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The value of seasonal forecasts for irrigated, supplementary irrigated, and rainfed wheat cropping systems in northwest Mexico

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ABSTRACT

Half of global wheat production occurs in irrigated cropping regions that face increasing water shortages. In these regions, seasonal forecasts could provide information about in-season climate conditions that could improve resource management, helping to save water and other inputs. However, seasonal forecasts have not been tested in irrigated systems. In this study, we show that seasonal forecasts have the potential to guide crop management decisions in fully irrigated systems (FIS), reduced irrigation systems (supplementary irrigation; SIS), and systems without irrigation (rainfed; RFS) in an arid environment. We found that farmers could gain an additional 2 USD ha^{-1} $season^{-1}$ in net returns and save up to 26 USD ha^{-1} $season^{-1}$ in N fertilizer costs with a hypothetical always-correct-season-type-forecast (ACF) in a fully irrigated system compared to simulated optimized N fertilizer applications. In supplementary irrigated systems, an ACF had value when deciding on sowing a crop (plus supplementary irrigation) of up to 65 USD ha^{-1} $season^{-1}$. In rainfed systems, this value was up to 123 USD ha^{-1} when deciding whether or not to sow a crop. In supplementary irrigated and rainfed systems, such value depended on initial soil water conditions. Seasonal forecasts have the potential to assist farmers in irrigated, supplementary irrigated, and rainfed cropping systems to maximize crop profitability. However, forecasts currently available based on Global Circulation Models (GCM) and the El Niño Southern Oscillation (ENSO) need higher forecast skill before such benefits can be fully realized.

1. Introduction

Wheat provides approximately 20% of calories consumed by humans (Food and Agriculture Organization 2012), and wheat crops cover approximately 22% of the world's cultivated land (Licker et al. 2010) across developed and developing countries. Irrigated wheat production accounts for almost half of global wheat production, and approximately 90% of irrigated wheat production occurs in developing countries (Shiferaw et al. 2013). Groundwater depletion (Balwinder et al. 2011; Chen et al. 2010; Liu et al. 2013; Lv et al. 2013; Zhao et al. 2013), limited surface water resources, and increasing soil salinity (Seifert et al. 2011) create enormous challenges for regions that depend on these irrigated wheat systems. Demand for wheat will likely increase, given that global population is projected to exceed 9 billion by 2050 (BeVier 2012). Increases in water price (Shiferaw et al. 2013) and reduction in water quality (Lv et al. 2013) will further exacerbate the challenges farmers face in irrigated regions. Improvements in crop management and breeding are needed to secure future wheat production increases.

The Yaqui Valley is one of the most important wheat producing areas in Mexico, accounting for approximately 40% of national wheat production (Schoups et al. 2006). It comprises approximately 225,000 ha of irrigated cropland cultivated mainly during the winter season (Ortiz-Monasterio and Raun 2007). More than 50% of this cropland is used for wheat (Lobell et al. 2004). The Yaqui Valley climate is arid with an average annual precipitation of 300 mm; most of which falls between June and September (Schoups et al. 2006), outside the wheat growing season. Maximum air temperature can exceed 34 °C at the end of the wheat growing season (April–May). Further, Yaqui Valley agro-climatic conditions are representative of about 40% of wheat production areas in developing countries (Verhulst et al. 2011). These regions face many of the same water challenges, temperature conditions (Asseng et al. 2011; Lobell et al. 2012), and environmental issues (Seifert et al. 2011).

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As in other parts of the world, farmers in the Yaqui Valley make resource allocation decisions before the beginning of the season and currently must do so without the aid of information on climate conditions of the coming season (Asseng et al. 2012; Lobell et al. 2004; Lobell et al. 2005; Moeller et al. 2008). Without such climate information, farmers cannot tailor their management practices, such as crop rotation (Cossani et al. 2007) or fertilizer rates and timings (Asseng et al. 2012), to the climate of the coming season. Such mismatches in agricultural practices and seasonal climate result in increased yield gaps and decreased resource use efficiency (Cossani et al. 2010; Sadras et al. 2003). Hence, seasonal forecasts can provide an important tool for improving the productivity and efficiency of cropping systems (Meinke and Stone 2005). However, such a tool is only valuable if the available information leads farmers to change their decision-making process (Hammer 2000). Seasonal forecasts are widely used in rainfed conditions for different applications, such as optimizing nitrogen (N) management under seasonal variability (Asseng et al. 2012; Moeller et al. 2008; Yu et al. 2008), predicting stored soil water at planting (Hammer et al. 1996) or making decisions about cropping systems (Carberry et al. 2000). Recent studies on short-term (Mishra et al. 2013) and long-term (Calanca et al. 2011) weather forecasts have investigated optimizing crop irrigation management and predicting soil water availability. In the Yaqui Valley, weather forecasts are used to predict daily crop evapotranspiration (ET) for water management (Abdelghani et al. 2008) However, due to short lead times, these studies lack information about the inter-annual climate variability (Hunt and Hirst 2000), limiting the overall optimization of the system.

Using seasonal forecasts to make decisions about N management, sowing, and supplementary irrigation has not been widely explored in irrigated and supplementary irrigated cropping systems. Hence, the objectives of this study were to evaluate potential and actual seasonal forecasts for assisting crop management decisions in fully irrigated (FIS), supplementary irrigated (SIS), and rainfed cropping systems (RFS).

