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Evaluating strategies for improved water use in spring wheat with CERES

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ABSTRACT

More efficient use of water in agricultural systems is widely needed. However, most irrigated systems are characterized by heterogeneous climate and soil conditions that interact strongly with irrigation management, making optimal irrigation decisions difficult to achieve. Here we investigated the impact of reduced irrigations on spring wheat yields in the Yaqui Valley of Mexico, a region experiencing increased water scarcity. Two years of field experiments containing three irrigation treatments each were used to evaluate the CERES-wheat crop model, with good agreement between observed and modeled yields. The model was then used in a sensitivity analysis whereby seven irrigation strategies were applied across a range of possible soil and climatic conditions. Results indicated that yield losses from reduced irrigations depend greatly on year, corresponding to large variations in rainfall between growing seasons. Estimates of the best timing strategy for a given number of irrigations were more robust with respect to climate variability. Soils also exhibited a strong interaction with irrigation, with the difference between initial soil moisture and wilting point deemed particularly important in this system. The optimal economic strategy was determined for each hypothetical soil based on the observed historical distribution of growing season climatic conditions. The results of this study demonstrate the need to consider soil and climate variability when interpreting experimental results, and the ability of the CERES model to serve this need by quantifying the relative importance of different heterogeneous factors.

1. Introduction

Wheat is the most widely grown crop in the world, with irrigated wheat systems contributing over 40% of wheat production in the developing world (Pingali and Rajaram, 1999). Efficient use of water in these systems is increasingly important as demand for both food and freshwater resources is rising (Wallace, 2000). One component of improved water use in these regions is a better quantitative understanding of the relationship between irrigation practices and grain yield. With this knowledge, the value of each unit of water applied to a field can be estimated and compared with alternative uses within and beyond the agricultural sector.

Experimental trials provide a well-established means to evaluate wheat yields under different irrigation scenarios. However, only a limited number of different management

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alternatives can typically be tested given time and resource constraints. In addition, the dependence of water management on soil and climatic conditions means that results of experiments may be specific to the trial location(s) and/or year(s) (White et al., 2002). Tools that can extrapolate results beyond experimental conditions are therefore needed when attempting to quantify the effect of irrigation management at a different site, in a different year, or for larger spatial or temporal scales that embody a collection of different soil and climatic conditions. Crop growth simulation models have proven useful in this context (Hartkamp et al., 1999). White et al. (2002) argue that validated crop models should become standard tools for interpreting results of experiments.

CERES-Wheat is one common wheat simulation model, and is distributed with the Decision Support System for Agrotechnology Transfer software package (Tsuji et al., 1994). Previous studies have documented the successful simulation of soil moisture (e.g., Eitzinger et al., 2004) or wheat yield (Panda et al., 2003; Tubiello et al., 1999) under water stress with CERES. However, few if any have used CERES to extrapolate experimental results across different conditions. In this study, we test CERES on data from an irrigation experiment conducted in the Yaqui Valley, Mexico, and then combine the model with data on climate and soil variability to evaluate different strategies for improved water use in wheat production.

The Yaqui Valley (YV) exemplifies many of the pressures that exist and are likely to increase in developing world wheat systems. With a drought occurring since 1996 and increased demand from urban consumers, the reservoirs that feed the irrigation system in YV have been at record lows (Addams, 2004). In response, farmers first reduced the number of irrigations and maintained the area planted to wheat. As water levels continued to decrease, they limited area planted to wheat (2003–2004 harvested area was only 20% of the 1980–2002 average of 140,000 ha). The number of irrigations has been widely reduced from the traditional five irrigations (one pre-plant and four auxiliary) to four or even three in many fields. Currently, there is great interest from farmers and water managers to know the impact of these changes on yields, and the potential impact of further reductions in irrigation. For example, a common question is whether farmers are better off planting a certain area under four irrigations or twice as much area with only two. Questions such as these concerning the optimal use of limited water are increasingly relevant in many regions, where deficit irrigation has become more common (Mugabe and Nyakatawa, 2000; Panda et al., 2003; Schneider and Howell, 2001).

2. Methods

2.1. *Irrigation experiments*

Trials were performed during the 2000–2001 and 2001–2002 wheat growing seasons at the International Maize and Wheat Improvement Center (CIMMYT) station in YV (27.4°N, 109.9°W). The soils in the experimental area are coarse sandy clay mixed with montmorillonitic clay, and are classified as Typic Calcicorthid. Three irrigation regimes were used: a total of five, four and three irrigations. Five irrigations represent what farmers used roughly 10 years ago for wheat, four irrigations is currently the most common practice, and three irrigations may be the future practice if problems of low water supply continue to worsen. During the summer months (June–October) prior to the experiments, a uniform maize crop was planted without fertilization and with full irrigation over the whole experimental area to homogenize the area for residual nitrogen and moisture.

The irrigation treatments were arranged in a randomized complete block design and were separated by soil borders which were roughly 80 cm tall and 3.2 m wide to insure that there was no movement of water from one irrigation strategy to the other. The main plots were eight 80 cm beds wide (6.4 m) and 142 m long. These were divided into two sub-plots of four beds each with different planting patterns (two rows versus three rows on top of the beds), and 10 sub-plots were randomized consisting of five wheat cultivars grown at low (75 kg N ha^{-1}) and high (225 kg N ha^{-1}) rate of N within each sub-plot. Three replicates of each treatment were performed each year.

All units were planted on December 7 in 2000 and December 11 in 2001, which is within the recommend planting date for farmers in this region. For the purposes of this study, the experimental results were averaged over the two planting methods and only the high N rate sub-plots (more representative of farmer practices) were used. The unfertilized maize crop planted during the summer ensured that a rate of 75 kg N ha^{-1} in wheat would be N deficient, while the 225 kg N ha^{-1} rate is within the range of N rates commonly used by farmers in the region (Lobell et al., 2005b).

The timing of the irrigations changed according to the number of irrigations using the following rules: for three irrigations, water was applied at pre-plant, booting (Z41) and watery ripe (Z71) stages; for four irrigations, at pre-plant, 1st node (Z31), heading (Z51), and early milk (Z73); for five irrigations at pre-plant, tillering (Z23), 1st node (Z31), heading (Z51) and early milk (Z73). Irrigations were stopped when the central upper part of the beds was wet. Details of the irrigation experiments are given in Tables 1 and 2.

Soil moisture was monitored for each irrigation treatment by collecting soil gravimetric samples at 0–15, 15–30, 30–60, and 60–90 cm depth before and 3–4 days after each irrigation. The amount of water infiltrated was determined as the difference in total moisture from 0 to 90 cm before and after irrigation. This approach was necessary because the irrigation system in the experimental station does not allow for accurate measurements of applied water, yet it potentially ignores losses to evapotranspiration during the period between moisture measurements. However, potential evapotranspiration, measured at a nearby weather station, is typically 1–4 mm day^{-1} during November–February and 2–5 mm day^{-1} during March–April. The total water losses from actual evapotranspiration during the 3–4-day interval after irrigation were therefore likely small relative to the applied amounts.

Anthesis date was recorded when 50% of the spikes in the plot had extruded anthers. Physiological maturity was considered reached when 50% of the peduncles in the plot had turned yellow. Grain yield was measured in an area of 4.8 m^2 with a small plot combine.