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Climate change impact on Mexico wheat production

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ABSTRACT

Wheat is one of the most important cereal crops in Mexico, but the impact of future climate change on production is not known. To quantify the impact of future climate change together with its uncertainty, two wheat crop models were executed in parallel, using two scaling methods, five Global Climate Models (GCMs) and two main Representative Concentration Pathways (RCPs) for the 2050s. Simulated outputs varied among crop models, scaling methods, GCMs, and RCPs; however, they all projected a general decline in wheat yields by the 2050s. Despite the growth-stimulating effect of elevated CO_2 concentrations, consistent yield declines were simulated across most of the main wheat growing regions of Mexico due to the projected increase in temperature. Exceptions occurred in some cooler areas, where temperature improved sub-optimal conditions, and in a few areas where rainfall increased, but these increases only provided negligible contributions to national production. Larger and more variable yield declines were projected for rainfed wheat due to current and projected spatial variability of temperature and rainfall patterns. Rainfed wheat, however, only contributes about 6% of Mexico's wheat production. When aggregating the simulated climate change impacts, considering temperature increase, rainfall change, and elevated atmospheric CO_2 concentrations for irrigated and rainfed wheat cropping systems, national wheat production for Mexico is projected to decline between 6.9% for RCP 4.5 and 7.9% for RCP 8.5. Model uncertainty (combined for crop and climate models) in simulated yield changes, and across two scaling methods, was smaller than temporal and spatial variability in both RCPs. Spatial variability tends to be the largest in both future scenarios. To maintain or increase future wheat production in Mexico, adaptation strategies, particularly to increasing temperatures affecting irrigated wheat, or expanding the cropping area, will be necessary.

1. Introduction

Wheat is one of the major cereal crops in the world because of its importance as a main source of energy and protein in human diets (Curtis et al., 2002). In Mexico, wheat is among the top five produced crops: national production during the 2015–2016 season was 3.8 million tons (around $750 million value), cultivated on 720,000 ha (SAGARPA, 2016b). Production is concentrated in Sonora, Baja California, Sinaloa, Guanajuato, and Michoacán states, which together represent about 86% of the total national production (SAGARPA, 2016a). More than 90% of the produced wheat is irrigated due to the arid and semi-arid climate in most of the wheat production area. Rainfed wheat production is typical of the high elevation areas in the central and southern states and Mediterranean-type climate in Baja California, where winter and spring temperature and rainfall are more suitable for the cropping system (Escobar, 2014).

Past global temperature trends already show the effects of warming temperatures on wheat production. Historical wheat yield analysis showed a 5.5% global decline in aggregated wheat production since 1980, as a result of increased global mean temperature (Lobell et al., 2011). In Mexico, Asseng et al. (2014) reported warming decadal trends in Obregon (Sonora) and Toluca (Mexico State) of 0.46 and 0.27 °C,

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respectively, which have caused wheat yield declines from 2 to 3% per decade for the period from 1980 to 2010. However, Lobell et al. (2005) reported that wheat yields in Northwest Mexico have increased by 25% from 1980 to 2001, mostly due to cooling trends in night minimum temperature likely causing reduced plant respiration.

Global temperature trends in the future suggest continuous warming by up to 2 °C at mid-century (IPCC, 2013), which may result in further wheat yield decline if no adaptation strategies are applied (Asseng et al., 2014; Challinor et al., 2014). Elevated atmospheric CO_2 in the future can have a positive effect on crop growth and yields but its response is limited to temperature, nitrogen (N), and water conditions (Alexandrov and Hoogenboom, 2000; Kimball et al., 2001). Climate change projections for Mexico differ in severity, but all of them report a warmer and drier climate by mid-century (Conde et al., 2011; Karmalkar et al., 2011; Peterson et al., 2002; SAGARPA and FAO, 2012), increasing the concern over how climate change will further affect wheat production. Few studies on the effects of climate change on Mexico's wheat production were conducted in the past. SAGARPA and FAO (2012) conducted a study to determine the effects of climate change on Mexican wheat production by using one General Climate Model (GCM). Results showed average yield declines in the Northwest by up to 75%, but also projected 50% yield increases in Baja California and North Sonora. Another study conducted by Parry et al. (2004) also using one GCM with multiple emission scenarios and yield transfer functions, projected a 5–10% yield decline in national production, even when considering adaptation strategies. The use of one GCM and one method to estimate impact yields limits these studies and increases uncertainty, as climate and crop model responses tend to vary widely (Giorgi and Francisco, 2000). In addition, the use of many GCMs is a common practice nowadays when conducting climate change assessments (Semenov and Stratonovitch, 2010).

