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A long-term analysis of the historical dry boundary for the Great Plains of North America: Implications of climatic variability and climatic change on temporal and spatial patterns in soil moisture

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ABSTRACT

The boundary between the humid eastern and the arid western regions of the Great Plains of North America is of great economic interest and historic intrigue, yet its location is controversial. Areas to the east of this boundary have historically enjoyed the benefits of fertile soil coupled with more favorable rainfall and reliable surface water, permitting conventional agriculture to flourish over a remarkably large percentage of the eastern Great Plains. The expansion of population and agriculture during the nineteenth century across the western Great Plains tested the extent that non-irrigated, row crop agriculture could be successful in areas where year-to-year rainfall was unreliable. In this paper, we quantify the historic annual variability of soil moisture and hydrologic conditioning in the Great Plains resulting from climatic variability, show the regions that historically demonstrate unreliable precipitation, and identify the extent of arid regions of the central United States based on modeled annual soil moisture variability. We asked how arid climates have influenced soil formation patterns at small cartographic scales, and how soil properties buffer or enhance soil moisture regimes (at the udic–ustic boundary) to climate variability at larger cartographic scales. At small cartographic scales, a climate-only model worked nearly as well as a climate-and-soils model in mapping the region's soil moisture boundary; however, a climate-only model missed important local soil influences. Finally, we demonstrate that long-term climate and climate variability are reflected in the depth and concentration of the calcic soil properties. From a practical standpoint, our work highlights that soils with higher water holding capacity dampen periodic short-term rainfall deficits, while soils with lower water holding capacity can exhibit edaphic drought during otherwise normal climate years.

1. Introduction

In John Wesley Powell's landmark 1878 report on the arid lands of the Western United States, he wrote that when moving across the Great Plains from east to west at approximately the midway point of the United States there begins a region “so arid that agriculture is not successful without irrigation” (Powell et al., 1879). Powell deemed this boundary between the humid region and the arid regions corresponded with the 20-inch (50.8 cm) isohyet of annual precipitation, assuming that precipitation was evenly distributed throughout the year. Today, the 20 inch isohyetal boundary would be considered arbitrary because it does not consider differences in evapotranspiration associated with temperature gradients from south to north or the seasonal distribution of precipitation in the Great Plains where more precipitation falls during spring and summer months of the year (Hoerling et al., 2014). The 20 inch isohyetal boundary, falling approximately along the 100th Meridian, does however, approximate the normal westward reach of moist air from the Gulf of Mexico due to the interaction of upper level air masses from the Pacific Ocean and surface outflow from the Gulf of Mexico (Forman et al., 2001).

Settlement of the North American Great Plains began at the end of the American Civil War with agricultural lands encroaching on the 100th Meridian by the 1870s (Lewis, 1966). Since Powell's report on the western lands, agroecosystems have expanded westward well beyond the 20-inch isohyetal line of annual precipitation, resulting in drastic impacts on the historic native landscape (Libecap and Hansen, 2002). Increased exploitation of the pedosphere by human activity

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marks a turning point in our history where agriculture has grown to become the primary impact on Great Plains ecosystems. As soil properties are the key integrator of long-term climate for agroecosystems (Parton et al., 1987), it is important to recognize changes in soil climate zones during this period.

The dramatic expansion of agricultural activities in the 20th Century across the Great Plains has made the potential response of soil moisture to climate change of interest to land managers and policy makers. In particular, the frequency, duration, and depth of droughts are of interest, given the history of severe drought in the region during the 1930s, 1950s, 1980s, and most recently in 2012–2013. Extreme drought conditions occurring in many portions of the Great Plains in the past decade have stimulated research on the ecosystem consequences of more frequent summer droughts and increases in temperature within this region resulting from broader global increases in temperature. This work has shown that the Great Plains are becoming increasingly vulnerable to drought due to an increase in the cultivation of marginal lands and the depletion of groundwater from the Ogallala Aquifer (Little, 2009; Steward et al., 2013). Climate models vary regarding projections of annual precipitation trends in the region (IPCC, 2014), but there is a general consensus that variability in the hydrological cycle is intensifying—with the most likely future climatic scenario predicting an increase in the frequency of extreme precipitation events and greater inter-annual variation in precipitation (IPCC, 2014).

One of the early attempts to classify soils in the United State divided them at the highest level into pedocals and pedalfers (Marbut, 1935). The pedocal–pedalfer soil boundary was defined as a zero line where mean annual precipitation and evapotranspiration were equal (Jenny, 1994). Pedocal soils were distinguished by the assumption of an accumulation of calcium and magnesium in the form of pedogenic carbonates in arid or semi-arid regions, while pedalfer soils were identified by the absence of carbonates and were enriched in aluminum and iron sesquioxides in humid regions. The now generally antiquated terms of pedocal and pedalfer are still used in quaternary geology and soil geomorphology to distinguish arid and humid soil climatic zones (Monger and Martinez-Rios, 2000). The boundary between the semiarid and humid climate regimes also still exists in U.S. Soil Taxonomy at the suborder level, and a basic wet-dry categorization has evolved into the modern soil moisture regime's conceptual framework (e.g., udic, ustic, and aridic). However, soil moisture classes were originally based on their agricultural usage (Forbes, 1986). For example, aridic soils are defined as typically too dry to support crops without irrigation, ustic soils support crops that are drought tolerant, and udic soils do not require irrigation to successfully grow crops.

