Irrigation water use and technical efficiencies: Accounting for technological and environmental heterogeneity in U.S. agriculture using random parameters

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ARTICLE INFO

Keywords:
Irrigation water use efficiency
Technical efficiency
Random parameters
Stochastic Production Frontier
U.S. agriculture

ABSTRACT

Decision-making units (DMUs) face considerable variations in their production possibilities as well as the characteristics of the production environments under which they operate. Consequently, DMUs are likely to experience substantial differences in productivity and efficiency levels. In contrast, the received literature assumes that DMUs share similar technological possibilities and only differ with respect to their level of inefficiency. This study develops an analytical framework using random parameters, which accommodates heterogeneity in production possibilities and in characteristics of the production environment. We use this framework to analyze variations in the output elasticity of irrigation across DMUs, and how these differences influence: 1) irrigation water use efficiency (IWUE), using a non-radial input-oriented approach that isolates and measures the efficient use of the irrigation input; 2) technical efficiency, which radially measures the efficient utilization of all inputs; and 3) shadow prices of irrigation withdrawals. We find that IWUE and technical efficiency averaged 72.6% and 83.6%, respectively, and shadow prices averaged $77.5 per million gallons of irrigation water, albeit with significant regional variations.

1. Introduction

The efficient management of water resources, given rising water demand and projected reductions in precipitation as a result of climate change, has become a critical issue in U.S. agriculture [57]. Several regions in the United States continue to experience significant drought and water shortages, which directly threaten the viability of the agricultural sector [56]. Increased climatic variability characterized by rising temperatures and reduced precipitation means that irrigated agriculture is now conducted under conditions of water scarcity [18]. As a result, irrigated agriculture is in direct competition with other uses of water such as domestic, industrial, and hydroelectric [43,64].

Consequently, the threat of water scarcity has become an issue of concern among policy makers and stakeholders alike with conversations emerging on how best to manage this scarce resource (e.g., [7,11,33,36,47,61,65,68,69]).

Evidence within the United States that establishes the connection between climatic variability and the need for secondary sources of water, such as irrigation, has been building for several years. A major argument is that rising temperatures raise crop evapotranspiration rates, reduce soil moisture rapidly and hence increase crop water demand [28,55]. This changing temperature and precipitation patterns have lead directly to modifications in farming systems and resource use (e.g. [13,24,34,50]), and to a growing reliance on irrigation

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http://dx.doi.org/10.1016/j.wre.2018.02.004
Received 21 July 2017; Received in revised form 9 January 2018; Accepted 23 February 2018
Available online xxxx
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Please cite this article in press as: E. Njuki, B.E. Bravo-Ureta, Irrigation water use and technical efficiencies: Accounting for technological and environmental heterogeneity in U.S. agriculture using random parameters, Water Resources and Economics (2017), http://dx.doi.org/10.1016/j.wre.2018.02.004
(e.g., [13,24,38,48]). The agricultural sector is now the second largest consumer of water resources in the United States accounting for approximately 115,000 million gallons per day, with 62.4 million acres of land under irrigation [59]. It is projected that demand for agricultural water use will continue to rise resulting in a strain in water available for household and industrial purposes [47].

Irrigation expansion can be expected, in the short term, to reduce the negative effects stemming from climatic variability [35]. However, the longer-term potential for improved irrigation practices to solve the agricultural sector water problems will diminish due to water scarcity and competition with other sectors of the economy [47]. The focus will then have to shift to sustainable water resource management and land-use intensification in order to raise productivity [16].

Sustainable agriculture, characterized as an integrated system of plant and animal production practices that over the long term enhances environmental quality and the natural resource base upon which the agricultural economy depends, requires the protection and enhancement of water resources [57]. Sustainable use of water resources in turn entails the adoption of updated and modern water management and irrigation technologies [11,28,43,47] in order to improve the timing and application of irrigation [6]. It also requires that water be valued as an economic good in order to make this resource a tradable commodity [44], as creation of markets can improve the allocative efficiency of water [61]. Finally, sustainable water use requires policies that favor conservation by placing more emphasis on practices such as water harvesting, precision irrigation techniques, and deficit irrigation [17,18,39].

