Simulating the Effect of Climate Change on Winter Wheat Production Systems for Conditions in Eastern Wyoming

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Antecedents

In 2010, a group of researchers, with the University of Wyoming as a leading institution, were granted by USDA-NIFA with funds to develop a project on “Legume Adoption Practices in Western Central United States: Economic and Environmental Benefits in Face of Increased Climatic Variability”. The goal of this project was to prepare for the process of developing a multi-disciplinary regional-scale integrated grant proposal aiming to understand the functional adaptability of dryland agroecosystems to changes triggered by increased climatic variability and assess the regional ability to sustainably produce food and feed despite changing environments. The specific objectives of the proposal were to: (1) evaluate the impact of changing climate on current environmental crop production conditions in the western central United States; (2) simulate region-specific most-suitable-legume cropping scenarios that reduce the use of energy, nitrogen fertilizer, and water by ten percent (based on 2010 usage), and increase carbon sequestration by fifteen percent by 2030; (3) develop a plan for collaboration between research, education and outreach that will assist current and future agriculture producers in transition to and adaptation of new sustainable technologies and mitigating cultural practices to attain modeling goals in objective two; and (4) write a successful application for an integrated multi-agency and multidisciplinary proposal for 2011 NIFA AFRI solicitation of grant proposals in the area of Mitigation and Adaptation to Climate Change. This report summarizes the results of a modeling effort within the specific objective (2). The preliminary results of this report were obtained using average conditions representing a dryland winter wheat production in southeastern Wyoming.

Summary

Dry land winter wheat is an important crop for Wyoming agriculture. However, dry land winter wheat production faces various challenges, such as climate change and variability. For instance, projections for future climate change call for warming in the Western central region of the United States where there are extensive areas of dryland winter wheat production. While warming would increase growing season length and contribute to fewer frost days, it would also lead to enhanced evaporation and plant water demand. This situation could eventually modify the soil-water balance which in turn could negatively affect winter wheat production. On the other hand, the growing conditions in Wyoming call for urgent need to use conservation cropping approaches if production is to be sustained in the long term. Among others, legume crops are suggested as options to traditional winter wheat-fallow system; however, the benefits of the adoption of this approach are not yet well known. The objective of this study was to determine the effect of climate change on growth and development of dryland winter wheat production systems for conditions in eastern Wyoming. Specific objectives were to conduct an exploratory analysis of the effect of climate change on water balance, soil carbon, and soil nitrogen on dryland winter wheat production systems. The CERES-Wheat model of the Decision Support System for Agrotechnology Transfer (DSSAT), previously calibrated with observed data from variety trials conducted in Torrington, WY, was used. The crop rotation tool of CSM-DSSAT was used to simulate two crop rotations and one climate change scenario, including traditional winter wheat-fallow and intensive winter wheat-spring legume for a period of 30 years. Daily outputs were analyzed focusing on phenology, yield, seasonal evapotranspiration, extractable water at the end of the growing season, total soil organic carbon soil and N uptake. Our results showed that the variability of the simulated yield was greater under a climate change scenario than under actual conditions. For the intensive rotation using both, observed weather data and climate change data, the average simulated yield of wheat was significantly reduced compared to the traditional wheat-fallow rotation; this was due to the negative effect of the legume spring-summer crop in terms of reduction of extractable soil water for the next winter wheat crop.

Contents

Introduction

Dry land winter wheat is an important crop for Wyoming agriculture, with an average area planted of 75,000 ha during the 2009 and 2010 growing seasons (USDA, 2011). However, maintaining a consistent high wheat yield is a challenge for farmers as it varies due to the effects of spatial and temporal variability of weather conditions, among other biotic and abiotic factors. The Intergovernmental Panel on Climate Change (IPCC) projects that temperatures in the major grain-growing areas of North America will rise by 3-4 degrees Celcius by 2100. Such abrupt changes will create major challenges, significantly altering the area suitable for wheat (Olmstead and Rhode 2010). Adjusting to climate change will require shifts in the location of production along with changes in germplasm, sowing dates, tillage practices, and water management at specific locations (Rosenzweig and Hillel, 2008).

