Agricultural Water Productivity under Spatial Adjustments

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Abstract:

With the demand for agricultural water expecting to be increased because of the expanding population growth and with water use efficiency in agricultural sector tending to be low, policy recommendations are needed to encourage farmers to increase agricultural water productivity. The main objective of this paper is to develop a spatial model that determines optimal water allocation and to generate measures of agricultural water productivity along a canal, taking into account the head versus tail disparities in water allocation along a canal. The second objective is to analyze agricultural water productivity change into its components, change in variable inputs and change in water usage, and examine the effect of efficient water usage effort on agricultural water productivity.

Keywords: Agricultural water productivity; Spatial model; Quantity and quality of agricultural water

1. Introduction

After recent projections for food and agricultural production for the next three decades, water is at the center of the discussion (United Nations, 2015). Given the increase in population growth, food demand will increase and the agricultural sector will likely have to expand the use of irrigation water to meet this rising demand. However, water scarcity leads to significant water management issues in the agricultural sector. For this reason, experts are trying to find out ways to allocate this scarce resource more efficiently and to produce increasing quantities of food with decreasing quantities of water.

Agriculture plays an important role in the water crisis as it is by far the largest user of water. At a global level, about 70 percent of total water withdrawals are used for agricultural irrigation (Molden & Oweis, 2007). FAO (2012) considers "an increase in agricultural water productivity as the single most important avenue for managing water demand in agriculture." Improving water productivity in agriculture ("*more crop per drop*") with a continuously growing population can lead to better use of scarce water resources and sustainability of the ecosystems (Scheierling *et al.*, 2016). The water savings can be used to improve water allocation on a local level, and farms that utilize the same water source can have access to reliable water allocations regardless of being placed close to or far away from the water source.

Agricultural water productivity ("*crop per drop*") is a partial productivity measure of economic performance that focuses on a single input, water, and is affected by the farmers' managerial abilities, environmental conditions among other factors. In the case of a single output, output per unit of water is a thorough measure of the level of productivity, and it can be used to compare the performance of farms. The first studies about partial productivity measurement in the agricultural sector paid attention to output per unit of labor (labor productivity) and output per unit of land (land productivity). Given the large amounts of water used in agriculture, even small improvements in agricultural water productivity can have a significant effect on local and global water resources (Scheierling *et al.*, 2016).

This work attempts to develop a spatial model for measuring water productivity in agriculture by assuming that water use follows a gravity system where individual farms draw this resource across a path (i.e. canal) extending from the water source and ending at the last farm. Water prices and production technology in the model are location specific. The quantity of water in the canal decreases with distance from the water source, with farmers at the tail end of the canal facing potential water scarcity. For example, farmers near the water source are said to consume a disproportionate share of irrigation water, while tail farmers are left with limited and unreliable residual supplies (Wade, 1982).

This spatial model is a first attempt to estimate agricultural water productivity to capture the differences in water productivity due to head versus tail disparities in water allocation in the agricultural sector. The theoretical framework for the spatial model, based on Isard and Liossatos (1979) and Knapp and Schwabe (2008), derives the rules for the economic optimization of water supplied to farmers at various distances from a water source. The majority of studies that make use of spatial models are looking for the efficient allocation of water among farmers across the canal, but they do not analyze how an improvement in water productivity along the canal can have a positive impact both on the profits of farmers, and on water management issues. Both of these improvements are especially important in developing countries with intense water scarcity issues, (Chakravorty, Hochman, and Zilberman, 1995; Chakravorty and Roumasset, 1991).

Finally, the usage of the directional distance function for approaching the production technology of the farms will give us the opportunity to estimate the change in the agricultural water productivity when both reduction in inputs and expansion of outputs are observed (Färe and Grosskopf, 2000; Färe et al., 2005). However, this paper is not only limited to measure and analyze agricultural water productivity, but also to suggest policy scenarios that are needed to improve water productivity in agriculture.

Lastly, a second serious concern for water policymakers has to do with the impact that extensive water use can have on the environment. The increasing usage of chemicals and the intensification of agriculture due to higher food demand can result in water quality issues. Scarce water resources and water quality deterioration are two of the major concerns related to the management of water sources for agriculture, and various mechanisms are needed to both enhance food production efficiency and sustain the quality of the environment with a continuously growing food demand.

