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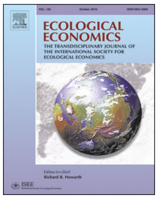

Simulating Crop-Water Production Functions Using Crop Growth Models to Support Water Policy Assessments

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ABSTRACT

Crop-water production functions are important tools for quantifying effects of water scarcity and climate change on agricultural production, and are also widely used within hydro-economic models to support design of inter-sectoral water management policies. Here, we introduce a new methodology for simulating crop-water production functions using process-based crop growth models, which captures explicitly the interacting effects of farmers' intraseasonal irrigation decision-making, stochastic weather conditions, and physical and socio-economic water supply constraints on seasonal crop yield response to water. Through a case study application for groundwater irrigated corn production in the Texas High Plains, we demonstrate that constraints to irrigation scheduling caused by aquifer depletion, combined with farmers' limited foresight of future weather conditions, have significant impacts on estimated seasonal crop-water production functions. Our results highlight that the failure to account for these factors fully in previous simulation approaches will lead to errors in estimates of the impacts of groundwater depletion on farmers' future resilience to drought and climate change. Our proposed simulation methodology is generalizable to different production systems or crop growth models, and provides a tool for assessing how economic benefits derived from irrigation vary spatially and temporally due to heterogeneity in biophysical conditions and irrigation practices.

1. Introduction

Irrigation is fundamental to agricultural productivity and food security worldwide (FAO, 2011). However, the availability of water for agriculture is under threat in many regions due to growing competition from cities and the environment for a share of limited freshwater resources, coupled with shifts in precipitation patterns and rising irrigation demands as a result of climate change (Elliott et al., 2014; McLaughlin and Kinzelbach, 2015).

Efforts to manage competing demands for scarce water resources from agriculture and other sectors fundamentally require knowledge of the value of irrigation water in crop production, and how this value varies over space and time due to differences in physical (e.g. weather/climate, soil type) and socio-economic (e.g. input/output prices, regulatory context) production conditions. Central to any such economic analysis of the value of irrigation water are crop-water production functions, which describe mathematically how crop yields respond to variable irrigation water inputs for a given set of climate conditions and farm management practices (Steduto et al., 2012). Crop-water production functions can be linked with farm economic models to evaluate how agricultural production and welfare outcomes will be affected by future shifts in water availability due to climate or policy change (Maneta et al., 2009; Foster et al., 2014; Esteve et al., 2015; Giuliani et al., 2016). Moreover, production functions also provide an essential input to hydro-economic modeling studies that seek to quantify the economic impacts of basin-scale policies to determine the optimal allocation of water use between agriculture and other users such as the environment, cities or hydropower (Cai et al., 2003; Bekchanov et al., 2015; Erfani et al., 2015; Kahil et al., 2015). For example, production functions linked with basin-scale hydro-economic models can provide a powerful tool for evaluating spatial and temporal trade-offs between agricultural profitability and environmental outcomes in groundwater-fed irrigation systems, where impacts of spatially distributed pumping on hydrologically-connected surface water ecosystems are a major driver of policy efforts to regulate agricultural water abstractions (Kuwayama and Brozović, 2013). Accurate estimation of crop-water production functions therefore is essential for accurate prediction of the impacts of water scarcity on agriculture, and for reliable design of economically efficient policies to manage rising inter-sectoral competition over limited freshwater resources globally.

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Historically, crop-water production functions have been developed based on empirical observations of crop yield response to applied irrigation from surveys of farms or regions (Hexem and Heady, 1978; Barrett and Skogerboe, 1980; Ayer and Hoyt, 1981; Moore and Negri, 1992; Zhang and Oweis, 1999; Kipkorir et al., 2002). However, due to the large costs associated with collecting empirical datasets and challenges in generalizing empirical functions to new environments or changing hydrological conditions (Young and Loomis, 2014), it is increasingly common for mathematical crop models to be used to simulate crop-water production functions for use in economic water policy analysis. Such models enable rapid assessment of the value of irrigation across diverse production conditions that would be infeasible using empirical techniques, and have been widely used as part of hydro-economic studies to support basin-scale water policy design and intersectoral water resource allocation (e.g. Kuwayama and Brozović, 2013; Kahil et al., 2015; Esteve et al., 2015; Giuliani et al., 2016; Noël and Cai, 2017).

