# The Microeconomics of Water Demand under Deficit Irrigation: A case study in southern Spain.

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**Abstract.**

This contribution presents an exploratory analysis of the microeconomics of deficit irrigation (DI) as a technique with growing prevalence in water scarce areas, as it is the case of southern Spain. We analyze farmer decisions based upon their subjective beliefs about water production function that farmers could attribute to this technology. The dynamic nature of water policy means that these technologies, which can be labelled as water saving techniques, have a relevant impact on the farmers' decision process about the applied water doses and the structure of the water demand.

## 1. Introduction

This study attempts an exploratory analysis of the microeconomics of deficit irrigation (DI) that may significantly impact the economics of irrigation on its two fundamental variables, water use (applied irrigation dose) and price (elasticity to water cost). Molden et al (2010) argue that water productivity can be improved by practices including water harvesting, supplemental irrigation, deficit irrigation, precision irrigation techniques and soil-water conservation practices. Our research focuses on the technique of deficit irrigation as defined by consisting of the supply of irrigation water below the total irrigation requirements throughout the crop cycle (Molden et al., 2010).

Regarding water dose used by farmers, a majority of the water models are based on the assumption that there is limited availability of irrigated land, but water supply is unlimited (*i.e.*, it significantly exceeds crop needs). Accordingly, water is treated as a variable input and land as a constrained resource. In their model of deficit irrigation, Berbel and Mateos (2014) expanded the model developed by English (1990) to account for deficit irrigation. This model will serve us to analyze the behavior among our sample of farmers when they decide the water dose applied to their crops.

On the price side, advocates of water pricing generally put forward three arguments (Perry, 2001). First, it serves as a cost recovery instrument for water services. Second, it provides an incentive for the efficient use of scarce water resources, and third, it acts as a source of finance to continue providing essential water services in the future (Kumar & Singh, 2001). Furthermore, water pricing is considered a suitable way of reflecting the economic and social value of the resource and of allocating it efficiently to different uses (Johansson, 2000), as well as a strategic tool for water and environmental policy as remarked in the Water Framework Directive

(European Commission, 2000) and the Blueprint to Safeguard Europe's Water Resources (European Commission, 2012).

As described above, this paper aims to analyze the impact of DI schemes on the structure of water demand through the test of the following hypotheses. Firstly, farmers maximize returns for the water considering water volume as fixed and land as a variable input, instead of the conventional economic optimum of maximum returns for the land with water as the variable input and land as the limited factor. This behavior is consistent with the perception of the water resources in basins or in locations where water is considered the most important limiting factor for agricultural production as it is the case for many farmers around the world, especially for those with extensive crops in dry countries where the strategy is to maximize returns for the water, not land. And secondly, in areas where farmers adopt DI as a predominant strategy in response to water scarcity, the structure of the water demand function is also impacted in its elasticity with respect to price, leading to an ineffectiveness of water pricing at curtailing water demand, unless a disproportionate high threshold price is reached.

In order to test the above-mentioned hypotheses, we surveyed farmers of irrigated intensive olive groves located in southern Spain in order to determine: (1) whether farmers have rational expectations regarding the water-yield relationship; (2) whether the decisions regarding the level of water use correspond to the maximization returns for water or, conversely, whether farmers behave as if they are maximizing returns for land; (3) whether threshold estimates, obtained through the elicited marginal product values of water, imply water pricing ineffectiveness.

The structure of the paper is as follows. Section 2 analyzes the impact of DI techniques on water-use decision making, followed by the study of the implications of this irrigation technique on the structure of water demand and water-price decision making in Section 3. The case study and results are presented in Section 4 and 5, respectively. Finally, main conclusions are summarized in Section 6.

## 2. Implications of DI on water-use decision-making.

Most of the decision-making models in agriculture are based on the use of objective data about economic and physical attributes (Anderson et al., 1977). Alternatively, Hardaker and Lien (2010) argue that decision-making analysis should explore the subjectivist view where the probability of an outcome is defined as the degree of belief in an uncertain proposition. This is in contrast to the dominant approach based on objective probability, which is defined as the limit of a relative frequency ratio (Anderson et al.,1977).

This paper adopts the alternative approach for two reasons. Firstly, in the context under analysis there is a lack of robust, scientifically observed data. Secondly, we want to compare observed behavior regarding water use with the theoretical predictions produced by economic theory on the microeconomics of DI as explained in the seminal work of English (1990).