2. Methods and materials

This methodology tests how climate information could potentially improve nitrogen management decisions in an arid environment considering three different cropping systems. These systems differ in the amount of irrigated water available during the wheat growing season. The nitrogen recommendations are based on a crop model that determines the optimal seasonal N amount according to the irrigated water available for the wheat growing season and the climate condition forecasted for the wheat growing season at the beginning of the season. A seasonal forecast thus allows farmers with different irrigated water restrictions to manage nitrogen fertilizer applications season-type specific based on the seasonal rainfall forecast.

Fig. 1 is a flow diagram of the different modules that comprise the methodology. Historical weather data and agricultural practices of the Yaqui Valley were entered into a crop model. The model was calibrated and simulations were run for 27 years of data. The crop model simulated wheat growth and returned an expected yield for each N fertilizer management option in each year. This procedure was repeated for each of the three cropping systems. Season-specific tercile categories were built using seasonal forecast data and historical weather information.

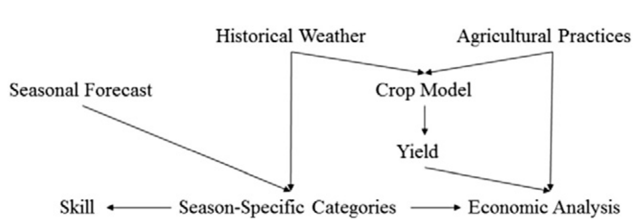

Fig. 1. Flow diagram of the different modules that comprise the methodology.

The skill of the forecast was then computed to evaluate the ability of the forecast to predict the tercile category correctly. Finally, based on the yields and recommended agricultural practices determined for each season-specific category, an economic analysis was performed comparing the net returns for a farmer following the forecast to those of a farmer not following the forecast.

2.1. APSIM Nwheat model

The widely adopted and tested wheat model, the Agricultural Production System Simulator (APSIM; Keating et al. 2003) Nwheat model (Asseng et al. 1998; Asseng et al. 2001a; Asseng and Milroy 2006; Asseng et al. 2001b) was used in this study. The APSIM Nwheat model includes modules that simulate growth, development, and yield of wheat crops, as well as soil water, N, and carbon dynamics. The crop module accounts for crop development and growth, water and nitrogen uptake, and considers various stress conditions of a wheat crop (Keating et al. 2003). The model calculates an attainable yield for a specific environment, limited by temperature, solar radiation, rainfall, water, and N supply (Asseng 2004; Lobell et al. 2009). The Nwheat model also includes a temperature stress algorithm to capture the effect of temperature increases on wheat growth processes such as leaf growth and photosynthesis (Asseng et al. 2011).

2.2. Model calibration

APSIM-Nwheat was calibrated using experimental data collected during the 2011–2012 wheat-growing season in the Yaqui Valley at the CIMMYT experimental station in Obregon, Sonora (27°25′N, 109° 54′W) with an elevation of 38 m asl and a Hyposodic Vertisol soil type (Calcaric, Chromic) (Verhulst et al. 2009). The experiment consisted of a set of wheat genotypes sown in 3.5 m long and 1.6 m wide plots each containing two raised beds with two rows per bed. These were grown under four different treatments designed to represent a range of temperature and soil moisture conditions. The treatments included a fully irrigated treatment (I) with sowing date November 24, a drought treatment (D) with two irrigation applications and a sowing date of December 11, a heat stress treatment (H), fully irrigated with sowing date February 27, and an extreme heat stress treatment (EH) during grain filling, and fully irrigated with sowing date March 30. Experimental plots were managed intensively to ensure crop production was not limited by nutrient availability or biotic stress (including weeds, diseases, and insect pests). One representative genotype was selected (CIMMYT GID 5180708) for calibration and subsequent simulations.

2.3. Simulations

Simulations used historic climate data (1982–2009) of a Yaqui Valley weather station (27°11′N, 109°32′W) obtained from the Centro de Investigaciones Agrícolas del Noroeste (CIANO). Gaps in solar radiation data were filled from the AgMERRA historical climate forcing dataset (Ruane et al. 2013). A common planting date of mid-November was chosen for all simulations (Lobell and Ortiz-Monasterio 2008). A seeding rate of 120 kg ha^{-1} was considered consistent with current practices (Lopes et al. 2013; Reynolds et al. 1994).

Specific management practices were tested in each system. For the fully irrigated system (FIS), automatic irrigation was applied every time the available soil water was below a critical fraction of available soil water (0.5) to avoid water stress. The typical concentration of nitrogen as NO_3 and NH_4 was 0.0457 mg N l^{-1}, equivalent to 0.0457 kg ha^{-1} for 100 mm of irrigation applied. Seven N treatments were used in the irrigated system, from 60 to 240 kg N ha^{-1} in increments of 30 kg N ha^{-1} split into two applications, one at sowing and another 40 days after sowing (DAS). For the supplementary irrigation system (SIS), a limited irrigation of 100 mm was applied per season, split into two applications, one at sowing and another at 80 DAS. 120 kg N ha^{-1}