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A web application for cotton irrigation management on the U.S. Southern High Plains. Part I: Crop yield modeling and profit analysis

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ABSTRACT

Irrigated cotton (*Gossypium Hirsutum* L.) production is a central part of west Texas agriculture that depends on the essentially non-renewable water resource of the Ogallala aquifer. Web-based decision support tools that estimate the profit effects of irrigation for cotton under varying lint price, production cost, and well capacity conditions could help to optimize the agricultural value of the Ogallala's water. The crop modeling and profit analysis component of such a support tool is demonstrated here. This web application is based on a database of modeled yields generated from the meteorological records of four weather stations under un-irrigated (dryland) conditions and under center pivot irrigation with 12 total irrigation (TI) levels spanning deficit to full irrigation conditions. The application converts the database's dryland and irrigated yield outcomes into corresponding values of profit per hectare based on user-defined yield values and production costs. Given the resulting values of dryland and irrigated profit per unit area and the additional constraints of a user's well capacity and center pivot area, the application also calculates the profit effects of dividing center pivot area into dryland and irrigated production under the 12 irrigation levels.

1. Introduction

1.1. Cotton production in the U.S. Southern High Plains

During 2001–2010 the state of Texas accounted for approximately one-third of the upland cotton produced over the United States, with the majority of production concentrated in the Southern High Plains (SHP) region. Although, on average, 42% of planted SHP cotton acreage was irrigated with water pumped from the Ogallala aquifer during that time, those acres accounted for 66% of the region's cumulative 10-year production (NASS, 2011). However, over recent decades that irrigation has also led to declines in the aquifer's saturated thickness that have not been compensated for by natural recharge (Sophocleous, 2010; McGuire, 2011). This drawdown of an essentially fossil water resource has led to questions about the long-term viability of this semi-arid region's agricultural economy (Brooks and Emel, 2000; Guerrero et al., 2008; Scanlon et al., 2012) and a search for strategies to reduce groundwater withdrawals (Colaizzi et al., 2008). A recent High Plains Underground Water District proposal includes gradually decreasing caps on annual pumping that will restrict water use to 38.1 cm (15 in.) per hectare per year after January 1 2016, which has met with some resistance from west Texas farmers and landowners (Galbraith, 2012; Magelssen, 2012).

Southern High Plains cotton producers, indeed, any producers growing high water demand crops with a diminishing water resource, face a challenging future. Under such circumstances there is a clear need for decision support tools that show the impact of water on yield and profitability. Such tools might also help define practices that maximize the value of irrigation. However, the problem addressed by such an application is probabilistic, dynamic, and complex. Cotton yields in the SHP region are strongly influenced by growing season climate conditions, which, given the area's limited potential for summer seasonal climate forecasts, is best described by climatological probability. The ongoing variation in price and cost conditions makes converting yield outcomes into profit outcomes a problem that requires new solutions on a year-to-year basis. In semi-arid irrigated production yield and profit may also be influenced by the amount and timing of irrigation, and the tradeoff between pumping and other production costs and the corresponding returns from lint and seed yield sales. With increasing awareness of the Internet in the agricultural community, and the graphic and computing ability of client and server-based languages such as JavaScript and PHP, one solution to this problem is to provide such a support tool through web browsers.

A common management scenario for SHP cotton production is center pivot irrigation over circular areas within 65 ha "quarter

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section" or 259 ha "full section" plots which are supplied by central wells with a specified pumping capacity. The purpose of this and a companion paper is to describe a web-based application intended to help SHP cotton producers estimate profitability in a similar production setting. This paper focuses on the application's lint yield database, the budget equations that convert yields to profits, and the problem of calculating profit over a center pivot area given the constraint of well capacity. A companion paper (Mauget et al., submitted for publication, hereafter, Part II) describes the software components and external features of the web-application itself.

1.2. CSM-CROPGRO-Cotton model and application overview

Given the relatively limited number of yield outcomes generated by field studies such as Wanjura et al. (2002) or Borodovsky et al. (2000), the application's design is based on a yield database containing a larger set of simulated yields generated by Cropping System Model (CSM)-CROPGRO-Cotton, which is a component of the DSSAT suite of crop modeling software (Jones et al., 2003; Hoogenboom et al., 2010). The CSM-CROPGRO-Cotton model (hereafter, CROPGRO-Cotton) simulates crop development and seed yield production based on daily weather inputs, cultivar and soil characteristics, and management practices. Additional details of this model and its origins and calibration can be found in Pathak et al. (2007, 2012) and Ortiz et al. (2009). While providing a representative yield response to varying water levels this modeling approach can also produce larger samples of simulated yields, and thus better estimates of the probability of yield and profit outcomes, than the limited numbers of yields available from the corresponding field studies. The steps involved in generating this database includes:

- Using the CROPGRO-Cotton model driven by historical weather data from four SHP weather stations to generate modeled yield outcomes per hectare under un-irrigated (dryland) conditions and center pivot irrigated conditions under twelve increasing irrigation levels.
- Calibrating the modeled yield responses to varying water levels to agree more closely with the water vs. yield response function of comparable irrigated field study results and mean regional dryland yields.
- Combining the yield outcomes from the four sets of simulations to produce a database of densely populated seed and lint yield distributions for dryland and center pivot irrigated production under each irrigation level.