Measuring the relationship between crop yield and used water is the most general approach to water management. It was initially developed by Doorenbos and Kassam (1979), while Steduto et al (2012) present an updated and comprehensive review of the coefficients that regulate crop response to water supply. Traditionally, a farmer determines the irrigation dose (W) taking into account the level of evapotranspiration (ET), the value of the effective rainfall and irrigation efficiency. Additionally, irrigation efficiency depends on the uniformity of application and the relative irrigation supply (RIS). RIS is a ratio of the applied supply of irrigation water compared to the maximum irrigation needs (Molden et al., 1998), in contrast to the relative water supply which


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also includes rainfall. When irrigation tightly fills the gap of water requirements after they are met by rain, RIS is near unity. In the short term, the decision variable that can be managed is the irrigation dose.

The value of water, and water demand, is a function of marginal productivity, which when multiplied by the product's price yields the marginal value of water. The marginal productivity of relative irrigation water supply is the partial derivative of the production function *Y(w)* with respect to water "*w*".

A majority of the water use models are based on the assumption that there is limited availability of irrigated land, but water supply is unlimited (*i.e.*, it significantly exceeds crop needs). Accordingly, water is treated as a variable input and land as a constrained resource. This assumption implies that farmers displaying rational economic behavior should maximize the following profit equation:

$$Z = P_y Y - P_w W - C \tag{1}$$

where $Z$ denotes profit, $P_y$ is the price of the crop, $P_w$ is the price of water, and $C$ represents fixed costs. In their model of DI, Berbel and Mateos [13] expanded the model developed by English (1990) to account for deficit irrigation, efficiency changes and the situation in which land is not a binding constraint and water is a limiting factor. Thus, farmers who behave rationally in an economic sense seek to maximize total net income:

$$Z \cdot A = A \cdot \left(P_y Y - P_w W - C\right) \tag{2}$$

English and Raja (1996) illustrate this model with an example based on a quadratic water response production and cost functions, such as those represented below:

$$Y(w) = a_1 + b_1 W + c_1 W^2 \tag{3}$$

$$C(w) = a_2 + b_2 W \tag{4}$$

The solution to the optimization problem posed in Equation (1) takes land as the fixed input and water as the variable input. This is based on the conventional assumptions regarding farmer decision-making; that is, that they are seeking economic optima in the use of inputs such as water and others that are considered "freely variable inputs". The solution to this optimization problem represents the maximum return to land and is determined by the value of water dose "$W_l$" given by:

$$W_l = \frac{b_2 - P_y b_1}{2\, P_y c_1} \tag{5}$$

The solution to the second problem posed in Equation (2) considers water as a limited input while land becomes a freely variable input. This alternative model gives the maximum return to water (dose "$W_w$"):

$$W_w = \left(\frac{P_y a_1 - a_2}{P_y c_1}\right)^{1/2} \tag{6}$$

Finally, it is relevant to the microeconomic analysis of irrigation to determine the maximum yield solution. This straightforward solution is widely used to determine the maximum irrigation requirements; by solving Equation (1) the maximum yield is found at the point "$W_m$" represented by:

$$W_m = \frac{-b_1}{2\, c_1} \tag{7}$$

The latter solution is relevant in terms of agronomic analysis, and it is equal to the economic optimum when the price of water is zero in the land-constrained model (Equation (1)). Regarding the parameters in the model, English (1990) included all variable costs linked to water application in $P_w$. Our simplified model focuses on water; therefore, we do not consider substitution relationships between irrigation water and other inputs but consider them as fixed.

This research aims to compare the actual dose that a farmer applies to a crop with these three solutions to the optimization problem upon estimations obtained from a sample of olive groves farmers in southern Spain who extensively use DI techniques, as it is shown in Section 5.

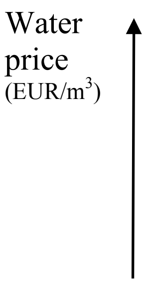
**3. Impact of DI on water-price decision-making.**

The majority of water pricing related literature focuses on analyzing farmers' responsiveness to pricing pressures and how price policies prompt the implementation of more efficient water use techniques. Nevertheless, there is a growing body of literature that concludes that irrigation water demand has a very low elasticity and water pricing is not particularly effective at curtailing water demand. As the price of water is only rarely determined by the market, the analysis of water demand for irrigation becomes problematic. Consequently, the value of water needs to be derived by modelling an optimization problem of farmers' production function (Dinar & Letey 1996; Rosegrant et al., 2001; Jeder et al., 2014).