The reminder of this paper is organized as follows. The next section presents the theoretical framework of the spatial model, and the derivation and decomposition of agricultural water productivity change into various components using the theoretical framework. The last section provides some concluding remarks and policy recommendations.

2. Model Specification

2.1. Spatial Optimization Problem

We consider a single cropping season model of a water distribution system. Water is conveyed from a point source (e.g. a dam or an aquifer) into a canal. Farms are located on either side of this canal and draw water from it for agricultural purposes. To focus on improvements in on-farm water use efficiency, we assume that there is no water lost in conveyance and investment is not made for improving the canal quality (e.g. earthen canal). However, farms can invest in technology that increases the efficiency of water drawn, such as usage of drip or sprinkler irrigation, relative to flood or furrow irrigation (Chatzimichael et al., 2015). This work develops a spatial model of a water project in which water is used by individual farms across a path extending from the water source to the last farm. For simplicity purposes we will present the spatial model for two farms first.

Defining the technology as

$$T = \{(x, w, y\,):\ x\ and\ w\ can\ produce\ y, x \geq 0, w \geq 0\}$$

Both farms produce the same output (y). we can specify a two-input production function of crop yield for each farm. More specifically, one input will be the quantity of supplied water (w) and the second one will be an aggregated index of all the other inputs used by the farm (x). Thus, each farm produces output (y) using input (x) and water (w) from the canal. Let p be the output price of the crop, z the aggregated input price, and τ the price of water. The production function has the usual properties that apply to stage II of the neoclassical production function:

$f(\cdot) > 0\,; f'(\cdot) > 0\,;\ f''(\cdot) < 0$

In the case that we want to expand the spatial model for N farms, we need to account for the distance of each farm from the source of water. If r represents the distance of each farm from the source, then r=0 stands for the first farm, making the assumption that there is no loss of water from the source to the first farm of the system, and r increases while we are moving away from the source. The variable r can take values from the interval $[0, R]$, where R stands for the fixed length of the system. Let the amount of water available at the source be $\Omega(0)$ and the quantity of water used by farm i be $w_i \geq 0$,with $i = 1,2, \dots, N,$ then the relationship between source water and the received water is given by:

$$\Omega_B(r) = \Omega_A(r) - w_A(r)$$

The socially optimal maximization problem of N farms producing one output using an aggregate input factor and water, considering the impact that distance has on the availability of water along the canal, is given by:

$$\max_{x,w} \pi = \int_0^R \left[p_r f^r\big(x(r), w(r)\big) - z(r)x(r) - \tau(r)w(r)\right] dr \tag{1}$$

$$s.t. \dot{\Omega}(r) = -w(r) \tag{2}$$

$$\Omega(0) = w_0 \tag{3}$$

$$x(r), w(r) \geq 0 \tag{4}$$

where $\dot{\Omega}(r)$ is the spatial rate of change of instream flow at point x, and $w(r)$ is the amount of water delivered to the farm at location x.

The objective of the above maximization problem (eq. 1-4) is to select the amount of delivered water, w(r), and the level of input use, x(r), to maximize the farmers' profits accruing along the canal in a single cropping period, subject to the equation of motion. Based on the equation of motion, the instream flow adjusts to each location according to the volume of water diverted and applied to the crop. Finally, we assume that the canal inflow at x=0 is fixed at an exogenously determined level w_0.

An approach to spatial optimization problem can be a modification of Bellman's dynamic programming equation (Kamien and Schwartz, 1991) for in the case of spatial adjustment:

$$0 = \max_{x,w}[pf(x,w) - zx - \tau w - \pi_{\Omega} w + \pi_r] \tag{5}$$

where the optimal choices are expressed as $x^* = x(p,z,\tau,\Omega)$ and $w^* = w(p,z,\tau,\Omega)$. The optimized programming equation is given by:

$$0 = [pf(x^*,w^*) - zx^* - \tau w^* - \pi_{\Omega} w^* + \pi_r] \tag{6}$$

where $\pi_{\Omega} = \pi_{\Omega}(p,z,\tau,\Omega)$ and $\pi_{\mathrm{r}} = \pi_{\mathrm{r}}(p,z,\tau,\Omega)$

From the profit maximization problem, if we take the first order conditions we will get:

$$\frac{\partial H}{\partial x} = pf_x - z = 0 \tag{7}$$

$$\frac{\partial H}{\partial w} = pf_w - \tau - \pi_{\Omega} = 0 \tag{8}$$

The marginal value product of input use is equal to the input price in (7), while (8) presents the marginal value product of water use is equal to the water price plus the shadow value of instream flow.

