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Plot-scale modeling of soil water dynamics and impacts of drought conditions beneath rainfed maize in Eastern Nebraska

Paolo Nasta*, John B. Gates

Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln, Lincoln, NE, USA

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ABSTRACT

Intermittent drought periods pose major challenges to the management of rainfed agricultural systems because their productivity is sensitive to water stress during crop development. The objective of this study was to assess soil water dynamics and crop stress patterns during the drought year of 2012, which was among the most severe on record in the US Corn Belt. The study utilized a continuous matric potential profile monitoring record from June 2008–December 2012 beneath a rainfed corn plot in Eastern Nebraska to provide a direct comparison of the 2012 growing season with moderate to relatively wet periods within 2008–2011. The analysis was based on a transient unsaturated zone model that was calibrated with laboratory-measured water retention functions and matric potential measurements from heat dissipation sensors. In each year of the model simulation, soil water storage volumes steadily decreased during the growing season and increased episodically following precipitation events outside of the growing season. Precipitation during the 2012 growing season was <50% of the mean for growing seasons 2009–2012 consequently, soil water storage loss during 2012 was ~14% of initial storage in comparison to 8–9% in 2009–2011. Model results suggest that the 2012 soil water deficit was partially buffered by upward flux of deep soil moisture, with approximately 17% of root water uptake in 2012 deriving from moisture redistributed from below the root zone. Nevertheless, root zone matric potentials exceeded the crop wilting point ($\psi = -8000$ cm) in 2012 for the first time within the monitoring record. These results highlight the need for heightened attention to drought resilience of rainfed cropping systems given future climate predictions that involve increase rainfall intermittency.

1. Introduction

Current and future rates of global food production are highly dependent upon the productivity of rainfed agriculture. As of 2000, approximately 75% of global harvested agricultural area and 66% of total cereal crop production was associated with rainfed agriculture (Portmann et al., 2010). Although typically less productive in terms of crop yield per unit area than irrigated systems (Bruinsma, 2003; Siebert and Döll, 2010), it is likely that rainfed crop production will account for a significant percentage of future gains in global food yields (Rosegrant et al., 2002). One key factor that affects the continued importance of rainfed agriculture is that water supply for large-scale irrigation is likely to become increasingly scarce in many regions. Long-term declines of groundwater storage volumes have been widely documented in many irrigated basins (McGuire, 2009; Scanlon et al., 2012; Aeschbach-Hertig and Gleeson, 2012), and recent estimates have suggested that global groundwater extractions exceed sustainable levels by a factor of two or more on average globally, with much higher values apparent in several major agricultural regions (Wada et al., 2010; Gleeson et al., 2012). Thus, optimizing crop yields of rainfed systems is critical for both meeting future global food security goals and sustaining freshwater resources.

Rainfed production of corn (*Zea mays* L.) in the United States plays an important role in global grain supply given that >50% of global corn exports derive from the US and that approximately 60% of planted corn area in the US is currently managed under rainfed conditions (USDA/NASS; http://www.nass.usda.gov/; last accessed 12 December 2012). Mean annual rainfall generally decreases from east to west across the US Corn Belt, and as a result the spatial distribution of rainfed cultivation is largely centered upon central and eastern areas where seasonal water availability (from residual soil moisture and precipitation during the growing season) is greatest. Although rainfed crop yields per hectare in these areas are often amongst the world's highest (FAOSTAT 2010 data, http://faostat.fao.org; last accessed 12 December 2012; Kucharik and Ramankutty, 2005), yields can be sharply reduced

Abbreviations: RWU, root water uptake; RMSE, root mean squared error; DOY, day of year; GS, growing season; WY, whole year.

* Corresponding author. Tel.: +1 4028906874.
E-mail address: paolo.nasta@unina.it (P. Nasta).

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Nomenclature

α	water retention shape parameter, cm^{-1}
a	empirical coefficient in Eq. (5), $cm\,d^{-1}$
b	empirical coefficient in Eq. (5), –
β	transpiration efficiency function, –
D	water drainage, $cm\,d^{-1}$
ε	soil porosity, $cm^3\,cm^{-3}$
E_a	actual evaporation, $cm\,d^{-1}$
E_p	potential evaporation, $cm\,d^{-1}$
ET_0	reference potential evapotranspiration, $cm\,d^{-1}$
ET_c	maize potential evapotranspiration, $cm\,d^{-1}$
H_r	relative humidity, –
K	hydraulic conductivity, $cm\,d^{-1}$
κ	extinction coefficient, –
K_c	crop coefficient, –
K_s	saturated hydraulic conductivity, $cm\,d^{-1}$
LAI	leaf area index, $cm^2\,cm^{-2}$
m	water retention shape parameter, –
n	water retention shape parameter, –
P	gross precipitation, $cm\,d^{-1}$
Q	cumulative water flux, cm
R	net rainfall, $cm\,d^{-1}$
ρ_b	dry bulk density, $g\,cm^{-3}$
RI	rainfall interception, $cm\,d^{-1}$
R_n	net solar radiation, $MJ\,m^{-2}\,d^{-1}$
T	air temperature, °C
τ	tortuosity parameter, –
t	time, d
T_a	actual transpiration, $cm\,d^{-1}$
T_p	potential transpiration, $cm\,d^{-1}$
WS	water storage, cm
W_{sp}	wind speed, $m\,s^{-1}$
ψ	soil matric potential, cm
ψ_{max}	maximum allowed soil matric potential, cm
ψ_{min}	minimum allowed soil matric potential, cm
ψ_{obs}	observed soil matric potential, cm
ψ_{sim}	simulated soil matric potential, cm
ψ_{surf}	surface soil matric potential, cm
z	soil depth, cm
z_r	root zone depth, cm
θ	soil water content, $cm^3\,cm^{-3}$
θ_r	residual water content, $cm^3\,cm^{-3}$
θ_s	saturated water content, $cm^3\,cm^{-3}$

