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Climate change and dryland wheat systems in the US Pacific Northwest

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ABSTRACT

A regional assessment of baseline (1980–2010) and future (2015–2085) yields of dryland wheat-based cropping systems in the US Inland Pacific Northwest (IPNW) was conducted. The computer simulation-based assessment was done using CropSyst, a cropping systems simulation model, and projected daily weather data downscaled to a 4 × 4 km grid using 12 general circulation models (GCMs) for two atmospheric CO_2 representative concentration pathways (RCP 4.5 and RCP 8.5). The study region was divided into 3 agro-ecological zones (AEZs): continuous cropping (CC), continuous cropping-fallow transition (CCF), and crop-fallow (CF), with the following typical rotations assigned to the zones: winter wheat (WW) – summer fallow (SF) (CF zone), WW – spring wheat (SW) – SF (CCF zone), and WW – SW – spring pea (CC zone). By the 2070s (2065–2085), precipitation in the IPNW is projected to increase by about 8 and 12% compared to the baseline period under RCP 4.5 and 8.5, respectively. Mean temperature during the WW growing season will increase about 1.5 and 2.3 °C under RCP 4.5 and 8.5, respectively, but will not change noticeably during the SW growing season due to the adaptive early planting used in this study. Concurrently, atmospheric CO_2 concentration will increase from today's average of ~400 ppm to 532 ppm to 801 ppm by 2085 depending on future emissions of greenhouse gases. Soil water-crop growth interactions, which show large variation across the region, will modulate crop responses to these changing conditions, with our results showing an overall increase in yield across the IPNW. By the 2070s, the mean ratio of future to baseline WW yield will range from 1.29 to 1.35 under RCP 4.5 and from 1.41 to 1.64 under RCP 8.5 depending on the AEZ. The mean yield ratio for SW across AEZs will range from 1.38 to 1.53 under RCP 4.5 and 1.54 to 1.91 under RCP 8.5. Given substantial climatic heterogeneity in the region, these gains will not be distributed equally across the region or within AEZs, and overall they will not be shared equally by all growers.

1. Introduction

Climate change presents challenges new to the world's growing human population (Ericksen et al., 2009). With the population projected to reach 11 billion by 2100 (United Nations, 2015), an accurate estimation of major crop yields such as wheat is needed to assess food security (Shewry and Hey, 2015). A global reduction of wheat production is projected as a result of warming and changes in precipitation (Asseng et al., 2011, 2015), but the outlook is more varied and complex when both climate change and rising atmospheric CO_2 concentration are considered, with positive and negative outcomes expressed globally (Ortiz et al., 2008; Wilcox and Makowski, 2014).

Crop vulnerability to climate change and the capacity of agriculture to adapt to new conditions vary regionally. Some regions will experience yield improvements while others will experience declines (Kristensen et al., 2011; Laurila, 2008; Olesen et al., 2011). In a meta-analysis of simulation studies evaluating the effects of climate change on wheat yields (Wilcox and Makowski, 2014), yield decreased in more than 50% of studies if the mean temperature change was higher than 2.3 °C, or if precipitation did not increase in the future. High atmospheric CO_2 could compensate for the effects of temperature and moderate declines in precipitation.

Agriculture contributes to a major portion of the economy in the climatically diverse Inland Pacific Northwest (IPNW) region of the US. Around 17% of the nation's wheat is produced in Oregon, Washington, and Idaho (USDA). Although some parts of the IPNW have very low precipitation, cereal based dryland cropping systems have long existed in this region (Schillinger and Papendick, 2008).

The IPNW has historically experienced relatively wet winters and dry summers. A wide range of precipitation and temperature regimes exist across the IPNW, with annual precipitation ranging from 180 mm to 1130 mm, and temperatures fluctuating largely in response to elevation and local topography. Climate change is expected to bring warmer and dryer summers in the IPNW, and temperature and

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precipitation increases during other seasons. In the IPNW, CMIP5 (fifth phase of the Coupled Model Inter-Comparison Project) models project a mean annual warming of 1.1 °C to 4.7 °C by 2041–2070 compared to the base period of 1950–1999 (Dalton et al., 2013). The frost-free season and the number of hot days are expected to increase with larger increases in the west and southeastern regions. The overall annual change in precipitation is projected to range from − 4.7% to + 13.5% (Creighton et al., 2015; Dalton et al., 2013).

Despite this variation in current and future climatic conditions across the region and potential deleterious effects for agriculture, rising atmospheric CO_2 concentration might counterbalance climate change effects and result in a more positive outcome. Elevated atmospheric CO_2 increases photosynthetic rate (CO_2 fertilization effect) in C_3 plants like wheat (Drake et al., 1997), and reduces stomatal conductance and plant transpiration thus enhancing crop water use efficiency which boosts dryland yields (Ainsworth and Long, 2005).

Few studies have looked at the yields in IPNW under climate change. Thomson et al. (2002) simulated baseline and future WW production in eastern Washington, northeastern Oregon and north-western Idaho, using just one general circulation model (GCM), two constant CO_2 concentrations for baseline (365 ppm) and future (560 ppm) scenarios, and sixteen grid cells (90 km × km) across the region. Wheat yields for the baseline averaged 4.52 mg ha^{-1} across the study region (including irrigated farms), increasing to 5.45 mg ha^{-1} for the future CO_2 condition. In another study (Stöckle et al., 2010), four representative locations in Washington State were evaluated using four GCMs. Winter wheat yield was projected to increase 13–15% by 2020 and 23–35% by 2080, with larger gains predicted on drier sites. Spring wheat yields only increased about 7% by 2020 and 2% by 2040 in high rainfall areas and declined by 7% by 2040 in the lower rainfall zone without any adaptation strategies. When spring wheat was planted 2 weeks earlier, by 2040 yield increased 11% in the high rainfall zone and 3% in the lower rainfall zone (Stöckle et al., 2010).