The studies of Bernardo and Whittlesey (1989), Ogg and Gollehon (1989), Dinar and Letey (1996) and Varela-Ortega et al. (1998) are good examples of attempts to model responsiveness to water pricing among farmers under restricted water supply (demand inelasticity). Nevertheless, it is still debatable whether or not water pricing is an effective measure in water demand management (De Fraiture & Perry 2007). Several studies claim that irrigation water demand is inelastic below a threshold price, and elastic beyond it (i.e. Perry 2001; Ray 2002). Thus, considerable price increases would be required to produce a reduction in demand, and such increases may involve important political considerations.

In our case study, as it is the case in many parts of the world, farmers do not freely decide on the amount of water they will use to irrigate their crops, as water access is restricted by water rights (or fixed allocations). Under conditions of water scarcity and low water prices, the amount allocated is likely to be below the amount of water that farmers would be willing to take at the prevailing price, thus promoting the use of DI techniques. This would encourage the use of irrigation doses that would maximize returns to water, rather than returns to land as proposed by English (1990) and illustrated, among others, by Berbel and Mateos (2014).

Figure 1 shows the relation between water price and demand under a fixed-allocation system. At low prices, water demand is constrained by fixed supply (Ws) and farmers optimize water use by choosing an appropriate crop, level of risk and efficient irrigation techniques, thus showing no response to price. Conversely, water demand becomes elastic to price at a certain threshold price. This is the point where price equals the productive value of an additional unit of water (water price equals marginal product value of irrigation water).



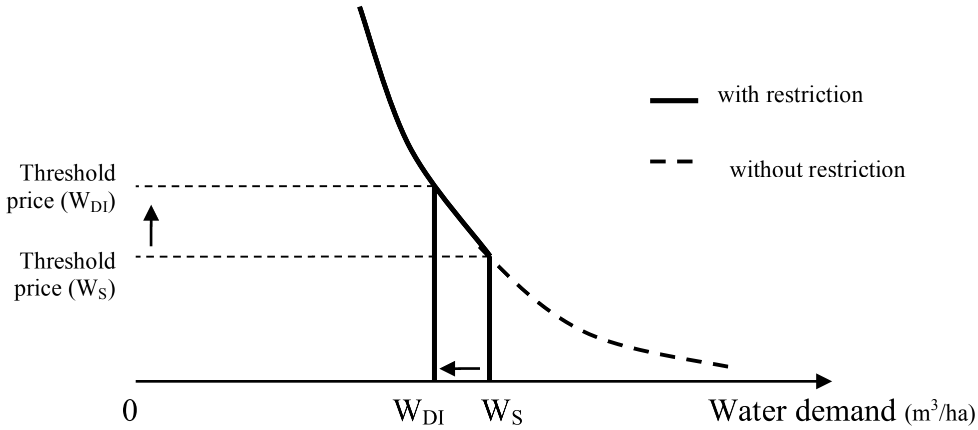



**Figure 1. Water demand under restricted supply ($W_S$) and deficit irrigation ($W_{DI}$).**

*Adapted from De Fraiture & Perry (2007)*

When DI techniques are extensively adopted, farmers' irrigation decisions are shown to be seeking a maximum return to water, as found by Exposito and Berbel (2016). This is because water is considered the fixed factor in this case, instead of the more conventional hypothesis that maximizes return to land. Thus, under the predominance of DI schemes, the allocated amount of water would fall from $W_S$ to $W_{DI}$ (Figure 1), shifting the theoretical threshold price upwards, after which point demand begins to show negative elasticity to price.

As Figure 1 illustrates, water pricing would be effective only if the price is set above a certain threshold, which would be much higher when DI techniques are extended in a context of restricted water supply, leading to significant reductions in farmers' profits. Furthermore, the concept of a threshold price is relative, depending on several agronomic factors (i.e. type of crop and land) and irrigation technology (i.e. gravity, sprinkler, drip); it is therefore essential to examine the nature and scope of the price threshold in order to assess the potential effectiveness of water pricing in certain agronomic locations (De Fraiture & Perry 2007). We believe this point is especially significant in the case of highly efficient farmers (those who already use high-efficient irrigation techniques, such as drip in our case study) and with respect to how their irrigation-demand decisions are based on their subjective perceptions.

