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Microeconomic analysis of irrigation efficiency improvement in water use and water consumption

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ABSTRACT

Increasing irrigation efficiency has been suggested as a solution in water scarce areas but its potential rebound effect (increased ex-post water consumption) is receiving growing attention; paradoxically, although improved irrigation efficiency may reduce water use, it may also increase water consumption. This paper undertakes an analytical review of the microeconomic foundations of the effects of water-saving investments and the resulting irrigation efficiency on water use and consumption. Moreover, it analyses the relationship between irrigation efficiency, water demand and water pricing. Findings show that improving efficiency would significantly reduce water use, though the impact on water consumption would be negligible even if there is a radical increase in water cost. Thus, the potential rebound effect would not be related to irrigation efficiency, but rather to other factors such as irrigated area expansion, crop-mix changes, and market forces.

1. Introduction

The commonly-held belief that improving the efficiency of irrigation through high-tech agriculture would translate into water savings and a more sustainable use of the resource has been put in doubt by a wide variety of studies (see Levidow et al., 2014; Scott et al., 2014, among many others). Irrigation modernization, understood as the enhancement of the efficiency, flexibility and reliability of irrigation through the transformation of water delivery and application systems, may have undesirable consequences in terms of an increase in the amount of water used and consumed, commonly known as the rebound effect. Mateos and Araus (2016) review the strategies for engineering, agronomical, breeding and physiological pathways for the effective and efficient use of water in agriculture stating that engineering solutions for water conservation at farm level do not imply basin-scale water conservation. In the same line, Lopez-Gunn et al. (2012) evaluate the role of irrigation modernization questioning the reality of anticipated water savings whilst Molle and Tanouti (2017) show that, in the case of Morocco, implementation of drip irrigation tends to be associated with higher crop density, a shift to more water-intensive crops, and the reuse of 'saved water' to expand cultivated areas, resulting in higher water consumption. In our analysis, this rebound effect is defined as the paradoxical increase in water consumption resulting from the introduction of more efficient irrigation technology aimed at reducing water use.

The European Commission (2012) has recently identified a potential rebound effect in irrigation water-saving measures as a relevant issue to account for and has stipulated that subsidies should be granted for water-saving investments that explicitly devote at least 50% of the 'water saved' to environmental goals (European Council, 2013). In recent years, the potential rebound effect resulting from water-saving investments is receiving growing attention in the academic sphere (Berbel et al., 2015; Berbel and Mateos, 2014; Gómez-Gómez and Pérez-Blanco, 2014). A recent FAO report (Perry et al., 2017) also question the real water savings achieved by subsidizing the implementation of water conservation and saving technologies (WCSTs) in irrigated agriculture worldwide.

The Jevons paradox, as the rebound effect is also known, was first analysed in relation to energy consumption in the industrial sector (Jevons, 1865) and a majority of the existing empirical evidence shows that better (i.e. more efficient) technology does not necessarily imply less energy consumption and a cleaner environment (Fisher-Vanden and Ho, 2010). In industrial production processes, however, the energy is fully consumed, which is not the case with the use of water in irrigation. The extracted water (or used water) ends up as: i) beneficial evapotranspiration; ii) non-beneficial evapotranspiration; iii) non-recoverable runoff/percolation; and iv) recoverable runoff/percolation (Burt et al., 1997). The first three components constitute the consumed or depleted fraction, meaning that this water is not available for further use as it is consumed as evapotranspiration, incorporated into a

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product, or flows to a location where it cannot be readily reused (e.g., heavily saline water). The fourth component of the water abstraction (equivalent to the concept of 'water use' in this study, considering conveyance efficiency negligible for the sake of simplicity) is not consumed and is recoverable for further/later abstractions.

Thus, an increase in irrigation efficiency may reduce water use, but paradoxically (in a Jevons sense) may also increase water consumption. According to some authors, the rebound effect is linked to WCSTs implementation (Jensen, 2007; Pfeiffer and Lin, 2014; Rodríguez-Díaz et al., 2012; Scheierling et al., 2006; Ward and Pulido-Velázquez, 2008, among others). On the contrary, Huang et al. (2017) defend that using water saving technologies can reduce crop water use and improve the productivity of water. This controversial question is the focus of the present research.

Though some authors have concluded that an increase in irrigation efficiency may necessarily lead to a rebound effect (in the sense of the Jevons paradox), it has been difficult to build a methodological framework to explain it, and therefore, to predict the impact that an increase in the irrigation efficiency may have on water use and water consumption. Following the studies of Gómez-Gómez and Pérez-Blanco (2014) and Berbel and Mateos (2014), this work examines the microeconomic foundations of the effects of WCST investments and the associated increase in irrigation efficiency, addressing water use and consumption separately, as they are not equivalent. Moreover, we analyse the relationship between water demand (estimated as a response function of relative water use and consumption to changes in water cost) and irrigation efficiency, as efficiency enhancements affect water demand elasticity and thus, its responsiveness to water pricing measures. After presenting the analytical framework in the next section, Section 3 analyses the links between irrigation efficiency, water use and water consumption. A brief discussion on the findings and their policy implications is offered in Section 4. Finally, some concluding remarks are summarized in Section 5.

