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Enhancing soil drought induced by climate change and agricultural practices: Observational and experimental evidence from the semiarid area of northern China

Jingting Zhang[a,b,c], Jia Yang[c], Pingli An[a,b,*], Wei Ren[d], Zhihua Pan[a,b], Zhiqiang Dong[a,b], Guolin Han[a,b], Yuying Pan[a,b], Shufen Pan[c], Hanqin Tian[c,e]

[a] College of Resources and Environmental Science, China Agricultural University, Beijing 100193, China
[b] Key Ecology and Environment Experimental Station of the Ministry of Agriculture for Field Scientific Observation in Hohhot, Wuchuan, Hohhot 011705, China
[c] International Center for Climate and Global Change Research, Auburn University, Auburn, AL 36849, USA
[d] Department of Plant & Soil Sciences, College of Agriculture Center, Food and Environment, University of Kentucky, Lexington, KY 40506, USA
[e] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

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ABSTRACT

Increased water scarcity has led to a decade-long soil drought in the semiarid area of northern China, which caused food insecurity in this region. However, there is a lack of sufficient observational evidence about how climate change and agricultural practices have interactively affected this soil drought. Long-term *in situ* soil moisture measurements collected in agricultural experimental plots indicate that the mean temperature and precipitation during the growing season have reduced soil moisture by 11.2%, and agricultural practices have aggravated the soil drying trend in the 0–100 mm soil layer over the past three decades. Our results also show that planting water-expensive crops (*e.g.*, potato and maize) may aggravate soil drought. Crop rotation increases soil water consumption by 8.9–12.6% over continuous cropping. Excessive fertilizer use increases water consumption by 25.4–46.9% and decreases the water use efficiency (WUE) by 14.6–35.3%, while tillage accounts for the consumption of 10.3% more soil moisture than no-tillage. Our results indicate that agricultural practices, including crop rotation, a high fertilizer input, and tillage, may increase water consumption and aggravate soil drying. Our findings call for effective strategies for mitigating soil drought in semiarid regions, such as an adjustment of the cropping system, reduced fertilizer use, and improved conservation tillage.

1. Introduction

Droughts have become more intense and frequent since the 1980s in the context of climate change (Trenberth et al., 2014), especially in the semi-arid regions of the Northern Hemisphere (Wetherald and Manabe, 2002). Previous studies have suggested that the intensification of agricultural activities can change the dynamics of soil moisture due to its impact on infiltration, permeability, the water holding capacity and the moisture loss rate of the soil (Shaxson and Barber, 2003). Climate change and agricultural intensification may cause soil drought when available water in soil layers is lower than crop water demand (Leng et al., 2015; Sheffield and Wood, 2008). Soil drought may further deteriorate to agricultural drought, during which water shortages under a threshold last for an extensive period (Wang et al., 2011a). Agricultural drought is usually associated with crop reduction or failure, leading to a more direct and immediate impact on crop production than climatic stresses (Wang et al., 2011b; Ren et al., 2012; Leng et al., 2015).

China has frequently been affected by droughts due to substantial interannual and decadal variations in precipitation and temperature (Ma and Fu, 2003; Dai et al., 2004; Tian et al., 2016). The average grain loss associated with agricultural drought is approximately 39.2 billion kg/year, and since 1978, the average economic loss has accounted for 1.47% of the country's gross domestic product (Leng et al., 2015; MWRC, 2011). Northern China is home to 40% of the Chinese people, and it contains as much as 65% of China's arable land (PCOC, 2011; Liu et al., 2015), but only has 18% of China's water resources (Wang et al., 2011a; Ma and Fu, 2006). This water scarcity is even more severe in the semi-arid region of northern China (SANC) due to its ecological vulnerability and sensitivity to climate change (Deng et al., 2006; Seneviratne et al., 2010; Tian et al., 2016). People tend to use large amounts of water for enhancing food production. However, it has

* Corresponding author at: College of Resources and Environment Sciences, China Agricultural University, No. 2, Yuan Ming Yuan West Road, Haidian, Beijing 100193, China.
E-mail address: anpl@cau.edu.cn (P. An).

