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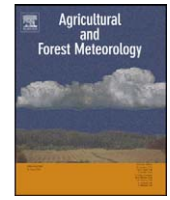

Limits to maize productivity in Western Corn-Belt: A simulation analysis for fully irrigated and rainfed conditions

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ABSTRACT

Unlike the Central and Eastern U.S. Corn-Belt where maize is grown almost entirely under rainfed conditions, maize in the Western Corn-Belt is produced under both irrigated (3.2 million ha) and rainfed (4.1 million ha) conditions. Simulation modeling, regression, and boundary-function analysis were used to assess constraints to maize productivity in the Western Corn-Belt. Aboveground biomass, grain yield, and water balance were simulated for fully irrigated and rainfed crops, using 20-year weather records from 18 locations in combination with actual soil, planting date, plant population, and hybrid-maturity data. Mean values of meteorological variables were estimated for three growth periods (pre- and post-silking, and the entire growing season) and used to identify major geospatial gradients. Linear and stepwise multiple regressions were performed to evaluate variation of potential productivity in relation to meteorological factors. Boundary functions for water productivity and water-use efficiency were derived and compared against observed data reported in the literature. Geospatial gradients of seasonal radiation, temperature, rainfall, and evaporative demand along the Western Corn-Belt were identified. Yield potential with irrigation did not exhibit any geospatial pattern, depending instead on the specific radiation/temperature regime at each location and its interaction with crop phenology. A linear and parabolic response to post-silking cumulative solar radiation and mean temperature, respectively, explained variations on yield potential. Water-limited productivity followed the longitudinal gradient in seasonal rainfall and evaporative demand. Rainfed crops grown in the Western Corn-Belt are frequently subjected to episodes of transient and unavoidable water stress, especially around and after silking. Soil water at sowing ameliorates, but does not eliminate water stress episodes. Boundary functions for water productivity had slopes of 46 and 28 kg ha^{-1} mm^{-1}, for aboveground biomass and grain yield, respectively. At high seasonal water supply, productivity was weakly correlated with water supply because many crops did not fully utilize seasonally available water due to percolation below the root zone or water left in the ground at physiological maturity. Fitted boundary functions for water-use efficiency had slopes (≈seasonal transpiration-efficiency) of 54 and 37 kg ha^{-1} mm^{-1} for aboveground biomass and grain yield, respectively, and an *x*-intercept around 25–75 mm (≈seasonal soil evaporation). Data collected from experiments conducted in low-rainfall environments indicated that the boundary functions for water-use efficiency, derived from this study, are broadly applicable.

1. Introduction

Yield potential is defined as the yield of a crop cultivar when grown in an environment to which it is adapted, with nutrient and water non-limiting and pests and diseases effectively controlled (Evans, 1993). Hence, yield potential for a given genotype is determined by the particular combination of solar radiation, temperature and plant population at a specific location (van Ittersum and Rabbinge, 1997). Yield potential can be diminished as a consequence of insufficient water supply to meet crop water demand. Thus, water-limited yield is determined by the genotype, solar radiation, temperature, plant population and the degree of water limitation (Loomis and Connor, 1992). Insufficient water supply can result from sub-optimal seasonal water supply (stored soil water plus growing-season rainfall) in rainfed systems or sub-optimal irrigation in irrigated systems. Accurate quantification of yield potential and water-limited limited yield is essential to estimate the magnitude of the exploitable gap between actual (*i.e.*, those achieved by farmers) and attainable yields, to predict global change scenarios, and to help formulate policies to ensure local and global food security (Cassman et al., 2003). The lack of data from experiments in which yield-limiting factors have been effectively

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controlled makes it difficult to obtain reliable quantifications of yield-potential and water-limited yield based on actual measurements (Duvick and Cassman, 1999). When such data are lacking, simulation models can provide reasonable estimates of yield potential and water-limited yields when soil and historical daily weather data are available, including solar radiation, daily temperature, and rainfall (*e.g.*, Amir and Sinclair, 1991a,b; Yang et al., 2004).

Although maize production is expected to increase substantially to meet the rapidly increasing demand for food, livestock feed, and biofuel at a global scale (Cassman et al., 2003; Cassman and Liska, 2007), there has been little increase in maize yield potential in the last 30 years (Duvick and Cassman, 1999; Tollenaar and Lee, 2002). Studies attempting to understand maize yield potential and its variation in relation to environmental factors have highlighted the crucial role of solar radiation and temperature (Muchow, 1989; Cirilo and Andrade, 1994; Otegui et al., 1995, 1996). A few studies have attempted to quantify yield potential and its variation at a regional scale using observed data (Duncan et al., 1973; Andrade et al., 1996) and simulation modeling (Hodges et al., 1987; Muchow et al., 1990; Wilson et al., 1995; Löffler et al., 2005). In all of these studies, maize yields were evaluated against mean meteorological variables for the entire growing season rather than specific growth phases that are most sensitive to environmental limitations (Otegui and Bonhomme, 1998). Likewise, it was not clear if the practices used at all locations were optimal for maximum attainable yield. As a result, measured or simulated yields appear to be well below maize yield potential. Finally, simulation models such as CERES-Maize (Jones and Kiniry, 1986) and the Muchow–Sinclair–Bennett model (Muchow et al., 1990) do not account explicitly for direct effects of temperature on gross carbon assimilation and respiration, which may have a significant impact on yield estimates in cool or warm environments (*e.g.*, Edmeades and Bolaños, 2001).