The projections for future climate change call for warming in the Western central region of the United States where there are extensive areas of dryland winter wheat production. While warming would increase growing season length and contribute to fewer frost days, it would also lead to enhanced evaporation and plant water demand. This condition could eventually modify the soil-water balance which in turn could negatively affect winter wheat production. Moreover, it is known that soil water has been reported as the major limiting factor in dryland crop production in the Central Great Plains (Lyon et al., 1998). Alternatively, the growing conditions in Wyoming call for urgent need to use conservation cropping approaches if production is to be sustained in the long term. Among others, legume crops are suggested as options to traditional winter wheat-fallow system; however, the advantages of the adoption of this approach are not well known yet.

Crop simulation models have the potential to help understanding the impact of climate change and climate variability and agronomic practices on plant growth and development as the models integrate the soil-plant-atmosphere complex. The Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al. 2004) is a comprehensive decision support system (DSS) for assessing management options (Tsuji et al. 1994). The cropping system simulation model (CSM) included in DSSAT v4.5 (Jones et al. 2003; Hoogenboom et al. 2004), is process-oriented, dynamic and simulates growth, development and yield for more than 25 different crops. The CSM-CERES-Wheat, a DSSAT crop model, simulates growth and development of wheat at a daily time step from planting to maturity. The simulations are based on physiological processes that describe the response of the crop to soil and aerial environmental conditions. Potential growth is dependent on photosynthetically active radiation and its interception, whereas actual biomass production on any day is constrained by suboptimal temperatures, soil water deficits, and nitrogen deficiencies. The input data required to run the DSSAT models include daily weather data (maximum and minimum air temperature, rainfall, and solar radiation); soil characterization data (physical, chemical, and morphological properties for each layer); a set of cultivar-specific coefficients characterizing the cultivar being grown in terms of plant development and grain biomass; and crop management information, such as plant population, row spacing, seeding depth, and application of fertilizer and irrigation. The soil water balance is simulated to evaluate potential yield reduction caused by soil water deficits. The soil water balance is determined on a daily basis as a function of precipitation, irrigation, transpiration, soil evaporation, runoff, and drainage from the bottom of the profile. The soil water is distributed in several layers with depth increments specified by the user (Ritchie and Godwin, 1989; Ritchie, 1998). The Century soil OM module is integrated into the CSM-DSSAT v4.5 in order to better model the dynamics of soil organic nutrient processes (Gijsman et al. 2002; Porter et al. 2010).

The sequence analysis tool of DSSAT v4.5 allows the user to conduct simulations of crop rotations or crop sequences and to analyze the results (Bowen et al. 1998). The main aspect of the sequence analysis is the consideration of experiments that are conducted across multiple cropping seasons. Therefore, the carry-over of the soil water and nutrient status is affected from one cropping season or crop to the subsequent one (Thornton et al. 1994).

Crop simulation models have been used for many different applications in various countries around the world. Garcia y Garcia et al. (2006) evaluated the capability of the CSM-DSSAT for simulating yield of cotton, maize, and peanut under various crop rotation sequences for selected farms in southwest Georgia, USA; Sarkar and Kar (2008) used the sequence analysis program of DSSAT to simulate a rice-wheat-fallow sequence in India and to assess the change in productivity of the rice-wheat system with climatic variability; Soler et al. (2011) used the CSM-DSSAT sequence analysis to simulate yield of different crops and to estimate the changes in soil organic carbon (SOC) for different cropping systems in West Africa.

The present study is a preliminary analysis of the climate change projections of warming and its effects in wheat rotation systems in the western central region of the United States. Warming may increase the growing season length, contribute to fewer frost days and enhance evaporation and plant water demand. These modifications could negatively affect winter wheat production. Therefore, the objective of this study was to determine the effect of climate change on growth and development of dryland winter wheat production systems for conditions in eastern Wyoming. Specific objectives were to conduct an exploratory analysis of the effect of climate change on water balance, soil carbon, and soil nitrogen on dryland winter wheat production systems.

Materials and Methods

Model Calibration and Evaluation

The CERES-Wheat model of DSSAT4.5 was calibrated using results from variety trials conducted in Torrington, WY. Due to limited information the cultivar coefficients were adjusted for a hypothetical wheat cultivar with average characteristics, including simulated average yield of 2960 kg ha^{-1}, average flowering on June 1st, and average physiological maturity on July 14th. The model performance was assessed with USDA-NASS data for dryland winter wheat yield following summer fallow representing Goshen County, WY.

