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Predicting farmer responses to water pricing, rationing and subsidies assuming profit maximizing investment in irrigation technology

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ABSTRACT

Recent research suggests that regional hydrologic and economic implications should be considered before adopting policies encouraging efficient irrigation technology. Investigating regional effects of irrigation efficiency investments relies on predicting how farmers will adopt irrigation technology and practices in response to different water management policies. Under water rationing, price changes, subsidies and other policies, farmers will typically trade-off water use with irrigation efficiency investment in order to maximize profits. We employ a self-calibrating profit maximizing model of agricultural production based on the existing California Statewide Agricultural Production Model (SWAP). The model embeds irrigation efficiency vs. capital investment trade-offs for different crops to predict production, water use, irrigation investments, yields and water productivity under different water management policies. Calibration to observed cultivated areas and water application for different crops is performed using the positive mathematical programming (PMP) method. The trade-off between irrigation efficiency and capital investment is modeled as a nested constant elasticity of substitution constraint that allows substitution between irrigation investment and total applied water. The model is applied to the Tulare Basin in California's southern Central Valley. Policy simulations include an increase in water price, water rationing, and rationing and irrigation efficiency subsidies. Our results show subsidizing efficient irrigation technology may have a little effect on total land and water use and so may not promote water conservation without other incentives or regulations. Of the three policies simulated, a water price increase of 20% is found to be the most conducive to gains in agricultural water productivity (43% gain).

1. Introduction

The term 'irrigation efficiency' has several definitions and should be used with caution (Jensen, 2007; Perry, 2007) particularly in economic work where efficiency is a synonym of optimality. In this paper irrigation efficiency is defined traditionally as the ratio of water consumed by irrigated crops to water diverted (Israelson, 1950). Increasing irrigation efficiency of a farm may not be optimal at the regional scale as it could eliminate water that previously was benefitting the environment or other users (Clemmens et al., 2008). While an efficient irrigation system is generally beneficial at the field scale, its regional impacts may not be and may actually increase overall water use (Ward and Pulido-Velazquez, 2008). Assessing such regional impacts will typically benefit from use of hydro-economic models (Harou et al., 2009) as demonstrated by Ward and Pulido-Velazquez (2008). For these and other reasons it has been suggested to replace the concept of efficiency of water use as a water management goal by 'water productivity', i.e. the net benefit per unit of water, which is always unambiguously a beneficial outcome (Molden et al., 2010; Perry et al., 2009).

Recent research has investigated the regional benefits of irrigation efficiency investments. Some such as Cooley et al. (2008) contend investment in more efficient irrigation systems will yield significant economic and environmental benefits. Other argue that water savings at the regional level (Clemmens et al., 2008) and regional economic benefits (Ward and Pulido-Velazquez, 2008) are often limited with any benefits occurring under specific hydrological and institutional conditions. Increased irrigation efficiency may have unintended regional effects: for example increased yields may increase evapotranspiration and consumptive water use or less 'wasted' water may translate into less drainage to surface water (return flows) and groundwater (recharge). The ambiguity and complexity of evaluating regional benefits of irrigation technology investments will ensure continued interest. Societal benefits of field-scale irrigation efficiency improvements must be considered

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on a case by case basis, investigating regional hydrological balance to determine if truly any water is 'saved' and if there are economic benefits.

Properly investigating regional effects of irrigation efficiency investments relies on predicting how farmers will adopt irrigation technology in response to institutional or water allocation changes. Various models and frameworks have been proposed to predict agricultural technology adoption as a result of water management policies (Dinar et al., 1992; Feder and Umali, 1993; Koundouri et al., 2006; Sunding and Zilberman, 2001). In this paper we explore how different water resources management policies affect agricultural production and irrigation practices in California. In particular, we study how changes in water resources availability, cost of capital investments in irrigation technology, and water prices potentially change total water use, capital investments in irrigation and cropping patterns in the study region.

The paper's main contribution is to accurately calibrate a model of the interaction of physical and economic reactions to water conservation policies. We recognize that the ability to substitute water application technology for applied water is much easier than the substitution in the production function. For example it is much easier to substitute irrigation system capital for applied water than it is to substitute pesticides for land. It follows that these two relationships have different elasticities of substitution which can be modeled by a set of nested CES functions. We assume that at our regional representative farm scale, it is possible to substitute capital for effectiveness in irrigation. One of the functions which can be referred to as the 'water application nest' results in a composite output which we term "effective water", but can be thought of as evapotranspiration. The top nest of the production function has inputs of land, labor, the cost of other inputs, and effective water. The novel methodological aspect of this paper is that for the first-time we are able to exactly calibrate both the water application nest and the main production function by using the correct valuation for the effective water composite input.