From (6) and the optimal solutions for x, w, π_{Ω}, π_r, we will obtain the fundamental partial differential equation of the value function $\pi(p,z,\tau,\Omega)$:

$$\begin{gathered} 0 = pf\big(x(p,z,\tau,\Omega)\,, w(p,z,\tau,\Omega)\big) - zx(p,z,\tau,\Omega) - \tau w(p,z,\tau,\Omega) \\ - \pi_{\Omega}(p,z,\tau,\Omega) w(p,z,\tau,\Omega) + \pi_r(p,z,\tau,\Omega)] \end{gathered} \tag{9}$$

Differentiating the optimized partial differential equation in (9) at the optimal point with respect to input price (z), we get:

$$0 = pf_x \frac{\partial x^*}{\partial z} + pf_w \frac{\partial w^*}{\partial z} - x^* - z\frac{\partial x^*}{\partial z} - \tau \frac{\partial w^*}{\partial z} - \pi_{\Omega} \frac{\partial w^*}{\partial z} - \pi_{\Omega z} w^* + \pi_{rz} \tag{10}$$

where $\pi_{\Omega \mathrm{z}} = \frac{\partial \pi_{\Omega}}{\partial z}$ and $\pi_{\mathrm{rz}} = \frac{\partial \pi_{\mathrm{r}}}{\partial z}$

Using (10), (7) and (8), we obtain:

$$x^* = -\pi_{\Omega z} w^* + \pi_{rz} \tag{11}$$

Differentiating the optimized partial differential equation in (9) at the optimal point with respect to water price (τ), yields:

$$0 = pf_x \frac{\partial x^*}{\partial \tau} + pf_w \frac{\partial w^*}{\partial \tau} - w^* - z \frac{\partial x^*}{\partial \tau} - \tau \frac{\partial w^*}{\partial \tau} - \pi_\Omega \frac{\partial w^*}{\partial \tau} - \pi_{\Omega\tau} w^* + \pi_{r\tau} \tag{12}$$

where $\pi_{\Omega\tau} = \frac{\partial \pi_\Omega}{\partial \tau}$ and $\pi_{\mathrm{r}\tau} = \frac{\partial \pi_\mathrm{r}}{\partial \tau}$

Using (12), (7) and (8), leads to:

$$w^* = -\pi_{\Omega\tau} w^* + \pi_{r\tau} \tag{13}$$

Rearranging (13) and substituting to (11), we have the following optimal solutions for x and w:

$$x^* = x(p, z, \tau, \Omega) = -\pi_{\Omega z}(1 + \pi_{\Omega\tau})^{-1}\pi_{r\tau} + \pi_{rz} \tag{14}$$

$$w^* = w(p, z, \tau, \Omega) = (1 + \pi_{\Omega\tau})^{-1}\pi_{r\tau} \tag{15}$$

Finally, differentiating the optimized partial differential equation in (9) at the optimal point with respect to the canal inflow (Ω), leads to:

$$0 = pf_x \frac{\partial x^*}{\partial \Omega} + pf_w \frac{\partial w^*}{\partial \Omega} - z \frac{\partial x^*}{\partial \Omega} - \tau \frac{\partial w^*}{\partial \Omega} - \pi_\Omega \frac{\partial w^*}{\partial \Omega} - \pi_{\Omega\Omega} w^* + \pi_{r\Omega} \tag{16}$$

where $\pi_{\Omega\Omega} = \frac{\partial \pi_\Omega}{\partial \Omega}$ and $\pi_{\mathrm{r}\Omega} = \frac{\partial \pi_\mathrm{r}}{\partial \Omega}$

With sufficient differentiability, the dynamic programming approach presented by Kamien and Schwartz (1991) can be applied to a spatial framework and used to develop the necessary conditions of optimal control.

2.2. Agricultural Water Productivity

The measure of the agricultural water productivity is defined as output per unit of water diverted and applied to the crop $({}^{y_i}/_{w_i})$, where $i = 1, 2, \ldots$, N. The main goal of this study is not only to measure the agricultural water productivity, but also to find out policy scenarios that can help farmers to increase it (*more crop per drop*).