The crop management inputs for CSM-CERES-Wheat model included planting date on September 15th, plant population of 250.000 plants ha^{-1}, row spacing of 20 cm. These are considered common wheat agronomic practices used by farmers in eastern Wyoming region.

Crop Rotations

The crop rotation or sequence tool of CSM-DSSAT V4.5 (Thornton et al. 1995) was used to simulate two crop rotations and two climate change scenarios for a period of 30 years. The two crop rotations simulated were traditional winter wheat-fallow and intensive winter wheat-spring legume (Table 1). The intensive wheat legume rotation had a crop every year while the traditional rotation had a crop every other year.

Table 1. Representation of the two simulated crop rotations across time.

Rotation	Year 1	Year 2	Year 3	Year 4	Years/cycle
Traditional W-F	W[1]	F[2]		W	2
Intensive W-F-L	W	F	L[3] F	W	2

[1]W = Wheat; [2]F = Fallow; [3]L = Legume

Climate Change Scenarios

Long term simulations were performed using a) observed daily weather representing conditions in Torrington, WY from 1980 to 2009, and b) a hypothetical scenario of warming climate change.

The historical daily temperature and rainfall data from Torrington, WY were extracted from NOAA-NCDC. Solar radiation was generated using the WGENR generator (Garcia y Garcia and Hoogenboom, 2005). The hypothetical climate change weather was estimated by adding 1.9^{o}C from January through May, 3.5^{o}C from June to August and 1.9^{o}C from September to December. The 1.9^{o}C reflects the regional average warming for western US and Great Plains, but the summer warming comes from downscaling results. After the temperature modifications, solar radiation for the climate change scenario was generated using maximum and minimum temperatures and precipitation following the same procedure as for the observed weather data. A study conducted by Garcia y Garcia et al. (2008) demonstrated that generated solar radiation can be used as input for crop simulation models when observed that are not available.

Soil Profile Information

The soil profile information was extracted from the USDA-NRCS Soil Characterization Data Base. The soil used for the simulations was Mitchell series, characterized by having soil layers with clay content varying between 9 and 14% and silt content varying from 33 and 38%, and pH between 7.8 and 8.0. Hydraulic soil properties, such as field capacity and wilting point, were estimated using SBuild, a DSSAT utility for soil information management.

Statistical Analysis

For the calibration and evaluation of the CSM-CERES-Wheat, the comparison between observed yield obtained from USDA-NASS and simulated yield values was assessed using the RMSE and the Index of Agreement (d) proposed by Willmott et al. (1985). According to the d-statistic, the closer the index value is to one, the better the agreement between the two variables that are being compared and vice versa. The observed and simulated yield variations were examined by plotting the normalized yield according to Meinke and Hammer (1995). The performance of the model to simulate the inter-annual variability of yield was assessed using the Z-score procedure to standardize the simulated yield and those obtained from USDA-NASS. The standardization converts all values into compatible units with a distribution that has an average of 0 and a standard deviation of 1, allowing for an easier comparison of yield series (Meinke & Hammer, 1997; Garcia y Garcia et al., 2005),

