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Meteorological limits to winter wheat productivity in the U.S. southern Great Plains

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A B S T R A C T

Although the U.S. southern Great Plains accounts for approximately 30% of total U.S. wheat (*Triticum aestivum* L.) production, yields in the region have rarely surpassed 3.0 Mg ha^{-1} and quantification of the wheat yield gap (Y_G) and meteorological factors associated with potential wheat productivity are scarce. Our objectives were to identify spatial gradients in key weather variables and to assess the meteorological drivers of wheat productivity and resource-use efficiency, and to quantify the wheat Y_G across Texas, Oklahoma, Colorado, and Kansas. Water-limited wheat grain yield (Y_w) was simulated for 30 consecutive years at 68 locations across the southern Great Plains using Simple Simulation Modeling-Wheat (SSM-Wheat), and actual soil and weather data, sowing date, and population density. Regional gradients in meteorological variables were determined for (i) the entire crop cycle, (ii) pre- and post-anthesis, or (iii) jointing-anthesis interval, and Y_w were related back to these variables using linear and stepwise multiple-regression. Boundary function analysis determined water productivity (WP) and transpiration-use efficiency (TE). Strong latitudinal gradients occurred for temperatures and longitudinal gradients for precipitation (P), evapotranspirative demand (ET_o), and solar radiation (Rs). Wheat Y_w averaged 5.2 Mg ha^{-1} and followed the longitudinal P gradient increasing from west (3.6 Mg ha^{-1}) to east (6.9 Mg ha^{-1}). Interannual Y_w variability was large with coefficient of variation (CV) increasing from 13 to 51% east to west. Meteorological variables accounting for major portions of the Y_w variability were water supply ($P + PAW_s$) in the west [82% of regression sums of squares (SS)] and cumulative solar radiation (R_s) during the anthesis – physiological maturity in the east (73% of SS). Temperatures during the anthesis-physiological maturity phase negatively affected grain yields across all locations and years (7% of SS). Wheat WP (17.2 kg ha^{-1} mm^{-1}) and TE (20.8 kg ha^{-1} mm^{-1}) benchmarks derived in this study align well with values reported for wheat grown in other regions of the world.

1. Introduction

Yield potential is defined as the yield achieved by an adapted cultivar when grown under non-limiting water and nutrient conditions with all biotic stresses properly managed (Van Ittersum et al., 2013). Several approaches exist to estimate a crop's yield potential for a particular region (Lobell et al., 2009; Van Ittersum et al., 2013). Provided non-limiting water conditions, the theoretical yield potential of a crop can be estimated as the product of total intercepted solar radiation, radiation-use efficiency, and the ratio between grain yield and crop aboveground biomass at physiological maturity (i.e. harvest index) (Hay and Porter, 2006). Following this approach, Sinclair (2013) estimated the theoretical yield potential of wheat as 12.9 Mg ha^{-1}. In rainfed agricultural systems, yield potential is often decreased due to inadequate total water supply and/or seasonal water distribution (Lobell et al., 2009). Therefore, the degree of water limitation needs to be taken into account when determining a crop's yield potential in rainfed environments, hereafter referred to as water-limited potential yield (Y_w) (Connor et al., 2011). Maximum yields measured in rainfed trials where manage-

Abbreviations: CV, coefficient of variation; ET_o, reference evapotranspiration; NASA Power, National Aeronautics and Space Administration Prediction Of Worldwide Energy Resource; NOAA, National Aeronautics and Space Administration; PAW, plant available water; PAWC, plant available water capacity; PAW_s, plant available water at sowing; PQ, photothermal quotient; R_s, incident solar radiation; SSM-Wheat, Simple Simulation Modeling Wheat; TE, transpiration efficiency; T_{max}, maximum daily temperature; T_{min}, minimum daily temperature; WP, water productivity; Y_w, water-limited yield; θ_{LL}, volumetric soil water content at the lower limit.

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ment strived to reduce biotic stresses, as well as rainfed yields derived from yield contests, can be used as estimates of the Y_w of a given crop during a particular growing season (Lobell et al., 2009). However, a more robust estimation of Y_w can be performed using crop simulation models (Van Ittersum et al., 2013). To date, estimations of the wheat Y_w in the southern Great Plains have been inconsistent, ranging from 3.8 Mg ha^{-1} (Fischer et al., 2014) to 6.7 Mg ha^{-1} (Patrignani et al., 2014). While results from field experiments suggest that wheat yields in the U.S. southern Great Plains are far below the Y_w, there are no studies attempting to investigate the long-term wheat Y_w with the use of crop simulation models in the region.

Approximately 9 million hectares are sown to winter wheat every year in the U.S. southern Great Plains (32–40°N; 96–104°W), which is the largest contiguous area of low-precipitation winter wheat cropland in the world (Fischer et al., 2014). Total annual wheat production from Colorado, Kansas, Oklahoma, and Texas combined often surpasses 20 million metric tons, accounting for over 30% of the U.S. wheat production (USDA-NASS, 2016a). Recent analysis of historical wheat yields in the region indicated that average farm yield have been nearly stagnant for the last 30-yr with state-level yields never surpassing 3 Mg ha^{-1} and county-level yields ranging from 0.2 to 3.6 Mg ha^{-1} (Patrignani et al., 2014). These yield levels are well below maximum yields reported from well-managed field trials across the region along the years, which ranged from 6.8 to 9.3 Mg ha^{-1} (Lingenfelser et al., 2016; Lollato and Edwards, 2015; Musick et al., 1994). Estimates of the magnitude of the difference between producer-reported yield and Y_w for the U.S. southern Great Plains, also referred to as yield gap (Y_G) (Lobell et al., 2009), are scarce and have been inconsistent. Fischer et al. (2014) compared state average yield to the average yield from modern cultivars at 13 locations of the Kansas wheat variety performance tests to conclude that the Y_G in Kansas is approximately 1 Mg ha^{-1} (36%). Meanwhile, Patrignani et al. (2014) used the boundary function of the relationship between county-level wheat yields and seasonal precipitation to estimate an Y_G of ~4.7 Mg ha^{-1} (70%) in Oklahoma. Maximum yields reported from field trials (6.8–9.3 Mg ha^{-1}) and from yield contest-winning fields (5.7–8.1 Mg ha^{-1}) (http://kswheat.com/producers/yield-contest/; verified 26 October 2016) tend to agree with the latter Y_G assessment. However, these individual yields are most likely not representative of average regional Y_w over several years, as a robust assessment of a region's Y_w via well managed field studies is costly and impracticable (Cassman et al., 2003).

