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Innovative Applications of O.R.

A stochastic dynamic programming approach to analyze adaptation to climate change – Application to groundwater irrigation in India

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ABSTRACT

Agricultural sustainability under climate change is a major challenge in semi-arid countries, mainly because of over-exploited water resources. This article explores short- and long-term consequences of farmers' adaptation decisions on groundwater resource use, under several climate change scenarios. We model farmer decisions on crop choice, investment in irrigation and water application rates, using a stochastic dynamic programming model with embedded year and season decision stages. Several sources of risk are considered that may impact farmer decisions, with poor rainfall affecting crop yield and market prices, while driving crop and borewell failure probabilities. We further investigate the performance of water management policies for groundwater resource conservation. This is achieved through policy simulations from a calibrated version of the stochastic dynamic model, using data from a field survey in the Berambadi watershed, Karnataka state, southern India. The most relevant and novel aspect of our model is the joint consideration of (i) investment decisions about irrigation over a long-term horizon and with the probability of borewell failure, (ii) several water management policies, and (iii) detailed farmers' water practices and the representation of crop choice for each agricultural season with crop failure.

1. Introduction

Climate change is a significant challenge for sustainable agricultural production in the coming decades, especially since world's food demand is expected to double by the year 2050. Predictions of climate change impacts indicate a reduction in most crop yields under both irrigated and rainfed conditions, an increase in weeds, diseases and pests and changes in crop development and pollination periods (Kahil, Connor, & Albiac, 2015).

Agricultural systems in semi-arid areas depend greatly on irrigation and encounter increasing challenges due to climate change (e.g., growing uncertainty about the performance of adaptation strategies to climate change, severe depletion of natural resources), high volatility in crop market prices, rise in energy costs and greater pressure from public regulation (e.g., agricultural, environmental and health policies). In the Deccan Plateau in India, aided by state policy that subsidizes electricity and improved irrigation technology (e.g., new drilling and submersible pump techniques), the countryside has witnessed the proliferation of individual, electrical pump-driven borewells that abstract water from underground aquifers (Javeed, Sekhar, Bandyopadhyay, & Mangiarotti, 2009; Sekhar, Rasmi, Javeed, Gowrisankar, & Ruiz, 2006). This led to claims of a "democratization of irrigation", with smallholder farmers accessing irrigation water (Taylor, 2013). However, the low productivity of the aquifer (Dewandel et al., 2010; Perrin, Ahmed, & Hunkeler, 2011) and a rapid decline in the groundwater table level led to decreasing borewell yields (Ruiz et al., 2015), implying that groundwater-irrigated agriculture still largely depends on rainfall. Climate variability has increased over the last 50 years in this region (Jogesh & Dubash, 2014). Predictions indicate a 1.8-2.2°C increase in temperature by 2030, and southwestern regions of the state of Karnataka (southern India) are projected to experience a decrease in annual rainfall, especially during the monsoon season (Jogesh & Dubash, 2014). For a region that largely depends on monsoon patterns and winter months to maintain agricultural production, any shift in climate conditions would have a severe impact on natural resources and the local economy. Over the past two decades, rural India has been in the midst of a considerable crisis, illustrated by increasing levels of indebtedness and most tragically exemplified by the wave of farmer suicides, on the Deccan Plateau in particular. The need to cope with upcoming debt payments induces farmers to shift towards irrigated cash crops, and gaining control over water access is central to maintain household sustainability. Accessing groundwater may be a solution to provide

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water for crops on a more regular basis, but this solution must also account for consider social and cultural aspects of farmer indebtedness, including a new temporal horizon for debt repayment and accounting for the risk of failed wells (Taylor, 2013).

In this article, we model adaptive decisions of farmers facing climate change: long-term decisions about investment in borewell irrigation and short-term decisions about cropping systems and the irrigation water application rate for crops. We use a stochastic dynamic model of farmers' decisions to test socio-economic and water management policies under several climate change scenarios. Various policies are considered (subsidizing rainfed crops, reforming subsidized energy for irrigation, a water charge indexed on ambient groundwater level), and their impacts on farmer profit and groundwater level are compared. Each water conservation policy is considered along with a climate change scenario to evaluate the potential of each policy to mitigate the climate's impact on groundwater level. In the following sections, we first present the farmer's production problem and the data. We then describe the scenarios of climate change and water management policies as well as the simulation results. Finally, we discuss the results and the model to highlight the contribution of the paper to the literature as well as its caveats.

2. Literature review on long-term farmer decisions under uncertainty

Several fields in the literature have discussed models of farmers' decisions under risk and uncertainty, including irrigation management, ranging from environmental and resource economics to applications of operational research to hydrological issues. Krishnamurthy (2016) presented a theory that clarifies the properties of water management models under risk and uncertainty. Sekhri (2014) explored implications of groundwater irrigation on poverty in rural India using a detailed survey of agricultural wells.