Using the values in the yield database, the application:

- Converts the databases' modeled yield values for dryland and irrigated production into corresponding profit values per hectare under price, cost, and well depth conditions defined by the user.
- Estimates and displays distributions of total center pivot profit under 12 partitioning options that divide pivot area into dryland and irrigated production, given the dryland and irrigated profit values per hectare and the center pivot's area and well capacity.

Section 2 describes the modeling of dryland and irrigated cotton using the CROPGRO-Cotton model, the field study data used to verify the modeled yield response to irrigation, and how modeled lint yields were adjusted based on comparisons with the field study outcomes. Section 3 describes how profit per hectare is estimated from the adjusted yields under dryland and center pivot production, and explores the profit effects of lint price, pumping costs, and pump motor efficiency. Given dryland and irrigated profits per hectare at the 12 irrigation levels and a specified well capacity, Section 4 illustrates an approach to estimating the profit effects of dividing center pivot area into dryland and irrigated production at each level. Section 5 summarize results and provides a preliminary introduction to the companion paper.

2. Crop modeling methods and procedures

2.1. Weather data, crop ET, and crop modeling

The CROPGRO-Cotton model was used to simulate dryland and irrigated cotton production based on 1975–2004 weather data from the Crosbyton, Muleshoe, Plainview and Seminole weather stations (Fig. 1a). Each of the stations provided daily minimum and maximum temperature and precipitation data for each of those years' 30 summer growing seasons. More details concerning these primary meteorological input variables and the generation of the daily wind, dew point, and radiation values required by the model and used to calculate potential crop evapotranspiration for cotton (ET) can be found in Mauget and Leiker (2010). By aggregating together growing season climate variables, $ET_{c.}$, and modeled yields from these 4 stations over 30 growing seasons, the resulting 120 values can be used to form relatively dense distributions. Those distributions can in turn be used to more accurately estimate probabilities. For example, Fig. 1b bar & whisker distribution of the station's 120 May–September rainfall totals has a minimum of 8.23 cm, a 25th percentile of 21.13 cm, a 50th percentile of 29.21 cm, a 75th percentile of 37.18 cm, and a maximum of 57.02 cm. As estimated via the single crop coefficient method of Allen et al. (1998), the network's 120 values for May–September $ET_{c.}$ are also graphed and their percentiles listed in Fig. 1b. The distribution of the ratio of those values expressed as a percent is graphed in Fig. 1c. During 1975–2004 May–September rainfall as a percentage of May–September $ET_{c.}$ at the four sites never exceeded 72%, and in 75% of those 120 station-years rainfall was less than 44% of ET_c. Given the association of maximum yield with water levels that can maintain ET_c (Doorenbos and Kassam, 1979), Fig. 1c shows that achieving maximum potential cotton yields over the SHP region requires irrigation.

In the irrigated CROPGRO-Cotton simulations water was applied at time intervals consistent with a typical center pivot rotation period. After planting on May 15 irrigation was applied every 5 days during May 16–September 17, resulting in 25 irrigation events. The amounts of irrigation in these events varied from 1.12 cm (0.44 in.) to 2.24 cm (0.88 in.) in increments of 0.10 cm (0.04 in.). This resulted in 12 levels of total irrigation (TI) varying between 27.9 and 55.9 cm (11.0–22.0 in.) in increments of 2.54 cm (1.0 in.).

Fig. 1d shows the distributions of total water (TW), i.e., TI plus each site-year's May–September rainfall total, as a percentage of the same site-year's May–September $ET_{c.}$ value. The distribution for 45.7 cm of irrigation shows that when combined with May–September rainfall that level provided deficit irrigation, i.e., <100% $ET_{c.}$, in ~75% of the 120 site-years. When rounded to the nearest percent the median of Fig. 1d's 55.9 cm distribution equals 100% of ET_c. That distribution's 25th and 75th percentiles are 88% and 112%, indicating a 50% chance that TI level, when combined with May–September rainfall, would have provided $ET_{c.}$ within that range during 1975–2004. Thus of the 12 irrigation levels, 55.9 cm of irrigation, in a climatological sense, has the highest likelihood of providing a TW level close to 100% crop evapotranspiration. Given the association of 100% $ET_{c.}$ with maximum yields, and the 55.9 cm TI level's near equivalence to the 58 cm irrigation level estimated to maximize lint yields in Wanjura et al.'s (2002) 12 year