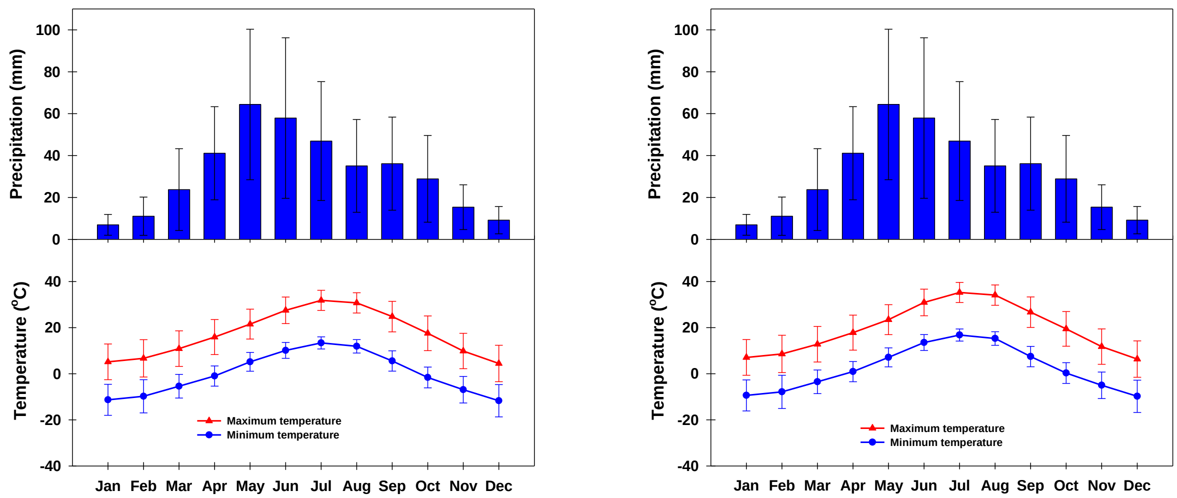
Daily outputs were analyzed focusing on phenology, yield, seasonal evapotranspiration, extractable water at the end of the growing season, total organic carbon in the soil and N uptake. The results are presented using the box plots exploratory data analysis, in which the box itself contains the middle 50% of the data, the upper edge (hinge) of the box indicates the 75th percentile of the data set and the lower hinge indicates the 25th percentile. The median yield value is indicated by a horizontal line in the box. The upper and bottom lines of the diagram represent the yield between the 10th and 90th percentiles. The dots beyond the lines correspond to outliers.

Results and Discussion

Weather Conditions

Wyoming has a relatively cool climate. For most of the State, mean maximum temperatures in July range between 29 and 35°C. For most places away from the mountains, the mean minimum temperature in July ranges from 10 to 15.5°C. In the wintertime it is characteristic to have rapid and frequent changes between mild and cold spells. January, the coldest month generally, mean minimum temperatures range mostly from -15 to -12°C. For most of the State, sunshine ranges from 60 percent of the possible amount during the winter to about 75 percent during the summer. The period of maximum precipitation occurs in the spring and early summer for most of the State. At lower elevations over the northeast portion and along the eastern border, where elevations are mostly in the range from 1,220 to 1,677m, annual averages are from 305 to 406mm (www.wrds.uwyo.edu).

The actual weather conditions reflect the characteristic winter with low monthly precipitation and low temperatures in Torrington, WY (Figure 1). The month with the highest precipitation is May with an average of 70 mm. The highest average temperature usually occurs in July under both, the actual weather and the hypothetical climate change scenario.

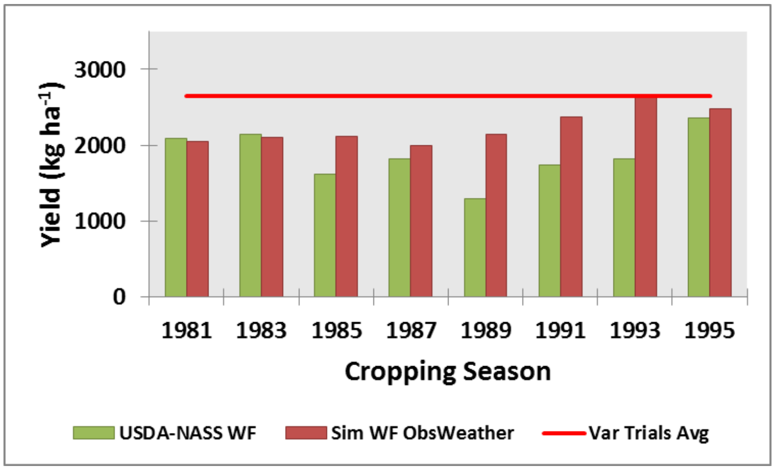


(a) (b)

