:10.1061/(asce)0733-9437(1990)116:3(399).

ENGLISH, M.; RAJA, S.N. (1996): Perspectives on deficit irrigation. *Agric. Water Manag*., 32, 1–14, doi:10.1016/s0378-3774(96)01255-3.

ESPARZA, G.; DEJONG, T.M.; WEINBAUM, S.A.; KLEIN, I. (2001): Effects of irrigation deprivation during the harvest period on yield determinants in mature almond trees. *Tree Physiol*., 21, 1073–1079, doi:10.1093/treephys/21.14.1073.

EXPÓSITO, A.; BERBEL, J. (2016): Microeconomics of Deficit Irrigation and Subjective Water Response Function for Intensive Olive Groves. *Water*, 8, 254, doi:10.3390/w8060254.

EXPÓSITO, A.; BERBEL, J. (2017a): Agricultural Irrigation Water Use in a Closed Basin and the Impacts on Water Productivity: The Case of the Guadalquivir River Basin (Southern Spain). *Water*, 9, 136, doi:10.3390/w9020136.

EXPÓSITO, A.; BERBEL, J. (2017b): Sustainability Implications of Deficit Irrigation in a Mature Water Economy: A Case Study in Southern Spain. *Sustainability*, 9, 1144, doi:10.3390/su9071144.

FERERES, E.; SORIANO, M.A. (2006): Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.*, 58, 147–159, doi:10.1093/jxb/erl165.

GARCÍA, J.G.; ROMERO, P.; BOTÍA, P.; GARCÍA, F. (2005): Análisis económico del cultivo de almendro en riego deficitario controlado (RDC). *Fruticul. Prof.*, 154, 43–50.

GIRONA, J.; MATA, M.; MARSAL, J. (2005): Regulated deficit irrigation during the kernel-filling period and optimal irrigation rates in almond. *Agric. Water Manag*., 75, 152–167, doi:10.1016/j.agwat.2004.12.008.

GOLDHAMER, D.A.; FERERES, E. (2016): Establishing an almond water production function for California using long-term yield response to variable irrigation. *Irrig. Sci.*, 35, 169–179, doi:10.1007/s00271-016-0528-2.

GOLDHAMER, D.A.; VIVEROS, M. (2000): Effects of preharvest cutoff durations and postharvest water deprivation on almond tree perfor- mance. *Irrig. Sci*., 19, 125–131.

GOLDHAMER, D.A.; VIVEROS, M.; SALINAS, M. (2005): Regulated deficit irrigation in almonds: Effects of variations in applied water and stress timing on yield and yield components. *Irrig. Sci.*, 24, 101–114, doi:10.1007/s00271-005-0014-8.

INTERNATIONAL NUT AND DRIED FRUIT (INC) (2020): Statistical yYearbook 2019/2020. Available online: https://www.nutfruit.org/industry/technical-resources?category=statistical-yearbooks (accessed on 2 February 2020).

JACOBSEN, S.-E.; JENSEN, C.; LIU, F. (2012): Improving crop production in the arid Mediterranean climate. *Field Crop. Res.*, 128, 34–47, doi:10.1016/j.fcr.2011.12.001.

LÓPEZ, M.L.; ESPADAFOR, M.; TESTI, L.; LORITE, I.J.; ORGAZ, F.; FERERES, E. (2018): Yield response of almond trees to transpiration deficits. Irrig. Sci., 36, 111–120, doi:10.1007/s00271-018-0568-x.

MINISTRY OF AGRICULTURE, FISHING AND FOOD (MAPA) (2018): Anuario de Estadística; Ministerio de Agricultura, Pesca y Alimentación: Madrid, Spain. Available online: https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuario-de-estadistica/ (accessed on 1 April 2020).

MINISTRY OF AGRICULTURE, FISHING AND FOOD (MAPA) (2019): Jornada de Frutos Secos: Caracterización del Sector; Ministerio de Agricultura, Pesca y Alimentación: Valencia, Spain.

MINISTRY OF ENVIRONMENT (MIMAN) (2007): Precios y Costes de los Servicios del Agua en España; Ministerio de Medioambiente: Madrid, Spain.

MOLDEN, D.; OWEIS, T.; STEDUTO, P.; BINDRABAN, P.; HANJRA, M.A.; KIJNE, J. (2010): Improving agricultural water productivity: Between optimism and caution. *Agric. Water Manag*., 97, 528–535, doi:10.1016/j.agwat.2009.03.023.

MONKS, D.; TAYLOR, C.; SOMMER, K.; TREEBY, M. (2017): Deficit irrigation of almond trees did not decrease yield. *Acta Hortic.*, 1150, 251–260, doi:10.17660/actahortic.2017.1150.35.

NOVELLO, R. (2019): Costes Operativos del Almendro; II Jornada Tecnica del Almendro: Caspe, Spain.

ROMERO, P.; NAVARRO, J.M.; GARCÍA, F.; ORDAZ, P.B. (2004): Effects of regulated deficit irrigation during the pre-harvest period on gas exchange, leaf development and crop yield of mature almond trees. *Tree Physiol*., 24, 303–312, doi:10.1093/treephys/24.3.303.

STEDUTO, P.; HSIAO, T.C.; RAES, D.; FERERES, E. (2012): Crop Yield Response to Water; Food and Agriculture Organization of the United Nations: Rome, Italy.

STEVENS, R.M.; EWENZ, C.M.; GRIGSON, G.; CONNER, S.M. (2011): Water use by an irrigated almond orchard. *Irrig. Sci*., 30, 189–200, doi:10.1007/s00271-011-0270-8.