We employ a self-calibrating agricultural production model for the Tulare Basin region of California's Central Valley to test this effect. Agricultural production models are partial equilibrium models, i.e. they model the economics of the agricultural sector without modeling other parts of the economy. These require the use of optimization methods, typically mathematical programming methods (linear and non-linear programming) are used. Calibration refers to setting model parameters which recreate observed quantities, in this case cultivated areas for different crop and water applied to those crops. A calibrated optimization procedure named positive mathematical programming (PMP) was introduced by Howitt (1995) and reviewed by Howitt (2005) and Henry de Frahan et al. (2007); Tsur et al. (2004, pp. 128–129) provides a summary. 'Positive', as in empirically based, implies output from a calibrated model should reproduce observed levels of decisions variables (in our case agricultural production and input use like water). Farmers optimize operations and investments considering many factors, several of which will be omitted from a model. A PMP optimization model, once calibrated to observed behavior, can be used for policy formulation as a predictive tool to investigate farmer behavior under different conditions. In this paper we endeavor to predict farmer irrigation efficiency technology investment response to different water management policies including pricing, rationing and subsidies.

The rest of the paper includes a full description of the PMP method developed and a description of the case-study area and available data. Policy scenarios are described then model results involving changes in cultivated area, irrigation technology investment, applied water, yield and water productivity are presented. A discussion of results and conclusions follow.

2. Methods

In this study we use a modified version of the Statewide Agricultural Production Model (SWAP Howitt et al., 2001) (http://swap.ucdavis.edu) to demonstrate the approach. The data is from the Tulare Lake Hydrologic region in California's Central Valley. The model is based on positive mathematical programming (or PMP after Howitt, 1995), a self-calibrated deductive method in which the objective function is calibrated by the use of a PMP cost function, to observed values on the decision variable.

Based on previous studies (Howitt et al., 2001; USBR, 1997) we assume that a substitution relationship between applied water per hectare and capital investments in irrigation efficiency exists. In this relationship, larger amounts for capital investments per unit area improve irrigation efficiency. This relationship is nested into a constant elasticity of substitution production function as in Medellín-Azuara et al. (2010), with four inputs: capital investments in water, applied water, land, and an aggregated input of all other production inputs including labor and supplies such as fertilizer and pesticides. The model in its base case calibrates to observed amounts of inputs using positive mathematical programming (or PMP after Howitt, 1995).

PMP allows us to model policies using a calibrated base case as a starting point. Two variants from the original SWAP model for California are developed in this paper: (1) a tradeoff CES function based on a constant elasticity of substitution function is introduced in the calibration step; and (2) a virtual input named effective water use is introduced as part of the production function. The effective water initial value is calibrated to the rate of evapotranspiration of applied water by crop group and region. The modeling framework is defined as a Nested Constant Elasticity of Substitution production function.

The novel additional step in the PMP process allows embedding the substitution relationship between water and capital irrigation investments in a calibrated production function. Previous versions of programming models for the Central Valley (USBR, 1997) include the tradeoff function in the model but assume yields are constant in a Leontief production function where calibration is limited to land use. The current approach allows more realistic policy evaluation since production inputs which include tradeoffs between water use and capital are adjusted by the model in any given policy scenario. This innovation allows us to explore agricultural production and irrigation practices based not only on observed water use efficiency, but also on the underlying economic incentives facing the farmer.

2.1. Model description

In this section we describe the process by which we calibrate the nested CES model using PMP. Fig. 1 shows the steps involved, and for each step we provide a description and the relevant equations. In Appendix A of this paper we show the full set of equations and parameters.

2.1.1. Step 1. Calibration phase

In this first step we solve a linear optimization program subject to limited resources constraints and calibration constraints following Howitt (1995). Five inputs are used in production namely: land, applied water, supplies, a water capital bundle, and a composite input called effective water. Effective water is the applied water that reaches the root zone and contributes to crop growth at the field scale; i.e. the beneficial consumed fraction following Perry et al. (2009). The level of effective water is a function of both the rate of applied water and the level of capital and labor invested in its application. We model the tradeoff between applied water and water related capital as a nested CES constraint that allows substitution between capital investments in irrigation and total