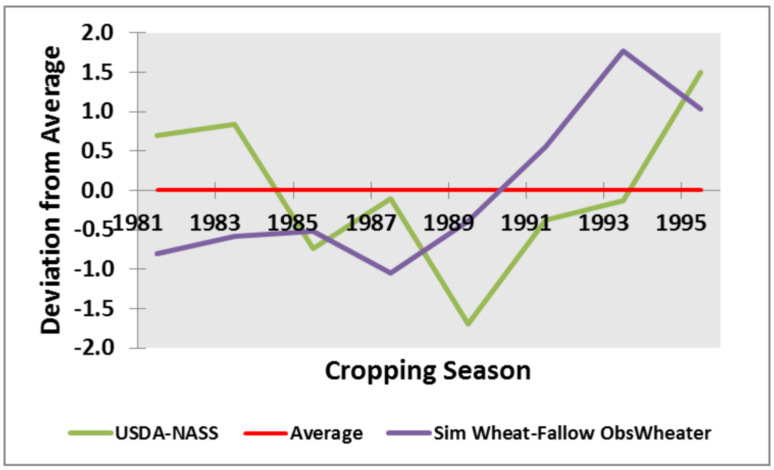
Figure 1. Monthly precipitation (mm), monthly average maximum and minimum air temperature for a) actual weather conditions and b) the hypothetical climate change scenario.

Model Calibration and Evaluation

Using the sequence analysis of DSSAT, the CERES-Wheat model simulated the yield with acceptable accuracy, with a Wilmott index (d) of agreement of 0.75 and RMSE of 515 kg ha^{-1}. The results of the calibration, the simulated yield and the observed yield obtained from USDA-NASS from 1981 to 1995, are presented in Figure 2a. The deviation from the average showed that the simulated yield followed the trend of the observed yield across years (Figure 2b).



(a)

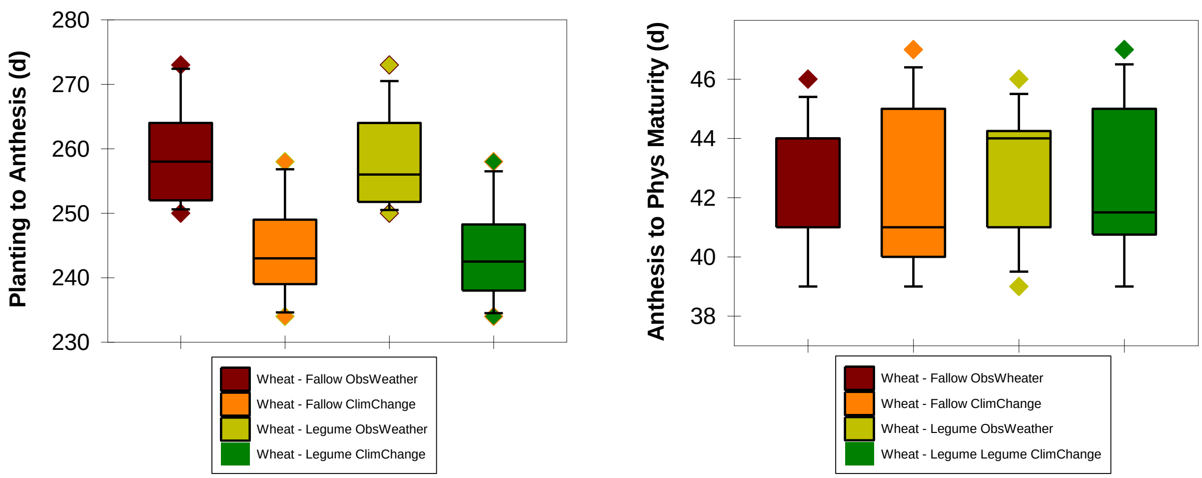


(b)

Figure 2. Calibration and evaluation of the CSM-CERES-Wheat model; a) comparison of observed yield (USDA-NASS Wheat-Fallow) and simulated yield using observed weather data for the traditional Wheat-Fallow rotation and b) performance of the model to simulate the inter-annual yield variability.

Effect of Climate Change on Phenology

The simulations of phenology using climate change weather data for the traditional wheat-fallow rotation resulted in 13 days reduction in the median days from planting to anthesis, mainly because of the acceleration of crop development with the warmer temperatures used in the hypothetical climate change scenario. The median period from anthesis to physiological maturity was also shortened under the climate change conditions (Figure 3). Similar results were reported in previous studies. In China, where significant warming trends were observed at many locations, the changes in temperature have shifted crop phenology and affected crop yields during the last decades (Tao et al., 2006). In Europe, climate change scenarios will lead to general advancement of the main phenological stages, shortening of the growing season and increasing the frequency of heat stress during anthesis with respect to the baseline (Moriondo et al., 2011).



a) b)

Figure 3. Simulated phenology; a) planting to anthesis and b) anthesis to physiological maturity, using both observed and climate change weather data, for the traditional wheat-fallow rotation and the intensive wheat-legume rotation.

