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Studying uniform and variable rate center pivot irrigation strategies with the aid of site-specific water production functions

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ABSTRACT

Irrigation management has evolved into a top priority issue since available fresh water resources are limited. Water production functions (WPFs), mathematical relationships between applied water and crop yield, are useful tools for irrigation management and economic analysis of yield reduction due to deficit irrigation. This study aimed at (i) designing and evaluating site-specific WPFs (using *k* nearest neighbors (*k*-NN), multiple linear regression, and neural networks), (ii) simulating yield maps for uniform, sector control VRI, and zone control VRI center pivot systems using the site-specific WPFs, (iii) using the best WPF to investigate different cotton irrigation and zoning strategies using integer linear programming, and (iv) comparing soil-based and WPF-based zones for sector control VRI systems. A two-year cotton irrigation experiment (2013–2014) was implemented to study irrigation-cotton lint yield relationship across different soil types. The site-specific *k*-NN WPFs showed the highest performance with root mean square error equal to 0.131 Mg ha^{-1} and 0.194 Mg ha^{-1} in 2013 and 2014, respectively. The result indicated that variable rate irrigation with limited sector control capability could enhance cotton lint yield under supplemental irrigation when field-level spatial soil heterogeneity is significant. The temporal changes in climate and rainfall patterns, however, had a great impact on cotton response to irrigation in west Tennessee, a moderately humid region with short season environment. We believe site-specific WPFs are useful empirical tools for on-farm irrigation research.

1. Introduction

1.1. Variable rate irrigation

The demand for food and fiber is increasing as the world's population grows. Irrigation management has evolved into a top priority issue since available fresh water resources are limited. Row crop supplemental irrigation is rapidly expanding in the moderately humid region of west Tennessee because of a trend of stabilizing yields by irrigation and high commodity prices. However, the soils of west Tennessee exhibit high spatial and temporal variability of soil characteristics that relate to moisture availability for crop production at the field-level. It has been shown in a variety of studies that soil characteristics such as soil water holding capacity and depth of soil significantly affects crop yield, hence irrigation strategies should be adjusted in regard to the soil type (Duncan, 2012). Consequently, variable rate irrigation (VRI) is recommended as the appropriate irrigation scenario to address field-level spatiotemporal heterogeneity and thus how, when, and where to irrigate (Duncan, 2012). VRI is expected to improve water-use efficiency, increase productivity, save fuel and decrease nutrient leaching (Pan et al., 2013). Several authors have stressed the potential water conservation that has been observed using VRI systems (Evans et al., 1996; Duke et al., 1997; Sadler et al., 2005; Hedley and Yule, 2009). For instance, Hedley and Yule (2009) compared VRI and conventional uniform irrigation methods and found that 9–19% of irrigation water was saved, which in turn reduced nitrogen leaching. The state-of-the-art zone control VRI systems, allow farmers to adjust irrigation applications across fields, by pulsing individual sprinklers or banks of sprinklers on and off. The sector control VRI systems cut pie shape zones simply by adjusting the revolution speed of the center pivot between given pairs of angles. Pan et al. (2013) analyzed soil water status

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through spatial and temporal data and suggested this method as a means to assess the potential of VRI and to schedule irrigation. Recently, Haghverdi et al. (2015b) used integer linear programing (ILP) to find the optimum number and spatial arrangement of irrigation management zones for center pivot systems with limited sector control capability. They used soil properties to delineate management zones, yet suggested to investigate crop response to water amount across different soil types as a means to provide crop-specific irrigation management zones.

In practice, the level of irrigation management being followed by the majority of producers is relatively low, while experience with successful zone control VRI management is rare among producers and service providers. Initially, the larger price tag, accompanied with the fear of complexity that is associated with using zone control VRI, are the two main stumbling blocks experienced by farmers. The sector control VRI systems require less capital investment and the operation/maintenance is also easier than that of zone control VRI. Most of the center pivots that farmers use today are equipped to allow a limited number of pie shape sectors to be made, without any additional control panel upgrades. The knowledge and full use of this capability is the perfect and most appropriate step in bridging the gap between current practice and cutting-edge zone control technology (Haghverdi et al., 2015b). Currently, it is not easy to quantify the potential production benefits of zone control and sector control VRI systems over conventional uniform irrigation systems in a given field, further contributing to producers' present hesitancy and reluctance, with regards to investing in VRI systems.

However, before the benefits of VRI can be achieved, it is necessary to identify the spatial heterogeneity of soil within a given field and delineate homogenous management zones wherein identical inputs of water can be applied. In practice, the number of zones depends on the target input, available equipment and the crop(s) planted. However, a corollary expectation is that varying the inputs within the management zones will facilitate optimal yields. This desire leads to the development of water production functions (WPF) where crop yield is mathematically related to the amount of irrigation water.