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induced severe environmental problems such as water and soil loss, desertification, grassland degradation, soil salinity, and land subsidence (Li et al., 2015; Liu et al., 2015). From both food and ecological security perspectives, therefore, it is critical to investigate the effect of climate change and agricultural practices on soil drought for mitigating agricultural drought and associated ecological problems.

Previous studies investigated the impact of climate change on soil moisture *via* either model simulations or satellite-retrieved soil moisture data (*e.g.*, Holsten et al., 2009; Piao et al., 2010; Dorigo et al., 2012). Indications are that the warming and drying trends may lead to changes in evapotranspiration (Thomas et al., 2000; Pan et al., 2015) and crop water demand (Tao et al., 2003), thereby reducing soil moisture and aggravating soil drought. For example, Holsten et al. (2009) found that warming decreased soil moisture by 4–15% in nature conservation areas in Brandenburg, Germany during 1951–2003 and that future climate change is expected to lead to a further decrease in soil moisture. Wang et al. (2011a) found that soil moisture droughts have become more severe, prolonged, and frequent during the past 57 years in the context of global warming, especially in northeastern and central China, which shows increased susceptibility to soil drought. Some studies have suggested that agricultural practices (*e.g.*, crop type selection, farming measures, fertilizer application, and irrigation management) may affect water use efficiency and soil moisture dynamics by changing the physical and biogeochemical processes of ecosystems (Alley et al., 2003; Rosenzweig et al., 2008; Tian et al., 2011). For example, the vegetation type has a strong effect on soil moisture dynamics (Holsten et al., 2009). Fertilizer use can increase transpiration, deplete soil moisture, and lead to soil drought in rain-fed agriculture regions (Gaiser et al., 2004; Huang et al., 2003).

While previous studies have investigated the effect of rainfall or warming on model-simulated or satellite-retrieved changes in soil moisture (Dorigo et al., 2012; Trenberth et al., 2014), long-term *in situ* observation/experiment-based assessments of soil moisture dynamics as affected by climate change are lacking. Moreover, the regional impacts of intense agricultural practices remain poorly understood. Therefore, an investigation of the mechanisms of soil drought in the SANC is crucial for food security and agricultural sustainability, and can provide useful insight into the mitigation of soil drought in semiarid regions. Our research objectives were to (1) investigate the impact of temperature and precipitation on soil moisture using long-term *in situ* observational climate and soil data collected from the National Agrometeorological Experimental Stations across the SANC during 1981–2010, and (2) to analyze the impacts of agronomic practices (*i.e.*, crop type selection, cropping pattern, fertilizer level, and conservation tillage) on soil drying *via* five field experiments conducted at the Wuchuan county experimental station from 2008 to 2014. We used volumetric soil moisture (VSM, %), water consumption (mm), and water use efficiency (WUE, g m^{-2} mm^{-1}) to quantify soil drought in this study.

2. Materials and methods

2.1. Study region

The SANC (Fig. 1) consists of parts of the Provinces Shanxi, Shaanxi, Heilongjiang, Jilin, Inner Mongolia, Hebei, Ningxia and Gansu (Zhao et al., 2002). Wuchuan County (approximately 40°47′–41°23′N, 110°31′–111°52′E) is located in the SANC with a temperate continental climate (Hu et al., 2014). The average annual precipitation (1960–2014) is approximately 342 mm, and more than 80% of the total annual precipitation occurs during the crop growing season from April to September. The accumulated temperature above freezing point is 2578 °C d. The frost-free period is approximately 124 days. The grain fulling stage (June–August) is associated with higher temperatures and precipitation. The soil type is mainly chestnut with high sediment concentrations in the arable layer (Zhang et al., 2015). The cropland in the study area is cultivated rain-fed fields without irrigation. All short-term experiments were conducted in the Scientific and Observing Experimental Station of the Agro-environment (SOESA) in Wuchuan County during 2008–2014.