Effect of Climate Change on N Uptake During the Growing Season

There was a positive effect of the legume on N uptake due to the ability of the legume to capture N and the fact that the legume crop was simulated to be incorporated into the soil and consequently determined an increase in the amount of simulated N available to wheat. The simulated median N uptake was greater for the intensive wheat-legume rotation using observed weather data (90 kg ha^{-1}); however, under the weather change scenario there was a decrease in the median N uptake by the wheat (Figure 4), and an increase in the variability, as showed by the upper edge of the box (75th percentile) and the lower hinge (25th percentile).

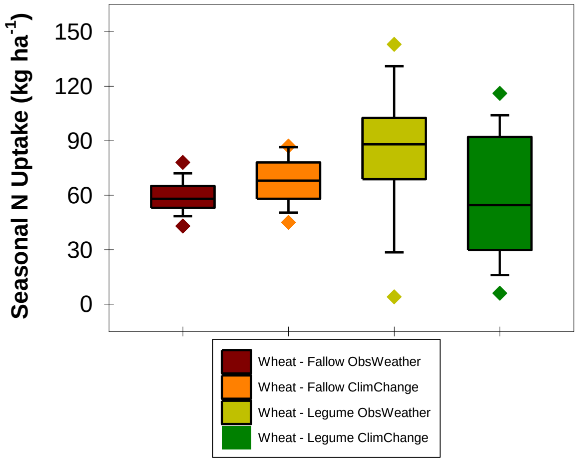


Figure 4. Simulated seasonal N uptake for wheat crop for the two rotations and the two climate scenarios.

Effect of Climate Change on Soil Organic Carbon

The simulated total soil organic carbon was greater for the intensive wheat-legume rotation than for the traditional wheat-fallow rotation due mainly to the incorporation of the legume into the soil (Figures 5 and 6). Interestingly, the adoption of a legume crop showed a stable to slightly increase on soil organic carbon under actual weather conditions, however, the soil organic carbon had a trend to decrease over the years in a condition of climate change. Disagreements regarding the effects of climate change on global soil carbon stocks have been reported (Davidson and Janssen, 2006).

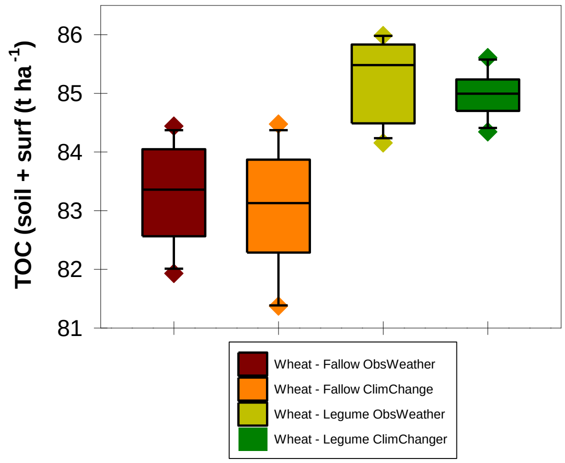


Figure 5. Simulated total soil organic carbon in the profile for wheat crop for the two rotations and the two climate scenarios.