2. Analytical framework: efficiency, yield and relative water use

According to overwhelming evidence from empirical research, the yield (Y) response to crop evapotranspiration (ET) may be expressed as in Doorenbos and Kassam (1979), which has been widely adopted in the agronomic literature as a general description of crop yield response to irrigation:

$$\left(1 - \frac{Y}{Y_m}\right) = K_y\left(1 - \frac{ET}{ET_m}\right) \tag{1}$$

where Y is actual crop yield; Y_m is the maximum crop yield for the crop in question; ET_m is maximum evapotranspiration; and K_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration. Furthermore, ET can be calculated as:

$$ET = R + (E \cdot W) \tag{2}$$

where R is the effective rainfall plus the variations in soil water storage during the crop growing cycle, W is the applied (or used) water, and E is the irrigation efficiency. Irrigation efficiency is defined as the maximum blue water[1] ready to be evapotranspired by the crop (total evapotranspiration less effective rainfall and soil water storage) divided by the used water ($E = (ET - R)/W$). It should be noted that, contrary to what is often believed, efficiency (E) is not a constant value but rather a variable function of the water applied, the crop ET and the effective rainfall (R). Eqs. (1) and (2) are combined to give the following equation:

[1] Blue water refers to agricultural water applied while green water refers to water from rainfall.

$$\left[1 - \frac{Y}{Y_m}\right] = K_y\left[1 - \frac{E \cdot W + R}{W_m + R}\right] \tag{3}$$

where W_m is the *net irrigation water requirements* for a maximum yield (i.e. $W_m = ET_m - R$).

Eq. (3) may be rewritten in terms of non-dimensional variables:

$$y = \frac{Y}{Y_m} = 1 - K_y + K_y\frac{r + E \cdot v}{1 + r} \tag{4}$$

where y is the ratio Y/Y_m, r the ratio R/W_m, the contribution of rainfall plus soil storage to the net irrigation requirements, and $v = \frac{W}{W_m}$ is the ratio of irrigation supply (also known in agronomy as relative irrigation supply or RIS), defined as the used water (W) divided by W_m, which is the net irrigation required to achieve the maximum yield (Y_m) when we have 100% irrigation efficiency. As the word 'supply' may lead to a misunderstanding from a strict microeconomic point of view, we will refer to the variable 'v' as relative water use.

As mentioned above, irrigation efficiency is not a constant value, and depends on the used water. The 'standard' efficiency value for the different irrigation technologies found in the literature, which we denote by E_0, usually ranges from 0.6 for furrow irrigation to 0.95 for drip irrigation. By definition, it can be seen that E_0 is the ratio between the agronomic parameter W_m (irrigation needs for Y_m) and the water used (W) required to achieve maximum yield (Y_m) for a given irrigation technology:

$$E_0 = \frac{W_m}{W} = \frac{1}{v} \tag{5}$$

Fig. 1 shows the yield-water response function, measured as the relative yield in relation to relative water use (v) for different irrigation systems (i.e. furrow, sprinkler and drip irrigation) for a crop with a K_y of 1.25 (typical of maize), according to the model developed by Berbel and Mateos (2014) and based on Wu (1988) and English et al. (2002). All simulations shown in the figures have been performed taking $r = R/W_m$ equal to 0.2, so the represented crop receives 20% of its water requirements from usable rain and the rest need to be fulfilled by irrigation (this value is typical of a wide range of crops in different climatic conditions, such as maize crop). Additionally, implicit in this value is the fact that the analysis refers to crops that use both rain and irrigation water, with the latter in greater proportion (what is also typical of water stressed locations such as Mediterranean regions). As discussed above, E_0 has been set to the typical efficiency values of 0.6 (furrow), 0.8 (sprinkler) and 0.95 (drip). Fig. 1 shows that as the value of E_0 increases, the response function shifts increasingly upwards and the drawn curve seems to shorten. For example, it can be seen that in order to achieve maximum crop yield in the case of a furrow irrigation system, water supply must reach a value of $v = 1.67$ (circle in Fig. 1).

Following Berbel and Mateos (2014), Fig. 2 shows the relationship between efficiency E and relative water use v. For deficit irrigation practices (i.e. water used is reduced below maximum levels and yield stress is allowed with yield losses, what it is typical of water stressed locations) with low values of v (that is, for $v \le 0.76$, denoted by a circle in Fig. 2), it can be seen that efficiency (E) equals 1 for all irrigation systems. In our case, deficit irrigation conditions refer to decreases in water used below economic optimal. Thus, when deficit irrigation is involved, crops take better advantage of irrigation water used, increasing efficiency. In other words, when the supply of irrigation is low (below the level of maximum yield), all the applied water is used by the crop for evapotranspiration, obviously with a yield below the maximum level.

Berbel and Mateos (2014) model define the efficiency as a function of two variables: the technological efficiency at maximum yield, or standard efficiency (E_0); and the relative water use (v), as shown in Eq. (6):