The udic–ustic soil moisture boundary is of interest to biogeographers as it approximates the boundary between the Bluestem Prairie and the Mixed Prairie (Küchler, 1964). Biogeographers in general have long sought the identification of boundaries between ecosystems using vegetation zones or indicator species to approximate ecosystem boundaries (Küchler, 1970); however, soil geographers cannot rely only on the vegetation to define ecological regions due to compensation factors in the soil that override the climatic effect on vegetation (Bailey, 2004). It is also likely that there is a lag time between vegetative response to climate and climate's manifestation in pedogenic features. These ecotonal transition zones are also of interest for other reasons. Within these transitional climatic zones soils with lower water holding capacity are subject to edaphic (soil-related) droughts during normal years (Herrick et al., 2013), just as soils with higher water holding capacity (as well as an increased organic matter and improved soil structure) have the potential to buffer the effects of droughts on soil moisture (Lal, 2015; Strickland et al., 2015).

The goals of this study are to (1) quantify regional inter-annual variability in the position of the calcareous and noncalcareous (pedocal–pedalfer) boundary on the Great Plains based on historical climatic data and soil moisture, (2) consider if soil landscapes with low water holding capacities are more sensitive to changing climate drivers, and (3) model the depth and concentration of calcic soil horizons as they relate to variability in the annual water balance. With these data, we can identify a generalized western limit in North America beyond which agroecosystems either have to be drought tolerant or irrigated to reliably and economically grow crops. In addition, we investigated the possibility that long-term climate patterns are reflected in edaphic properties, and that soils with higher water holding capacity can dampen inter-annual water deficits. We calculated annual continental scale soil water balance across the Great Plains using soil moisture models based on monthly precipitation and temperature data from 1895 to 2014. With the national Soil Survey Geographic (SSURGO) database (Soil Survey Staff, 2015) we then looked at the relationship between annual water balance, water holding capacity, and calcic soil properties. We hypothesized that (1) soils with lower water holding capacity (e.g., coarse textured soils with low organic matter) are more susceptible to changing climate drivers and short duration drought events, and (2) the increasing depth and concentration of calcic horizons is positively coupled with negative long term climatic soil water balances.

2. Materials and methods

2.1. Geographic setting

Soil scientists have long recognized that the Great Plains Region of North America (30°–50°N, 105–95°W) is an exceptional natural experiment in the role of climate as a soil-forming factor (Arkley, 1963; Jenny, 1994; Retallack, 2005; Ruhe, 1984) with east-to-west precipitation gradients and north-to-south temperature gradients driving soil formation processes. While climate varies markedly across the region, the variations of other soil formation factors are relatively modest (Retallack, 2005), due to the soil's age (consistently younger than 14ka), uniform surficial loess parent material, rolling-to-flat topography, and historically ubiquitous grassy plant communities. With this natural arrangement, the role of climate in the soil formation of the Great Plains can generally be interpreted along climatic gradients, displaying increasing temperatures from north-to-south and increasing moisture from west-to-east, allowing a coupled hydrologic and climatic model to reliably characterize soil moisture regimes from the climate record. Long-term (millennial scale) climate patterns imprint pedogenic properties on the soil (Monger and Rachal, 2013), allowing scientists to recognize long-term soil moisture regimes through an evaluation of the soil pedon, or more broadly, to derive soil moisture classes (for taxonomic classification purposes) from climatic data using deterministic soil moisture models as currently practiced in the United States (Newhall and Berdanier, 1996; Van Wambeke et al., 1986).

2.2. Newhall simulation model

The Newhall simulation model (NSM) was used to compute soil moisture regimes according to methodology used in USDA Soil Taxonomy (Newhall and Berdanier, 1996; Soil Survey Staff, 2014). The NSM simulates monthly water balance patterns of soil moisture in relation to the soil moisture control section (MCS) as a means to define the taxonomic class of soil climate. The MCS of the soil is defined by an upper boundary to which a dry soil (>1500 kPa tension, but not air-dry) will be “moistened” by 2.5 cm of water within 24 h and a lower boundary where the depth to which a dry soil will be moistened by 7.5 cm of water within 48 h (Soil Survey Staff, 2014; Zobeck and Daugherty, 1982). The stepwise NSM simulates downward movement of moisture into the soil profile based on the amount of water needed to bring all the soil above field capacity. Rate of soil water depletion depends on energy available for moisture extraction through calculated potential evapotranspiration. Soil water gains and losses are limited to the soil's water holding capacity, expressed as the difference between field capacity and permanent wilting point.