It is essential to consider risk and uncertainty when representing irrigation management and cropping system decisions because of the uncertain nature of water availability for irrigation and crop yield resulting from climate conditions. Iglesias and Garrote (2015) provided a literature review on agricultural adaptation to climate change in Europe that describes the possible drivers of adaptation and policy implications.

Regarding the consideration of risk and uncertainty, two main approaches can be found in the agricultural economics literature, depending on whether uncertainty and risk are considered embedded risks or not (Robert, Thomas, & Bergez, 2016). If they are incorporated as non-embedded risk into the objective function, one then assumes that the farmer cannot reduce their impacts *a posteriori*, in prices, yields and revenues, or in constraints, to represent stochastic resource availability (Briner & Finger, 2013; Graveline, 2016; McCarl, Dillon, Keplinger, & Williams, 1999). However, if uncertainty and risk are incorporated as embedded risks, both risk anticipation and adjustments allow for recourse in the decision.

The main advantage of incorporating risk is to consider stochastic variables such as prices, yields, borewell recharge and water availability for irrigation, which are all related to uncertain weather. In this way, relationships between farm production variables and climate are better considered and represented in models. Fernández, Ponce, Blanco, Rivera, and Vásquez (2016) used stochastic programming to model economic impacts of changes in water availability in small-scale agriculture in the Vergara River Basin, Chile. They applied a calibration method for risk programming models with mean-variance model specification developed by Petsakos and Rozakis (2015) to include risk in the objective function of agricultural models. Blanco-Gutiérrez, Varela-Ortega, and Purkey (2013) used a risk-based economic optimization model and a hydrologic water management simulation model to model a vulnerable drought-prone agro-ecological area in the Middle Guadiana River Basin, Spain. Similarly, Foster, Brozović, and Butler (2014) predicted optimal irrigation strategies under variable levels of groundwater supply for irrigated maize production in the Texas High Plains region of the United States, and assessed the limits of existing models for predicting farmers' land and groundwater use decisions.

In discrete stochastic programming, the decision problem is broken down into several decision stages in which new information is available. It can be represented by decision trees. The typical case treated with discrete stochastic programming is cropping pattern planning under weather and/or water uncertainty. For instance, McCarl et al. (1999), Mejías, Varela-Ortega, and Flichman (2004) and Connor, Schwabe, King, Kaczan, and Kirby (2009) defined an initial stage that models the choice of long-term capital investments that remain fixed for several years regardless of annual stochastic variations (water allocation and water price). The second stage addresses short-term (annual) decisions, such as water application rates and land for crops or fallow.

The use of dynamic programming to represent and solve water, nutrient or animal feed management problems in agriculture has a long history. Burt (1993) considered an expected present value problem and from dynamic programming generated a set of sequential decision rules for optimal feed rations and marketed animal weights. Randomness in input and output prices was considered, and properties of the stochastic model were examined for two cases of model application: infinite sequence and single batch. However, no empirical application was presented. Bryant, Mjelde, and Lacewell (1993) used a dynamic programming model to explore allocation of irrigation among crops under random climate conditions. During dry periods, a crop can be abandoned temporarily or permanently. Intra-seasonal irrigation rules were considered for maize and sorghum in the Texas High Plains. These authors also used a crop simulator to “simplify” decision rules for crop choice and irrigation application rates. Only two plots of fixed size were set, and a fixed irrigation volume was allocated to only one crop.

Ritten, Frasier, Bastian, and Gray (2010) developed a stochastic dynamic programming model for purposes similar to those of Burt (1993), i.e., to solve for optimal stocking rates under climate change. More precisely, they considered farmers' decisions when rainfall is unknown before the start of the growing season. Farmers maximized the current net value of their land, and the (random) dynamic state variable was vegetation density. When climate scenarios were introduced, profitability decreased as rainfall variability increased compared to the baseline climate.

Maatman, Schweigman, Ruijs, and van Der Vlerk (2002) also considered a stochastic programming model to represent farmers' sequential decisions in response to changes in expected rainfall and introduced a food security condition into the problem. More precisely, the farmer's objective was to minimize nutrient deficits at the household level and during several periods (i.e. beginning of the growing season, later in the growing season and after harvesting). They presented one of the first examples in the literature of application of stochastic programming with an explicit subsistence strategy for farmers and adaptation to climate change in an intra-seasonal setting. The method, two-stage stochastic models and multiple-recourse models differed, however, from nonlinear stochastic dynamic programming, and no investment decisions in irrigation were considered.

More recently, Livingston, Roberts, and Zhang (2015) apply stochastic dynamic programming to evaluating the benefits of corn-soybean crop rotations in the United States (Iowa). Using both experimental plot-level data and historical data on prices and crop yields, they compare short-run vs. long-run decision rules regarding crop choices with stochastic crop prices. They find that farmer decisions under risk aversion are very close to the risk neutrality