Thus, given the sensitivity of agriculture to secondary water sources in the face of water scarcity, the analysis of irrigation systems and how efficiently they are implemented in farm production has become of increasing importance. Within the hydrology literature, water use efficiency, is defined as the ratio of harvested biomass to water consumed in order to achieve a given yield (e.g., [17]). Water use efficiency has also been defined as the rate of carbon uptake per unit of water lost [53]. On the other hand, within economic studies, water use efficiency often refers to the effectiveness of applied irrigation (e.g. [35]), and the ratio of the minimum feasible water used to observed water usage associated with a given level of output, while holding other inputs and technology constant [30,67].

This study analyzes irrigation efficiency across the top agricultural counties in the U.S. The objectives are: 1) to develop an analytical framework that measures irrigation water use efficiency (IWUE) and technical efficiency (TE) while accommodating heterogeneity across U.S. counties in weather patterns, soil type, topography and drainage; 2) to analyze IWUE and TE in order to establish whether these components have improved or deteriorated over time; and 3) to estimate shadow prices for irrigation water in order to provide market signals as to the value of the resource, as well as the corresponding savings that would accrue from raising IWUE. Understanding the role that improvements in efficiency can have in enhancing irrigation water productivity is an important area of research and one that can provide useful information to stakeholders. The results from this study will add to the existing knowledge on water use efficiency and will provide insights for public policies that are compatible with conservation and enhanced productivity. The rest of the study is organized as follows: the next section presents the analytical framework as well as the methodology that is used to analyze IWUE and TE. Section 3 presents the data that is used for the analysis. Section 4 presents the results, and finally section 5 concludes and provides some suggestions for future research.

2. Irrigation water use efficiency

Irrigation water use efficiency (IWUE) is defined in the literature as the ratio of the minimum feasible requirement to observed water usage associated with a given level of output, while holding other inputs, technology and the environment constant [30]. IWUE, a non-radial measure of the irrigation input, makes it possible to evaluate the extent to which irrigation water applied can be reduced, while holding output constant.

The received literature on IWUE uses either non-parametric approaches, such as Data Envelopment Analysis (DEA) (e.g., [33,52]) or Stochastic Production Frontiers (SPF) (e.g., [14,30,67]). The aforementioned studies also combine traditional radial measures of output-oriented technical efficiency that incorporate all inputs (e.g. [1,37]), alongside non-radial input-oriented approaches that isolate the technical efficiency measurement of a single input, while holding other inputs constant (e.g., [31,45]). The problem with the DEA approach is the strong assumption that variables involved in the production process are observed and measured without error. This assumption seldom holds implying that DEA estimators are likely to be inconsistent [41].

In contrast, stochastic production frontier studies that investigate IWUE (e.g. [30]), usually adopt the following general formulation:

\[
y_i = f(x_i, w_i; \beta)\exp(v_i - u_i)
\]  

(1)

where the variables \(y_i, x_i, and w_i\) represent output, a vector of conventional inputs and water-use for firm-\(i\), respectively. Furthermore, \(v_i\) and \(u_i\) denote a two-sided statistical error term and a one-sided output-oriented technical efficiency term, respectively. Early studies on IWUE made a key assumption that the technical efficiency term, \(u_i\), was itself a function of exogenous factors such that, \(u_i = g(z_i; \theta) + \eta_i\), where \(\eta_i \sim iid \mathcal{N}(0, \sigma^2)\). This assumption raised considerable econometric problems. First, if the variables associated with the technical inefficiency term, \(u_i\), were correlated with elements in the first step (i.e., \(x_i, w_i\)) then the associated estimates generated in the first step were likely to be biased due to omission of relevant variables [32,22]. Moreover, the assumption of identically distributed errors are contradicted by the functional relationship between \(u_i\) and \(z_i\) [32,60]; hence, the need to include the vector \(z\) in the deterministic component of Equation (1) [41].

Furthermore, the aforementioned SPF studies rely on conventional translog specifications. The translog is a flexible functional form that incorporates squares and cross products of log-inputs which affords flexibility but violates key properties of a regular technology, notably: inactivity, strong disposability of outputs and inputs, and output and input closedness (see Refs. [40,42]). A translog production function cannot satisfy these properties globally and its use inevitably leads to inconsistencies with production economic theory. Thus, the Cobb-Douglas specification becomes a desirable alternative because it satisfies key regularity conditions globally. However, the
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