in situations where drought periods coincide with the growing season (Schlenker and Roberts, 2006; Grassini et al., 2009).

In 2012, the Corn Belt region was affected by the most severe drought to affect US agriculture in at least 25 years (USDA/ERS, http://www.ers.usda.gov; National Drought Mitigation Center, http://droughtmonitor.unl.edu, last accessed 12 December 2012). The transition from approximately 50 cm of precipitation in the 2011 growing season to 24 cm of precipitation in the 2012 growing season at the study site (High Plains Regional Climate Center; http://www.hprcc.unl.edu/maps/normals/; last accessed 10 December 2012) offers an excellent opportunity to gauge how soil water dynamics respond to temporal extremes in rainfall. This topic has high relevance for the resilience of rainfed agricultural systems with respect to climatic variability and drought (Rockström et al., 2004; Cooper et al., 2008; Rockström et al., 2009). In particular, recent modeling projections have suggested that future climatic conditions may include increased frequency and severity of extreme weather events (IPCC, 2007). Therefore, field investigations under extremes of moisture availability are desirable in order to gain a better understanding of how soil water and crop yields are affected by rapid climatic variability. Also, in cases where crop yields may strongly benefit from relatively small investments in supplemental irrigation during dry spells, detailed assessment of soil water dynamics can help to refine amounts and timing of water applications (Rockström et al., 2004).

The primary aim of this study was to assess plot-scale soil water dynamics and temporal patterns of crop water stress beneath rainfed corn during the 2012 drought-affected growing season in comparison to previous years (2008–2011). The study utilized near-continuous unsaturated zone profile matric potential monitoring in order to support transient modeling of soil water dynamics within and below the root zone. Monitoring of soil moisture and matric potentials has been widely used to characterize soil water availability beneath rainfed corn on a range of spatial scales (Assouline et al., 2012; Irmak et al., 2012; Li et al., 2012). Development of hydrologic flux estimates from matric potentials (e.g. partitioning the soil water budget into redistribution, drainage, evaporation and transpiration) further requires characterization of hydraulic properties of the vadose zone and crop physiological parameters that affect root water uptake (Feddes et al., 2004; Bastiaanssen et al., 2007). Although many previous studies have investigated soil water dynamics under irrigated corn using transient modeling with the Richards equation (recent examples from this journal include Panda et al., 2004; Chen et al., 2010; Mastrocicco et al., 2010), to our knowledge, this is the first reported modeling of root zone soil water dynamics under rainfed corn production to utilize continuous profile matric potential monitoring with heat dissipation sensors. Also, as a forward unsaturated zone modeling application, the study incorporates an uncommon level of detail in field measurements available for calibration and validation, including multiple years of hourly matric potential measurements at several depths within and below the root zone, local weather data, and layered unsaturated hydraulic properties determined by laboratory measurement (rather than pedotransfer functions, which have a higher degree of uncertainty).

2. Materials and methods

2.1. Study location

The study site is located within a rainfed (non-irrigated) field in Eastern Nebraska (near the town of Oakland, Burt County; 96.53° E, 41.83° N; 415 m a.s.l.) within an area of rolling terrain associated with glacial till and stream dissection of overlying loess units. Mean annual precipitation is about 66 cm/year from 1982 to 2012 (data for December 2012 incomplete at the time of writing), and local monitoring records show significant interannual variability in annual precipitation, ranging between 23 cm in 1983 and 105 cm in 1982 and a variation of approximately 4 °C in average annual temperature, ranging between 7.1 °C in 1996 and 11.5 °C in 2012 (Fig. 1a). Annual precipitation disproportionately occurs in spring and early summer (the wettest months are typically April, May and June; Fig. 1b).

2.2. Field and laboratory measurement methods

Heat dissipation matric potential sensors (model number 229L, Campbell Scientific, Pullman, WA) were installed in a vertical profile in the unsaturated zone on 5 June 2008 (depths 30, 61, 91, 152 and 244 cm). The heat dissipation sensor method was chosen over other widely-used methods, such as field tensiometry, for the combined reasons of (1) measurement range and (2) suitability for long-term monitoring. In contrast to tensiometric measurements, heat dissipation sensors have the distinct advantage of not needing