Water resources for agriculture are heavily exploited and there is increasing competition for limited water supplies in most countries with extensive irrigated agriculture (Rosegrant et al., 2002). Therefore, quantifying the maximum yield per unit of available water supply, hereafter called the water-limited yield, is essential for identifying water management practices and policies to optimize water-use efficiency (Wallace, 2000). Boundary functions provide a robust framework to analyze water-limited productivity (*e.g.*, French and Schultz, 1984; Passioura, 2006; Sadras and Angus, 2006). Yield is plotted against either: (i) water supply (stored soil water at sowing plus rainfall), or (ii) crop evapotranspiration (ET_C), on a seasonal basis, and a linear function is fitted to those data that delimit the upper frontier for yield. The first approach, namely water productivity (WP), provides a benchmark to help farmers set target yields and identify other yield reducing-factors, such as nutrients, pests, and diseases (Passioura, 2006). The second approach based on ET_C, namely water-use efficiency (WUE), provides a physiological frontier for water-limited productivity in which the slope represents the seasonal transpiration-efficiency (TE_S) and the *x*-intercept gives a rough estimate of seasonal soil evaporation (Sinclair et al., 1984). Despite the large number of reported yield/water supply relationships reported for maize, we were not able to find any explicit attempt to define maximum boundary functions for water productivity or water-use efficiency.

To fill this knowledge gap about maize productivity and its variability, we used a crop simulation model (Yang et al., 2004), regression and boundary function analysis to assess limits to maize aboveground biomass and grain yield in the Western Corn-Belt. The primary objectives of this work were to: (i) identify geospatial patterns of radiation, temperature, rainfall, reference evapotranspiration, and water-stress; (ii) explain geospatial variations in potential and water-limited productivity in relation to these climate variables; and (iii) determine boundary functions for water productivity and water-use efficiency.

2. Materials and methods

2.1. The Western Corn-Belt

The Western U.S. Corn-Belt (37–45°N; 92–105°W) includes about 7.3 million ha cultivated with maize, mostly located in Kansas, Nebraska, and South Dakota states (Fig. 1) (USDA-NASS, 2003–2007). Irrigated maize represents 43% of the total maize area (70% of the total irrigated cropland in the region) and accounts for 58% of the total annual maize production of 60 million Mg in the Western Corn-Belt. Average county-level yields range from 2.4 to 8.1 Mg ha^{-1} under rainfed conditions, and from 8 to 11.2 Mg ha^{-1} with irrigation. These values are well below the highest reported yields for rainfed (9–16 Mg ha^{-1}) and irrigated maize (15–21 Mg ha^{-1}) in the region (Duvick and Cassman, 1999).

Soil and climate in the region are described by Smika (1992). The landscape is undulate. Predominant agricultural soils are Haplustolls and Argiustolls with medium-to-high water holding capacity. Elevation increases by 118 m per longitude degree, from east to west (range: 309 m in Ames, IA to 1384 m in Akron, CO). The climate is continental and temperate, and the frost-free period decreases from the southeast to the northwest along the altitudinal gradient. Annual rainfall decreases from east to west, and its distribution follows a monsoonal pattern: 70–80% of the precipitation is concentrated in the spring and summer seasons. Evaporative demand exceeds rainfall during the summer growing-season such that most rainfed crops depend on stored soil moisture that accumulates from snow melt and spring rains (Loomis and Connor, 1992).

2.2. Model evaluation

Hybrid-Maize (Yang et al., 2004, 2006) is a process-oriented model that simulates maize development and growth on a daily time step under growth conditions without limitations from nutrient deficiencies or toxicities, or from insect pests, diseases, or weeds. It features temperature-driven maize development, vertical canopy integration of photosynthesis, organ-specific growth respiration, and temperature-sensitive maintenance respiration.

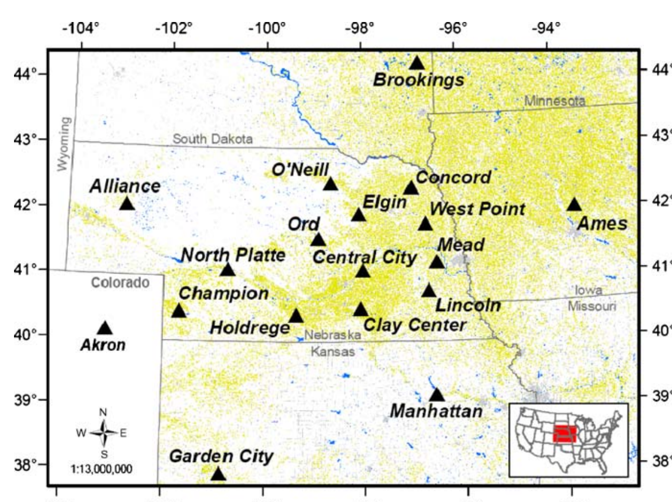

Fig. 1. Map of the Western U.S. Corn-Belt. States are named and their boundaries shown. Triangles indicate sites of meteorological stations used in this study. Inset shows location of area within U.S. Maize (yellow), water (blue), and urban (grey) areas are shown, except for Wyoming and Colorado (data not available).