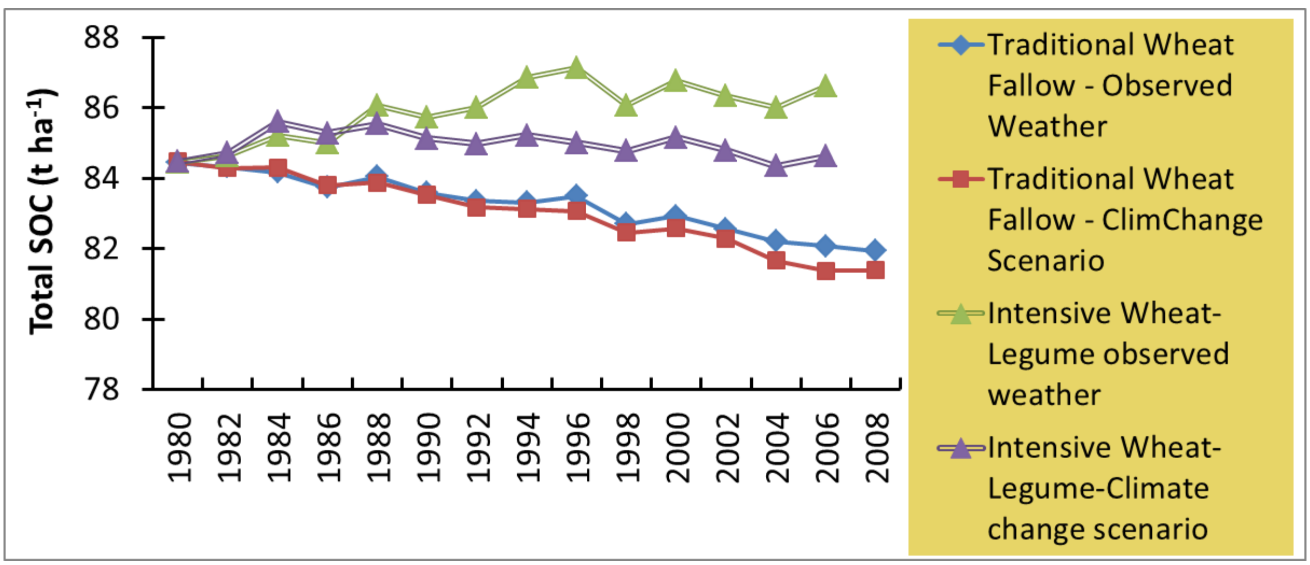


Figure 6. Simulated total soil organic carbon in the profile across years for wheat crop for the two rotations and the two climate scenarios.

Effect of Climate Change on Seasonal Crop Evapotranspiration (ETc)

The median ETc was similar for the traditional wheat-fallow rotation under the two weather scenarios, but it was reduced for the intensive legume-wheat rotation under climate change scenario (Figure 7), mainly due to a reduction of the growing season. The extractable water at the end of the season for the intensive rotation may also negatively impacted the crop evapotranspiration and finally the wheat yield.

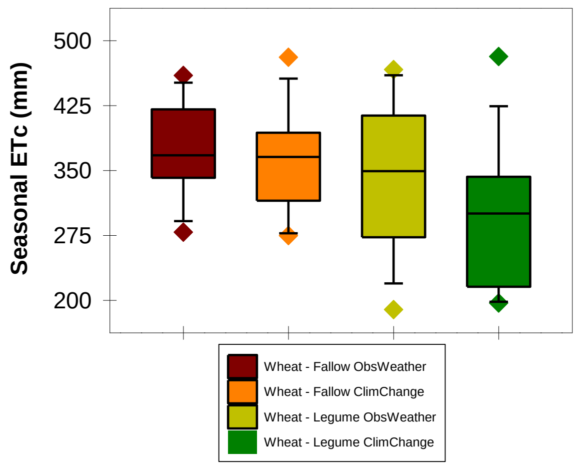


Figure 7. Simulated total evapotranspiration for wheat crop for the two rotations and the two climate scenarios.

Effect of Climate Change on Available Soil Water at the End of the Season

The simulated extractable water at maturity is an indicator of the amount of water left for the next crop and also an indicator of the water consumed by the crop during the season. The simulated median extractable water at maturity using observed weather data was greater than using the data for the climate change scenario (Figure 8). In other words, under a climate change scenario there was a clear reduction in the soil moisture content at the end of the season, indicating an increase in the levels of drought for the following crop, and consequently an increase of the yield reduction risk due to drought conditions. Eitzinger et al (2003), who studied the effect of water balance parameters and water stress on winter wheat production under different climate change scenarios using the CERES-Wheat model for a semi-arid agricultural area in central Europe, reported that despite higher yield levels, crop transpiration and water stress dropped significantly compared with current conditions, due to an increase in simulated water use efficiency and to a reduced total potential evapotranspiration caused by shortened growing period.