## 4. Materials

### 4.1. Case Study

The case study selected to analyze farmers' subjective beliefs about the water-yield relationship is focused on irrigated olive groves in Andalusia (southern Spain). The area under study forms part of the Guadalquivir River Basin, which is the longest river in southern Spain with a 650 km length. The basin covers an area of 58,000 $km^2$ with a population of 4.1 million (the most populated cities are Seville, Cordoba and Granada). It has a Mediterranean climate with an uneven rainfall distribution (630 mm) and an average annual temperature of 16.8 °C. Annual renewable resources are estimated at $7.1 \times 10^9$ $m^3$ for surface waters and $2.6 \times 10^9$ $m^3$ for groundwater. In 2014, per capita water consumption in the basin was 1,600 $m^3$, and agriculture was the top consumer with 87% of the total. Olive groves represent the main crop in the basin. Though initially famers simply installed drip irrigation systems into existing traditional groves (100 trees per hectare), new irrigation technologies have allowed farmers to significantly increase tree densities in order to create intensive groves (between 250 and 300 trees per hectare) or superintensive groves (around 800 trees per hectare).

### *4.2. Survey Description*

The field work was conducted in spring 2014 with information given by farmers of intensive olive groves in the Guadalquivir River Basin regarding yield and irrigation doses per ha, among other data, in the period 2010–2013. The original survey consisted of 99 observations (farmers), and average values in the survey are: (a) farm size: 40 ha; (b) density: 283 trees/ha; (c) allocation total water rights: 2,723 $m^3$/ha (referred to as the legal water quota owned by the farmer); and (d) irrigation doses: 1,028 $m^3$/ha. We observe a discrepancy here, as water use represents 38% of water rights (irrigation dose/water rights = 1,028/2,723), which we consider an indication of the dominant DI strategy studied in our research. Potential evapotranspiration (PET) in the year of the survey was estimated at 492 mm for the intensive olives.

The descriptive statistics of variables that characterize our survey (crop area, density, age of olive groves and assigned irrigation rights) are shown in Table 1. Although the variability within the sample seems high, the table shows that the observed farmers tend to apply an irrigation dose far smaller than that permitted according to their assigned water rights, displaying, on average, a preference for a scenario characterized by DI.

**Table 1.** Basic descriptive parameters.

| | **Area (ha)** | **Density (trees/ha)** | **Age (years)** | **Irrigation Rights ($m^3$/ha)** | **Yield (kg/ha)** | **Irrigation Dose ($m^3$/ha)** |
|---|---|---|---|---|---|---|
| Average | 40 | 283 | 15 | 2,723 | 6,382 | 1,028 |
| St. Dev. | 64 | 80 | 6 | 1,846 | 2,344 | 388 |
| Minimum | 1 | 208 | 4 | 200 | 333 | 200 |
| Maximum | 400 | 571 | 30 | 7,000 | 13,833 | 2,500 |

From our initial sample of 99 farmers, 51 were discarded as they presented estimation errors (i.e. increasing returns to scale) and/or missing information. Consequently, our sample was reduced to 48 valid behavioral observations.

### *4.3. Perceived Water-Yield Response*

The water production function was elicited by asking farmers about their expectations regarding water volume and yield for three irrigation levels: full irrigation, usual DI and extreme DI. We assume that farmers will give rational answers and we need values that:

- Identify the volume-yield for each of the three irrigation levels.
- Exhibit decreasing returns to scale for the different irrigation levels.
- Generate a water-yield curve in the “normal” agronomic range (maximum yield should be within the normal range for the crop and region).

An individual subjective water demand function has been elicited on an individual subjective water-yield curve in the 'normal' agronomic range (maximum yield should be within the normal range for the crop and region) as defined in Section 2. The answers given by farmers regarding their expectations as to water consumption ($m^3$/ha) and yield (k/ha) in three possible irrigation scenarios (extreme DI, usual DI and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full irrigation) make possible to estimate a quadratic production function (as defined by Equation 3).

## 5. Results

### *5.1. Water use decision-making.*

This paper aims to test the hypothesis that in the context of water scarcity, farmers maximize returns to water rather than the classical assumption that they aim for a maximum profit per hectare (when land is the limited input). In this regard, our study compares actual irrigation doses applied by farmers to a crop with the three optimal solutions to the profit maximizing problem as set out by English (1990) and described in Section 2.

To do so, we estimate the values of optimal solutions, $W_m$, $W_l$ and $W_w$, for each farmer of our survey sample. The descriptive parameters of the estimates in each individual microeconomic model are shown in Table 2, along with the values corresponding to the most frequently-used irrigation dose (usual DI) given by the surveyed farmers and the average real irrigation doses applied in the period 2010–2013.