2.2. Data source and experimental design

To analyze the impact of climate change on soil moisture, daily meteorological data (daily mean temperature and precipitation) during 1981–2010 were collected from 46 climate stations at the National Meteorological Networks of China Meteorological Administration (CMA). These sites are also Agrometeorological Experimental Stations (AESs) that collect long-term observational data of soil moisture, which was measured in the 0–50 cm soil layer in grasslands, croplands and mono-cropped fields (Table S1). Soil moisture in each field was measured by the gravimetric method in five soil layers (0–10, 10–20, 20–30, 30–40, and 40–50 cm) at the beginning (8th), middle (18th), and end (28th) of each month. The gravimetric method is the only direct method for measuring soil moisture and is indispensable for calibrating instruments used in indirect methods (Reynolds, 1970) (*e.g.*, automated probes). Although the results from the gravimetric method are affected by stones, the organic matter content, *etc*. in the sample, and unavoidable repeated sampling damages plant roots and changes the soil infiltration characteristics (Reynolds, 1970), the response of soil moisture (0–50 cm) measured by the gravimetric method to temperature and precipitation can be determined more accurately than that with automatic techniques (Wang et al., 2010; Hu et al., 2014). Moreover, the gravimetric method has been used to measure soil moisture by the AESs since the 1970s (Wang et al., 2010) so long-term (*i.e.*, more than 20 years) soil moisture data can be used to analyze soil moisture changes. We used soil moisture measured in grassland (6 sites) as the control variable. Soil moisture data measured in croplands covered with different crops during 1981–2010 was to analyze the impact of climate change on soil moisture in croplands. Mono-cropped fields include soybean (*Glycine max* (Linn.) Merr.) (3 sites), potato (*Solanum tuberosum*) (13 sites), sugar beet *(Beta vulgaris)* (3 sites), naked oats *(Avena nuda)* (3 sites), wheat (*Triticum aestivum*) (27 sites), and maize (*Zea mays* L.) fields (27 sites). Soil moisture in the mono-cropped fields was used to compare the impacts of the different crop types. Detailed information of mono-cropped fields is shown in Table S2.

To explore the effects of agricultural practices on soil moisture, short-term *in situ* soil moisture data (2008–2014) along with detailed management and yield data were measured in three experiments (see Table 1).

- Continuous-rotation cropping experiment. We designed a control treatment in grassland with No Tillage and No Fertilization (Control-NoT-NoF) and two group Continuous/Rotation cropping treatments in crop fields with Tillage and basal Fertilizer in 2008–2013. The continuous cropping experiment included potato (*Solanum tuberosum* Cv. Zi Huabai) continuous cropping (P-C-T-bF), millet (*Setaria italica* (L) Beauv. Cv. 5th Xingu) continuous cropping (M-C-T-bF), rapeseed (*Brassica rapa (campestris)* L. Cv. 7th Longyou) continuous cropping (Ra-C-T-bF). The crop rotation is the practice of growing a series of dissimilar or different types of crops in the same area in sequenced seasons (Bullock, 1992). The crop rotation experiment in the study included a potato-millet rotation (P-MR-T-bF, M-PR-T-bF) and a potato-rapeseed rotation (P-RaR-T-bF, Ra-PR-T-bF). Basal fertilizer was applied before sowing with ammonium dihydrogen phosphate (75 kg/ha) and urea (90 kg/ha), and no extra fertilizer was applied during the crop growth period.
- Fertilizer gradient experiment (see Table S3). Potato (*Solanum tuberosum* Cv. 1th Kexin) continuously cropped with tillage and different fertilizer gradients (P-C-T-gF) were implemented from 2008 to 2010. We designed a control treatment (no fertilizer, P-C-