Simulation of Y_w across several sites and years using mechanistically based crop models is a reliable alternative to costly field studies for assessment of long-term environmental Y_w for a given region (Van Ittersum et al., 2013). Simulation models account for different weather conditions across years and regions; as well as for interactions among crops, weather, and soils; allowing for detailed analyses of Y_w for a particular cropping system (Van Ittersum et al., 2013). Also, it facilitates analysis of geospatial gradients of weather variables and their influence in crop potential productivity (Grassini et al., 2009). Crop simulation models have been widely used to assess wheat Y_w for wheat systems of the globe, including: the Yaqui Valley in Mexico (Bell and Fischer, 1994; Lobell and Ortiz-Monasterio, 2006); the Pampas region in Argentina (Menendez and Satorre, 2007); India (Aggarwal and Kalra, 1994); and the wheat producing regions of Australia (Asseng et al., 1998; Gobbett et al., 2016; Hochman et al., 2013; Peake et al., 2014), Russia (Schierhorn et al., 2014), Spain (Abeledo et al., 2008), and China (Liang et al., 2011; Lu and Fan, 2013). Still, analysis of the wheat Y_w and the effects of weather gradients on winter wheat Y_w using crop models has not been performed for the U.S. southern Great Plains.

Water is generally the most limiting resource to crop productivity in modern rainfed agriculture (Connor et al., 2011). Quantification of the maximum yield per unit water supply provides a benchmark that can be used by farmers to set yield goals based on available water, and to identify limiting factors to on-farm productivity other than water supply (Grassini et al., 2009; Passioura, 2006). Grain yield plotted against seasonal water supply or crop evapotranspiration (ET_c) can provide an estimate of the system's water productivity (WP) and the crop's transpiration efficiency (TE) (French and Schultz, 1984). The linear function fitting the most efficient points represents the maximum production efficiency for a given amount of seasonal water or ET_c. Previous efforts in determining the WP for wheat systems in the U.S. southern Great Plains resulted in WPs ranging from 16.7 kg mm^{-1} in Bushland, TX (Sadras and Angus, 2006), to 22 kg mm^{-1} in west-central Oklahoma (Patrignani et al., 2014). Elucidation of geospatial gradients as efforts to benchmark WP and TE can help identify the physiological frontier for wheat water-limited productivity.

Quantifying long-term Y_w in the U.S. southern Great Plains is crucial for development of agricultural policies and priorities for agricultural research to ensure present and future global food security. Given the scarcity of measured data on wheat potential productivity in the region, the objectives of this research were to (i) find geospatial patterns in meteorological variables associated with wheat productivity (i.e. solar radiation, temperature, P, and ET_o); (ii) define the long-term Y_w and Y_G of winter wheat in the region based on a simulation analysis; (iii) identify weather factors across the geospatial climatic gradients that explain spatial variation in winter wheat Y_w; and (iv) define WP and TE of wheat grown under non-limiting conditions for different regions within the U.S. southern Great Plains.

2. Material and methods

2.1. Model description and performance evaluation

The SSM-Wheat crop model (Soltani and Sinclair, 2012) is a mechanistic crop model that simulates daily wheat growth and development based on soil characteristics and observed daily weather. Simulations of wheat growth and development in SSM-Wheat are for a crop free of limitations caused by diseases, insects, weeds, and also nutrient deficiencies. Crop response to vernalization and photoperiod are accounted for, and reductions in potential productivity result from water-deficit stress, occurrence of limiting temperatures, or inadequate photoperiod. Crop transpiration is simulated as function of crop daily dry matter production, effective daily vapor pressure deficit, and a TE coefficient (Tanner and Sinclair, 1983). Every parameter used in SSM-Wheat can be calculated from field collected data, which allows for parameterization of the model for different conditions based on field measurements. Recent comparison of different wheat simulation models indicates an advantage to the SSM-Wheat model when compared to other mechanistic models in transparency and robustness (Soltani and Sinclair, 2015).

We derived parameter values for the SSM-Wheat model using field collected data for wheat growth, development, and yield, in seven dryland site-years in Oklahoma where crop management strived to minimize stresses from nutrition, weeds, insects, and diseases, approaching the Y_w of winter wheat (Lollato and Edwards, 2015). Parameter values were based on data collected on Iba wheat genotype for phenology (i.e. days to emergence, anthesis, physiological maturity, and harvest maturity), aboveground biomass, leaf area index, plant available water (PAW) in the top 1200 mm of the soil profile, grain yield, and HI. The variety 'Iba' was selected for being a modern wheat cultivar with excellent yield potential and a broad spectrum of disease resistance, as well as broad adaptability and excellent yield record across a wide range of envi-