**Table 2.** Solutions to the microeconomic model and observed behavior.

| | Analytical Solution | | | Survey | |
|---|---|---|---|---|---|
| **$m^3$/ha** | **Max. Yield ($W_m$)** | **Max. Return to Land (Water Free) ($W_l$)** | **Max. Return to Water (Land Free) ($W_w$)** | **Usual DI ($W_u$)** | **Avg. Dose 2010–2013 ($W_o$)** |
| Maximum | 6,759 | 6,566 | 2,731 | 2,500 | 2,500 |
| Minimum | 538 | 613 | 248 | 600 | 600 |
| Median | 3,060 | 2,802 | 1,013 | 1,450 | 1,042 |
| Average | 3,178 | 3,005 | 1,163[1,2] | 1,357[1] | 1,103[2] |
| *St. Dev.* | *1,391* | *1,298* | *571* | *425* | *350* |

[1]At a 95% confidence interval, the *t*-test for the difference between means determines that Mean $W_u$=Mean $W_w$; [2]At a 95% confidence interval, the *t*-test for the difference between means determines that Mean $W_o$=Mean $W_w$.

As Table 2 shows, the solution for maximum returns for land ($W_l$), known as the traditional economic optimum, is very different from the average dose applied by farmers ($W_o$) and the usual DI dose ($W_u$). Furthermore, the average dose is close to the irrigation dose which maximizes returns for water when water is the limited resource ($W_w$). A simple *t*-test of significance between the mean values of the data distributions for $W_o$ and $W_u$, and that obtained from the estimated distribution of variable $W_w$, show that peer data distributions $W_o$ and $W_w$, as well as the peer $W_u$ and $W_w$, have similar distributions with statistically equal mean values. As the confidence interval includes zero at a 95% significance level, we can affirm that there is no significant difference between the means of the two contrasting data distributions. This result would seem to indicate that our farmers display similar behavior (on average) to that corresponding to the maximization of the returns to water, thus moving away from maximizing production or achieving the economic optimum.

Therefore, results obtained from the estimated microeconomic model would confirm that olive grove farmers tend to maximize returns to water, considering water volume as a fixed input and land as a variable input.

5.2. Water pricing decision-making.

In order to test our second hypothesis regarding the impact of DI on water demand structure and its elasticity to price, individual elicited threshold price levels have been obtained. Table 3 shows descriptive statistics of these elicited threshold levels given by the estimated marginal product value of water at the usual irrigation dose applied by each farmer, together with information regarding the current water cost. The average estimated marginal product value associated with the average applied water dose in our sample shows that the threshold price would be around 1.2 EUR/m$^3$, which is 10 times the current average water cost paid by our sample of farmers (0.11 EUR/m$^3$).

**Table 3**. Water cost and elicited threshold price.

| | **Water cost (EUR/m$^3$)** | **Applied Water dose (m$^3$/ha)** | **Threshold Price (EUR/m$^3$)** |
|---|---|---|---|
| Maximum | 0.30 | 2,500 | 4.68 |
| Minimum | 0.05 | 600 | 0.20 |
| Median | 0.08 | 1,042 | 1.03 |
| Average | 0.11 | 1,103 | 1.22 |
| *St. Dev.* | *0.09* | *350* | 0.88 |

Note: Average is the mean of all elicited individual parameters.

As mentioned above, the threshold price is influenced by the technology choice adopted by the farmer and the existing water management practices in the river basin. These two factors usually lead to an evolution of the economic value of water characterized by an increase of the marginal product value of water. Further, when DI techniques are widely adopted, an increase of the threshold price also occurs. Consequently, the marginal product value of water and the threshold price determine the structure of water demand and evolve independently from water cost, which is related to supply evolution and water policy measures. Thus, in the irrigated olive case study, water cost would not be expected to play a key role in determining our farmers' subjective water demand unless water price levels increase disproportionally and above the threshold price.

The case of our sample's median farmer is illustrated in Figure 2. In this case, the threshold price of water is estimated at 1.03 EUR/m$^3$, which is far higher than the median cost of water in the basin (0.08 EUR/m$^3$) and even well over our sample's higher cost (0.30 EUR/m$^3$). The grey shaded area represents the estimated economic rent associated with the resource and thus, with the farmer's surplus obtained by the application of the DI technique. In this case, and assuming the highest observed cost of water in our sample (0.30 EUR/m$^3$), the estimated economic rent would be equivalent to 1,099 EUR/ha.