Under the framework of spatial adjustment, the formula of agricultural water productivity change is given by:

$$AWPC = \frac{dy}{dr}\frac{1}{y} - \frac{dw}{dr}\frac{1}{w} \qquad (17)$$

where y=f(x,w,Ω) represents the production function for each farm.

Solow (1957), Jorgenson and Griliches (1967) and Christensen and Jorgenson (1970) are pioneering efforts in multiple factor definitions of productivity. Luh and Stefanou (1991) develop the multiple output total factor productivity growth under dynamic adjustment and present an estimation of growth indices for U.S. production agriculture. Based on the analysis above, we can find the first part of the right hand side of (17). The measure of the total factor productivity change under spatial adjustment is derived by totally differentiating the production function $f(x, w, \Omega)$ with respect to distance:

$$\frac{dy}{dr}\frac{1}{y} = \sum f_x \frac{dx}{dr}\frac{1}{y} + f_w \frac{dw}{dr}\frac{1}{y} \qquad (18)$$

where

$$\sum f_x \frac{dx}{dr}\frac{1}{y} = \sum \frac{zx}{py}\frac{dx}{dr}\frac{1}{x} = \sum \frac{zx}{py}\hat{x}, using\ (7) \qquad (19)$$

$$f_w \frac{dw}{dr}\frac{1}{y} = \frac{(\tau+\pi_\Omega)w}{py}\frac{dw}{dr}\frac{1}{w} = \frac{(\tau+\pi_\Omega)w}{py}\widehat{w}, using\ (8) \tag{20}$$

where “^” indicates the proportional rate of change over space.

Finally, using (19) and (20) in (18) we can find the agricultural water productivity change measure:

$$AWP = \sum \frac{zx}{py}\hat{x} + \frac{(\tau+\pi_\Omega)w}{py}\widehat{w} - \widehat{w} \tag{21}$$

or

$$AWP = \sum \frac{zx}{py}\hat{x} + \left(\frac{(\tau+\pi_\Omega)w}{py} - 1\right)\widehat{w} \tag{22}$$

In Equation (22) the agricultural water productivity change measure is decomposed into two components: impact of changing the variable inputs $\left(\sum \frac{zx}{py}\hat{x}\right)$ and impact of changing the water usage $\left(\left(\frac{(\tau+\pi_\Omega)w}{py} - 1\right)\widehat{w}\right)$.

3. Concluding Remarks

Current discussions on agricultural water management issues, due to irrigation water scarcity, have resulted in many policy recommendations aiming to enhance effective water usage. The magnitude of gains from the more effective use of agricultural water imply that water policy can aim toward efficiency- and productivity-enhancing techniques that will allow the farmers to produce the same amount of output with using less water. However, the effectiveness of these policies depends on the proper measurement of agricultural water productivity.

This work presents a framework for measuring water productivity in the agricultural sector. The analysis is carried out within a spatial framework, which enables the measurement of agricultural water productivity along a canal. This spatial model captures the differences in water productivity in the agricultural sector due to head versus tails discrepancies in water allocation across a canal. In addition, apart from measuring and analyzing the components of the agricultural water productivity change under the spatial framework, this study suggests different policy scenarios that can lead to an improvement in the agricultural water productivity. On the one hand, switching from high to low water consuming crops can have an immediate effect on the agricultural water productivity, as with less water the farmers can produce the same level of output. But on the other hand, agricultural extension is a mechanism by which better irrigation practices and information on optimal input use can be transmitted to farmers. However, this second scenario has only long-run effects because the transition from the traditional to new farming practices takes a long time.

Apart from capturing the quantity aspect of water, the proposed model can also be extended by considering debates about agricultural water quality. Disputes over water quality along a canal have recently been the source of international or intra-national conflicts over water rights. For studying the spatial patterns of pollution along a canal, we can model the behavior of the farmer who wants to optimally increase her profits along a canal, but she does not take into consideration the external effects on downstream farmers. As a result, upstream water use has spillover effects on downstream farmers (Hilary, 2002). In this case, despite the fact that the farmers face the same technology and output prices along a canal; due to externalities, the allocation of clean water among them is not efficient and market failure can arise.

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