Climate and crop simulation models contain errors due to their structure and parameterization, which cause uncertainty in projections (Asseng et al., 2013a; Tebaldi and Knutti, 2007). This uncertainty can be quantified through the use of multi-model ensembles (Asseng et al., 2013a; Martre et al., 2015; Wallach et al., 2016). Using the median or mean of multi-model ensembles has proven to be closer to observations than a single model in a diverse range of crops and environments (Asseng et al., 2013a; Martre et al., 2015; Palosuo et al., 2011; Rotter et al., 2012; Yin et al., 2017). The use of multi-model ensembles and different simulation methods provides a better understanding of the range of future climate change impacts on crop production and gives more confidence for building adaptation strategies for future decades (Asseng et al., 2013a; Dale et al., 2017). The main goal of this study was to explore the future impacts of climate change and its uncertainty on Mexican wheat production by using multiple climate and crop model and two scaling approaches.

2. Materials and methods

2.1. Simulation methods

The study was conducted using point and spatial simulation methods. Observed five year average (2010–2014) production and yield levels for wheat in Mexico (SAGARPA, 2016a) were used to select 32 reference locations for the point simulation method. Locations were selected capturing the diverse yield levels and environmental conditions for irrigated and rainfed wheat (Table 1, Fig. 1). Most reference locations are within the Northwestern states, where the majority of wheat production occurs. Major environmental characteristics for reference locations are provided in Table 1. An additional spatial simulation method was also conducted by using the MINK system, which is a is a global-scale gridded simulation platform (Robertson, 2017), using the same crop and climate models from the point simulations. Simulations were performed using 0.5° resolution considering the 2015 wheat production areas (SAGARPA, 2016a). Crop simulation models, input data for climate, crop management, soil profiles, planting dates, and cultivar selection and distribution were the same for both simulation methods.

2.2. Crop model selection and inputs

2.2.1. Crop simulation models

The CROPSIM and NWheat crop simulation models embedded within the platform of the Decision Support Systems for Agrotechnology Transfer, DSSAT v4.6 (Jones et al., 2003) were selected to conduct the study. Both models simulate the crop's life cycle based on Zadok's scheme (Asseng et al., 2013b; Hunt and Pararajasingham, 1995; Zadoks et al., 1974). CROPSIM temperature responses are structured in cardinal temperature functions that control crop growth and development, and organic matter mineralization (Hunt and Pararajasingham, 1995). The NWheat model was derived from ASPSIM-NWheat (Asseng, 2004; Asseng et al., 1998, 2004; Kassie et al., 2016). Temperature in NWheat affects phenology, biomass accumulation, CO_2 assimilation, leaf senescence during grain filling, rate of grain filling, and N demand to grain and vapor pressure deficit (Zheng et al., 2015). Both models run on a daily time step using the radiation use efficiency approach for crop biomass accumulation, and have been widely used to study cropping systems under different environments (Asseng et al., 2004; Asseng and Turner, 2007; Asseng et al., 2002, 2000; Lazzaretti et al., 2015; Ruane et al., 2016; van Bussel et al., 2016; Van Ittersum et al., 2003).

2.2.2. Observed data

Observed annual wheat yield, production, and planted area at state and district level for the baseline period (1980–2010) were collected from SAGARPA (2016a) to compare with the simulated wheat yields. Grain yield data was corrected to 0% moisture. In addition, wheat yields showed a positive linear trend through the baseline period, likely due to improvement in cultivar genetics and cultural practices. Therefore, wheat yields were detrended by using the following formula:

$$\text{Adjusted yield} = y + m^*(LY\text{-}CY)$$

Where:

y = yield for the current year
m = slope from the linear regression in baseline wheat yield
LY = last year from the baseline period
CY = current year to be adjusted

Phenology and yield related variables from a 6-year experiment conducted in Obregon, Sonora (Sayre et al., 1997) were collected to compare phenology and yield variables with the simulated data.

2.2.3. Climate data

The years 1980 to 2010 were selected as the historical baseline to compare with future climate change impacts on wheat production. This climate period was selected following the procedures of the Agricultural Model Intercomparison and Improvement Project (AgMIP) and it is considered a sufficient period to allow climatological analysis (Guttman, 1989; Rosenzweig et al., 2013; WMO, 1989). Climate data for the reference locations were collected from available gridded climate datasets within the MINK system (Robertson, 2017). The baseline and future climate data for each reference location were extracted from the grid cell where the reference point coordinates were located (Table 1). Daily maximum (T_{max}) and minimum (T_{min}) temperature, rainfall, and solar radiation in the MINK system were collected from National Centers for Environmental Prediction and University Corporation for Atmospheric Research (NCEP/NCAR) reanalysis database (Kalnay et al., 1996). The spatial resolution of the NCEP data for T_{max} and T_{min} was about 1.884 °N/S and 1.865 °E/W. Rainfall data at 0.5° resolution corresponding to the same time period was collected from the Global Precipitation Climatological Center of the National Oceanic