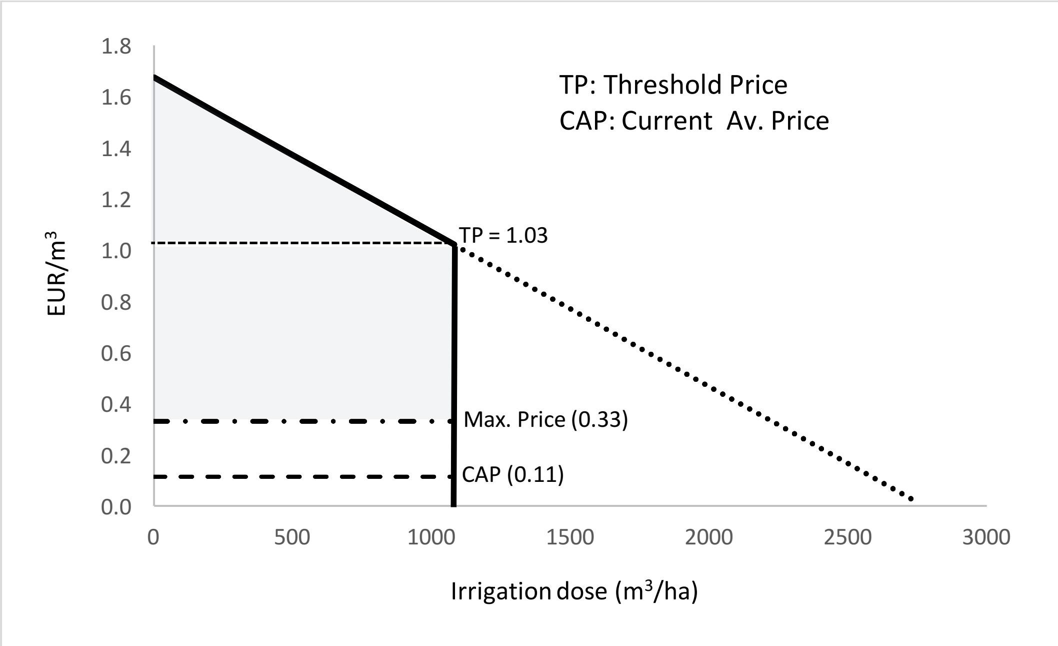


**Figure 2. Median farmer's elicited water demand.**

Figure 2 illustrates the water rent estimation, according to the definitions by Young and Loomis (2014). The figure shows marginal product value of water that is very close to those of Mesa-Jurado, Berbel and Orgaz (2010) who base their analysis for irrigated olives in an agronomic empirically derived water-yield response function, which is an alternative approach to our research that is based on subjective farmer beliefs. The similarity between our results based on farmer expectations and those based upon derivation of agronomic production function may be explained because farmers make their water volume decision considering scientific (agronomic field research) and administrative (the Basin Agency and Regional Government) information available and consequently, their personal experience may be reinforced by the knowledge from public domain explaining the convergence of farmer subjective expectations and public available agronomic functions.

## 6. Concluding remarks.

The past twenty years have seen substantial progress in the practical application of deficit irrigation for both annual and perennial crops (FAO, 2002). Most of the studies consider the agronomic technicalities of the optimal DI supply though the economic consequences have received scarce interest and the need for empirical tests is relevant.

This study has presented preliminary results regarding the microeconomics implications of DI on water demand at farm level, but further research is required in order to account for other aspects such as uncertainty and farmer attitudes toward risk, which may explain some of the observed differences between farmer behavior and microeconomic analytical predictions.

As we have pointed out, our research is focused on a specific area and crop (what clearly implies a limitation of this study) and it has demonstrated a general use of DI as a technique that allows the farmer to seek maximum returns to water and reduce price-elasticity of water demand till a disproportionate threshold price level (relative to current water costs). As a main conclusion, water pricing policy loses effectiveness in areas characterized by water scarcity and supply restrictions (i.e. in over-exploited aquifers and basins), as is the case of the Guadalquivir river basin in southern Spain (and in many other parts of the world with similar climatic and hydrological conditions). In this regard, we believe that the extensive adoption of this technique will have serious consequences for the river basin management, requiring further research that is beyond the scope of our preliminary analysis.

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