When applying simulation models to estimate crop-water production functions, a major challenge is the mismatch between the temporal resolution of production functions used in hydro-economic research and water policy, which are either seasonal or annual, and that of crop growth models, which typically run on a daily time step. Commonly, an assumption is made that limited seasonal irrigation will be scheduled optimally within each growing season, for example by linking the simulation model with optimization algorithms to determine the sequence of irrigation decisions (timing and rates) that maximize crop yields for different levels of total seasonal irrigation (Brumbelow and Georgakakos, 2007; Schütze and Schmitz, 2010; Linker et al., 2016). However, this approach introduces several unrealistic assumptions about farmers' intraseasonal irrigation decision-making, specifically that the farmer has perfect foresight of future weather and irrigation demands, and that no constraints exist to when and how irrigation can be applied during the growing season. In reality, producers make irrigation decisions based on limited information about future weather conditions due to the imperfect nature of weather forecasts (Jones et al., 2000; Shafiee-Jood et al., 2014), and irrigation scheduling is affected by a range of physical, technical, social, and regulatory constraints to water availability (Foster et al., 2014; Smilovic et al., 2016). Correct characterization of the rules and constraints that underlie intraseasonal irrigation decision-making is critical for reliable estimation of seasonal crop-water production functions, and, thus, for the reliability of water policy and management assessments that are based on these functions. Yet, to date, the majority of studies that have used crop growth models to simulate crop-water production functions have not considered explicitly limits to farmers' foresight about future climate and intraseasonal irrigation scheduling, thus potentially reducing the accuracy of resultant estimates of seasonal crop-water production functions and water policy assessments based on these functions.

In this paper, we make two main contributions to the literature on development of crop-water production functions for economic analysis of agricultural water use and management. First, we provide a detailed review of the different approaches used to estimate crop-water production functions, focusing, in particular, on recent applications of crop simulation models since previous reviews published on this topic (Vaux and Pruitt, 1983, Dinar and Letey, 1996; McKinney et al., 1999). Second, we introduce a novel methodology for applying crop simulation models to develop seasonal crop-water production functions for use in hydro-economic studies of agricultural water management. Our approach provides a framework for simulating crop-water production functions in agricultural systems where farmers' irrigation decisions are influenced strongly by stochastic and uncertain weather conditions during the crop growth season, and where intraseasonal irrigation scheduling decisions are constrained significantly by physical, economic, or technical factors. We demonstrate the utility of our simulation approach through an illustrative application for irrigated corn production in the Texas High Plains, an area where producers increasingly face significant constraints to irrigation decision-making due to regulatory changes to water policy and depletion of groundwater storage. Our results illustrate that timing of irrigation, expectations of climate, and intraseasonal irrigation supply constraints all have large impacts on estimated seasonal crop-water production functions. Critically, failure to consider these factors is likely to lead to misleading estimates of the impacts of drought and rising water scarcity on farmers' and rural economies, highlighting the value of our proposed simulation approach to support improved economic analysis of agricultural water use and management globally.

2. Crop-Water Production Functions: A Review

The crop-water production function expresses the relationship between seasonal applied irrigation and crop yield. Some agronomic studies have proposed an alternative definition of the production function, in which seasonal evapotranspiration rather than applied irrigation is specified as the dependent variable (Doorenbos and Kassam, 1979; Igbadun et al., 2007; Geerts and Raes, 2009). However, for the purposes of economic analysis of agricultural water use and management, it is common to adopt the former definition of the crop-water production function, as applied irrigation water is the variable that is of greatest significance to policymakers, water managers, and farmers.

Fig. 1 illustrates the typical relationship between seasonal applied irrigation and crop yield. It is noticeable that the crop-water production function is concave and can be divided approximately into four sections. In Zone 1, almost all applied water is consumed by the crop and converted in to harvestable yield, and hence the crop-water production function has an approximately linear slope. However, as the level of applied water is increased (Zone 2), marginal returns to further irrigation diminish as increasing proportions of applied water are lost through non-beneficial (i.e. non-consumptive) processes such as soil evaporation, deep percolation, and surface runoff. Eventually, yield reaches a theoretical maximum (Zone 3) beyond which further application of irrigation will not increase yield (as the crop is transpiring at maximum rate) and, in some cases (Zone 4), may even decrease yields due to water logging of the root zone and creation of anaerobic conditions that limit transpiration.

The shape of the crop-water production function in Fig. 1 has important implications for the economics of irrigation decision-making and agricultural water management (English, 1990; English et al., 2002). Given the concave shape of the crop-water production function, for non-zero water prices, the profit-maximizing and yield-maximizing

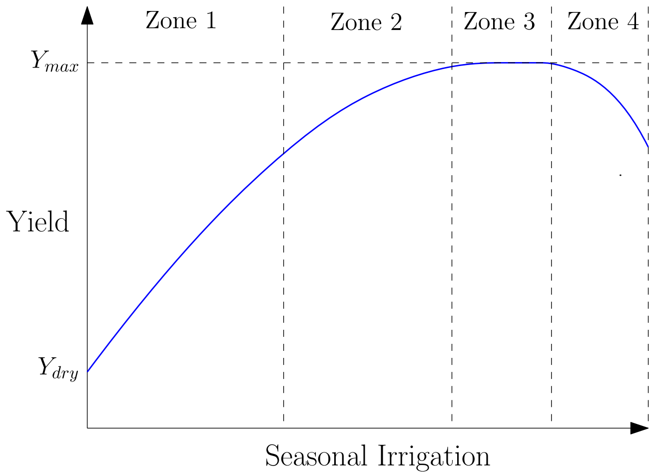

Fig. 1. Typical relationship between total seasonal irrigation and crop yield. Four main stages or zones of the production function are noted where marginal crop yield returns to irrigation are: (1) approximately linear, (2) less than linear/diminishing, (3) zero, and (4) decreasing.