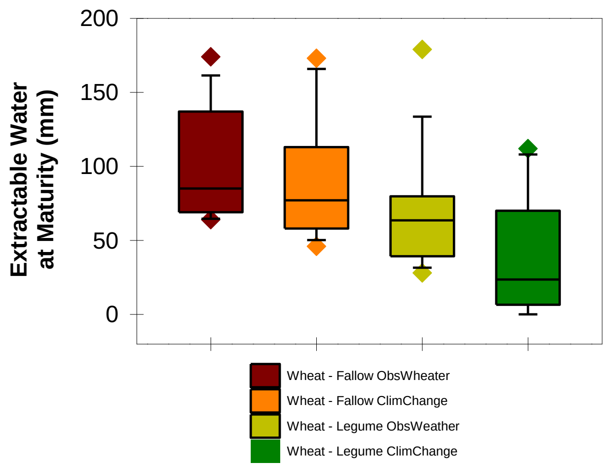


Figure 8. Simulated total extractable water at maturity for wheat crop for the two rotations and the two climate scenarios.

Effect of Climate Change on Yield

The median simulated yield of wheat was greater using the climate change scenario for the traditional wheat-fallow rotation, but considerable less for the intensive wheat-legume rotation. In addition, the simulated wheat yield variability was greater for intensive wheat-legume rotation (Figure 9), indicating the vulnerability of this system under both weather conditions, observed and climate change. Results reported by Wei et al (2005) also indicated that maximum wheat yield, average yield as well as the yield variability will increase under climate change scenarios. However, Deryng et al. (2011) using PEGASUS1.0 model suggested that if changes in temperature and precipitation are as predicted by global climate models for the 2050s, it will lead to a global yield reduction if planting and harvesting dates remain unchanged. However, adapting planting dates and cultivar choices increases yield in temperate regions and avoids between 7 and 18% of global losses.

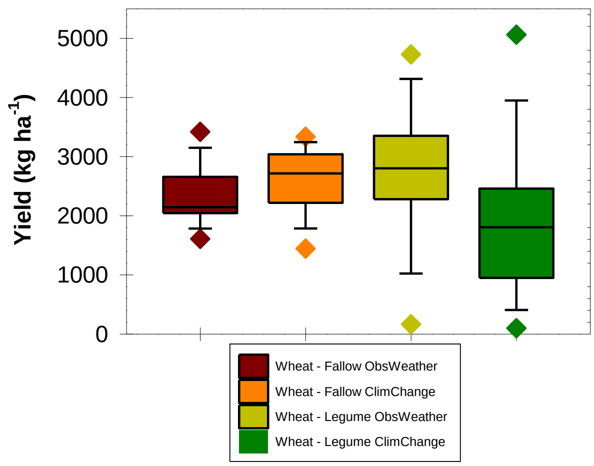


Figure 9. Simulated wheat yield boxplots for the two rotations and the two climate scenarios.

Conclusions

It was found in this exploratory study that under climate change scenario, the simulated wheat phenology is altered due to the warmer temperatures, in other words anthesis and physiological maturity are reached earlier than under actual weather conditions.

The traditional wheat-fallow system showed higher yield under a climate change scenario than under the actual conditions; the opposite was observed for the intensive wheat-legume system. However, the variability of the simulated yield was greater under a climate change scenario than under actual conditions.

The seasonal actual crop evapotranspiration was greater under actual conditions than those using the climate change scenario, mainly because under climate change scenario there was a reduction in the extractable water at the end of the season that caused an increase in drought risk for the following crop in the rotation. In short, the extractable water at maturity was reduced under the climate change scenario for both, the traditional wheat-fallow system and the intensive wheat-legume system.

The intensive legume system resulted in an increase on N uptake by the wheat crop, especially under actual weather conditions. For the traditional wheat-fallow rotation, the total soil organic carbon in the profile is reduced under both, actual and climate change scenarios; the opposite was observed for the intensive Wheat-legume system, in which the legume was incorporated into the soil, and total carbon was stable trough the years. However, the improvement in soil fertility caused by the incorporation of a legume in the system was not enough to overcome the negative effects of the intensification of the system that resulted in low extractable water for the next crop, and consequently there was an increase in the simulated wheat yield variability, especially under the climate change scenario.

Acknowledgments

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