1.2. Water production functions

The term production function (PF) may be assigned to any mathematical relationship between crop yield and input components such as water, fertilizers and energy (De Juan et al., 1996). In practice, almost all the derived PFs require crop water use as an independent variable. PFs predict total dry matter (or marketable product of each crop) as a dependent variable, while the independent variables are transpiration, evapotranspiration (ET) or the amount of applied water during irrigation (IW). The PFs are categorized into crop water production functions (CWPFs) and water production functions (WPF) that use ET and IW as independent variables, respectively. IW may consist of different components such as the crop water requirement, pre-planting irrigation, leaching requirement, and rainfall (Igbadun et al., 2007).

Recently, some studies have aimed to revisit and rebuild the concept of PF including the development of a WPF for water logging stress on corn (Kuang et al., 2012) and a rice water – fertilizer PF (Ai-hua et al., 2012). Tong and Guo (2013) included an estimation of uncertainty in CWPF along with the optimal allocation of water resources in an irrigation area. Saseendran et al. (2014) established location-specific CWPFs using long-term averaged data for corn in Colorado. They used the RZWQM2 model (Ahuja et al., 2000) and historical weather data to develop average corn CWPFs across years and locations. Sadler et al. (2002) applied WPFs at field level and observed significant differences in corn response to irrigation within and across soil map units. Holan et al. (2008) formulated spatially dependent WPFs that later were used by Stone and Sadler (2015) who reported high accuracies for the spatial modeling of corn yield. Wang et al. (2007) derived cotton and wheat water-salinity PFs. Dinar et al. (1986) derived cotton CWPF under saline conditions in California to improve irrigation management.

Classical PFs are useful tools for irrigation management and economic analysis of yield reduction due to deficit irrigation, but there are some shortcomings associated with them. The behavior of complex ecological systems is non-linear, but most PFs are based on easily built linear regression-based equations and are thus not particularly powerful representations of these systems (Dai et al., 2011; Haghverdi et al., 2014b). However, recent studies have investigated the use of more robust and non-linear techniques to predict yield and model complex systems, particularly powerful empirical algorithms derived from machine learning data mining tools (e.g. Fortin et al., 2010; Haghverdi et al., 2014b).

Data mining could be defined as the process of capturing important and useful information from large data sets (Mucherino et al., 2009). An extensive review on data mining methods and their application in agricultural related studies was gathered by Huang et al. (2010). Machine learning algorithms were employed to some extent for predicting yield of different crops. Fortin et al. (2010) used artificial neural networks (ANNs) for predicting potato tuber growth as well as its in-field variations in Canada. They reported that if enough data is input to an ANN model, one can precisely model site-specific tuber growth. Dai et al. (2011) adopted ANN and multi-linear regression models to simulate the response of sunflower yield to soil moisture and salinity. This resulted in ANN models having higher precision than regression for modeling relationships between crop yield and soil moisture and salinity at different crop growth periods (Dai et al., 2011). Haghverdi et al. (2014b) derived some novel WPFs and compared data mining-based methods with traditional regression procedures. They utilized ANN and decision tree modeling algorithms to derive water salinity PFs for spring wheat and found the results promising.

1.3. Site-specific water production functions & variable rate irrigation

Traditional irrigation/agronomic work tries to address the irrigation related questions by means of small plot trials over multiple sites and across several years. This is probably the best way to collect the necessary data in controlled environments following the statistical principles behind design of experiments. However, there are some shortcomings. Given the time consuming and labor intensive nature of field experiments, this approach becomes unrealistic for the near future (Drummond et al., 2003). In addition, this method relies on scaling and transforming small plot research findings to operational management of farmers' fields. In reality, each field has its own spatial and temporal heterogeneity of main attributes and this complexity requires site-specific irrigation management solutions. An alternative option is to simulate the behavior of the fields using mechanistic crop growth models. However, the drawback of these models is that they are time-consuming and expensive to develop because of the numerous inputs that need to be collected to run them (Drummond et al., 2003).

Precision agriculture (PA) enables farmers to collect numerous site-specific data. Empirical analysis of these data may be the key to aid farmers in their occupational practice. PA is successful if accurate and detailed information about crop response to specific conditions is provided (Drummond et al., 2003). Quantifying crop response to water is the first step toward optimizing irrigation, and is therefore a critical issue for farmers, governmental agencies and consulting companies. Given the time consuming and expensive nature of irrigation studies, developing computer tools and models are very helpful in providing a comprehensive understanding of irrigation-yield relationship for different crops across different soil