Although existing projections provide helpful information about the effect of climate change on IPNW dryland agriculture, the existence of a large precipitation gradient and fluctuating temperature conditions throughout the region, dictating zones with varying degree of crop intensity and use of fallow, generates a heterogeneous system that has not been accounted for by previous work. In addition, the large variation in weather projections of available GCMs implies that the use of a few GCMs in these studies does not reflect the underlying uncertainty that exists. Our objective is to provide a more detailed regional analysis at a high resolution and incorporating a larger number of weather projections, which will lead to a richer understanding of the variable impact of climate change in the IPNW.

2. Materials and methods

Wheat-based dryland cropping systems in the IPNW are closely associated with annual precipitation. The region is customarily classified into three agro-ecological zones (AEZ) (Douglas et al., 1992; Huggins et al., 2011): continuous cropping (CC), continuous cropping to fallow transition (CCF), and crop-fallow (CF). The CC zone is roughly comprised of the area with an annual precipitation of 450 to 1000 mm where annual cropping is feasible. In the CCF zone, with precipitation ranging from about 304 to 457 mm, a fallow period before winter wheat (WW) is necessary to ensure good yields, with WW typically followed by spring wheat (SW), a shorter season crop with lower water demand. The precipitation range in the CF zone is from 180 to 304 mm, which is too low to support annual cropping, and WW is typically planted every other year. The regional distribution of these AEZs is presented in Fig. 1, showing a distinctive east-west pattern. The upper-right corner of the figure situates the study region comprising mainly Washington State, but also including portions of Oregon and Idaho. Typical crop rotations in each AEZ were considered in this study (Table 1). More information on cropping systems in the IPNW can be found in Schillinger et al. (2003).

A 4 × 4 km grid was used to represent the regional climate variation, and downscaled gridded daily weather data from 12 GCMs (Abatzoglou and Brown, 2012) for the period 2015–2085 were used to drive the cropping system simulations. In this study we considered two RCPs including 4.5 and 8.5 Wm^{-2}. As baseline, gridded weather data for the period 1980–2010 were used, which were generated by combining attributes of two datasets: temporally rich data from the North American Land Data Assimilation System Phase 2 and spatially rich data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Abatzoglou, 2013). The previously prepared weather data set includes daily maximum/minimum temperature, precipitation, solar radiation, maximum/minimum humidity, and wind speed.

The USDA-NRCS STATSGO soil data base was used to obtain representative soil data required by CropSyst for each grid cell. Within each 4 × 4 km grid cell, the predominant cropland soil was chosen as an input to the model. Cropland data layers from 2007 to 2011 at a 30 × 30 m resolution (USDA - National Agricultural Statistics Service) were used to determine the fraction of cropland in each 4 × 4 cell. The sand fraction of the soils decreases from west to east while the fine fraction increases from west to east.

Crop simulations were performed using CropSyst (Stöckle et al., 1994; Stöckle et al., 2003), a cropping system model that has been widely used for climate change assessment studies under different climatic conditions around the world (e.g., Bocchiola et al., 2013; Donatelli et al., 2015; Jalota and Vashisht, 2016; Sommer et al., 2013; Torriani et al., 2007). Biomass production as a function of elevated CO_2 is approximated using a non-rectangular hyperbola function (e.g., Thornley, 1998), stomatal conductance is reduced by increasing CO_2 as presented in Allen (1990), and actual transpiration responds to soil water potential and water vapor atmospheric demand as described in Stöckle and Jara (1998). Other details are given by Stöckle et al. (2003). The ability of CropSyst to simulate wheat under elevated CO_2 has been recently confirmed using data from the Australian Grains Free-Air CO_2 Enrichment experiment (located in a semi-arid environment) (O'Leary et al., 2014).

For the current study, all rotations were managed as reduced tillage. A sweep plow was simulated prior to seeding for all crops. After WW harvest in CC and CCF, the soil was chisel plowed. The CropSyst model was used in automatic N fertilization mode, which had the effect of eliminating N stress. Pest and disease pressure were not modeled. Because many wheat varieties are grown in the region, for this system analysis study a "representative" cultivar was defined that conformed to the typical growing season and canopy ground cover in each AEZ. Generalized phenology and yield information (Papendick, 1996; Schillinger et al., 2006; personal communication) was used to adjust crop phenology parameters to simulate the phenology characteristic of the respective zone. For the most part, default parameters for wheat were used throughout the region. Minor adjustment of two WW parameters was done, one to reflect lower canopy coverage at the lower precipitation zone, and the other to reflect a slightly higher yield potential in the higher rainfall zone.

Simulations during a 30-year period (1980–2010) using historic weather records for 5 sites in the region that represented low, medium, and high precipitation zones were performed. The good agreement of simulated and observed yields from independent research conducted in the region indicated that the model could capture the yield differences among sites with very different annual precipitation amounts as well as yield differences between WW and SW cultivars (Table 2).

Within an AEZ, WW was sown on the same day regardless of scenario; day of year 243 in CF, 257 in CCF and 280 in CC. Seeding spring crops, however, depended on 15-day average temperature exceeding a required threshold beginning on March 1. This conditional mode of seeding was adopted only for the spring crops because early spring temperatures are expected to shift substantially as the century