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Soil water storage compensation potential of herbaceous energy crops in semi-arid region

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ABSTRACT

Large-scale vegetation construction has generally led to soil desiccation in arid and semi-arid regions. Energy crops with high biomass and water use efficiency are generally beneficial to agriculture and the environment. It is necessary to understand how to maintain the dynamic balance of soil moisture and biomass production on herbaceous energy croplands. In this study, soil moisture data at different depths of soil were obtained from long-term field observations for two energy crops, i.e., *Panicum virgatum* and *Miscanthus sinensis*, and a forage crop-*Medicago sativa*. Relative aridity of the soil and plant biomass were compared among different vegetation types, transects, and cultivation years. *Medicago sativa* soil was severely, even extremely, desiccative with increasing cultivation years, whereas there was nearly no desiccation in the soil of energy crops. The values of compared soil water storage compensation indexes in deep soil layers were higher than those in shallow soil layers, with the evaluated soil water storage compensation index being the smallest in the 40–80 cm layer. Energy crops had significantly higher aboveground biomass, mostly exhibiting more than 2.6 kg m^{-2}, while the aboveground biomass of *M. sativa* was only above 0.5 kg m^{-2}. Furthermore, the water use efficiencies of energy crops were obviously higher than that of *M. sativa* ($P < 0.05$). Our results indicated that deep soil moisture conditions were mainly determined by field crop types. Energy crops may be suitable candidates for compensating soil water storage and maintaining high biomass production in semi-arid regions.

1. Introduction

Large-scale vegetation construction has generally led to soil desiccation in arid and semi-arid regions. In addition to woodland, some artificial grasslands resulted in soil desiccation and degradation. *Medicago sativa* is one of the most important forage crops in the world because of its high nutritive value, drought-resistance and good adaptability to rigorous climate and poor soil conditions. Therefore, it is now the most widely promoted species for artificial grasslands, especially in arid and semi-arid regions (Li et al., 2007). It has been estimated that over one million ha of farmlands are cultivated with *M. sativa* in China, accounting for three-quarters of the total area of artificial grasslands in China. However, water scarcity is the key limiting factor for increasing grassland production in semi-arid regions. It has been reported that *M. sativa* can aggravate soil water consumption, gradually lead to soil desiccation, and even result in dry soil layers (Li, 2001; Shangguan and Zheng, 2006; Chen et al., 2008a; Jia et al., 2015, 2017; Huang et al., 2018). Soil desiccation generally occurs below the depth of soil affected by rainfall infiltration, it greatly reduces grassland productivity, and even leads to land loss (Li, 2001; Jia et al., 2015). Desiccation is usually caused by excessive consumption of deep soil water by vegetation when there is not enough precipitation (Huang et al., 2018). Several previous studies have indicated that it is hard to alleviate the problem of soil water shortage in a short period of time once soil desiccation occurred, even if the mode of land use is changed (Chen et al., 2008a; Huang and Gallichand, 2006; Jia et al., 2017; Huang et al., 2018).

Soil is one of the most important components of biological and geochemical cycles determining the transport processes of matter and energy (Keesstra et al., 2016; Kirchhoff et al., 2017). The UN has

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defined the Sustainable Development Goals and called for a sustainable use of resources, ecosystem restoration, biodiversity, carbon sequestration, and sustainable catchment management (Griggs et al., 2013; Keesstra et al., 2016). Restoration and rehabilitation strategies based on natural processes and cycles are sustainable as they use natural flows of matter and energy, and follow the seasonal and temporal changes of the ecosystems (Meli et al., 2014; Keesstra et al., 2018). There are proposals to use weeds or catch crops as a part of land greening in organic farming (Kirchhoff et al., 2017; Cerdà et al., 2018). The development of energy crops (i.e., herbs cultivated for providing feedstock for energy production – from direct combustion to liquid fuel production) has recently reshaped the agricultural production throughout the world fundamentally (Kaczmarek and Tryjanowski, 2016). Energy crops with low inputs, low water requirements, and highly efficient solar energy conversion resulting in high yields, are beneficial to agriculture and the environment (Venturi and Venturi, 2003; Alexander et al., 2014). Moreover, herbaceous energy crops also contribute more to ecosystem services such as soil and water conservation (Liu et al., 2012), and there is a great potential for energy crop production due to the existence of large areas of marginal lands which are not suitable for conventional agricultural production. Kaczmarek and Tryjanowski (2016) suggested that energy crops partly regulating soil water moisture could be planted on degraded lands which are not suitable for traditional agriculture. Growing energy crops may be beneficial for carbon sequestration and protection against land degradation. It is especially feasible for countries with abundant marginal lands which are not suitable for conventional agricultural production (Wei et al., 2012).

It is necessary to consider whether energy crops can effectively replenish soil water storage while maintaining higher biomass yields, in order to obtain a win-win goal of grassland production and soil moisture storage in arid and semi-arid regions. Energy crops mainly include perennial grasses and short-rotation coppices which can be grown under water-limited and nutrient-poor conditions with less tillage (Heaton et al., 2008; Karp and Shield, 2008; Oliver et al., 2009). In this study, two typical energy crops, i.e., *Panicum virgatum* and *Miscanthus sinensis* were selected, and a forage crop-*M. sativa* was used for comparison. The objectives of this study were to 1) examine the effects of the two energy crops and *M. sativa* on soil water properties, and 2) determine the soil water storage compensation potential based on maintaining the higher biomass for energy crops in semi-arid regions. This study will provide evidences for soil hydrology of energy crops cultivation in semi-arid regions.

2. Material and methods

2.1. Site area

The study was conducted at the Changwu Agro-ecological Experiment Station of the Chinese Academy of Sciences in Changwu County in Shaanxi Province, China. The station lies within 107°40′–107°42′ E and 35°12′–35°16′ N, between altitudes of 1215 and 1226 m. The experimental site is a typical tableland and gully region on the Loess Plateau. The area is characterized by a semi-humid continental monsoon climate and has an annual mean temperature of 9.1 °C and a mean annual frost-free period of 171 d. The mean annual precipitation is 584 mm, with most of the precipitation occurring from June to September and accounting for approximately 65% of the total annual rainfall, but the mean value of potential annual evaporation is approximately 1565 mm. The climate is cold and dry in winter and spring and hot and rainy in summer. The soil in Changwu County is Heilu soil, which is derived from deep moderate loamy Malan loessial soil. The soil is distributed on gully slopes (65%) and tablelands (35%). The unsaturated soil layer is deep, and the groundwater is located at a depth of 50–80 m below the soil surface. Since the 1970s, the natural vegetation has been gradually substituted by artificial forests and grasslands.

2.2. Experimental designs

Three types of artificial grassland, i.e., *M. sativa, P. virgatum*, and *M. sinensis* were established on the farmland in May 2012. These species are the most common species used in vegetation restoration and can improve soil properties relatively quickly. *Medicago sativa* is the dominant primary forage, and *P. virgatum* and *M. sinensis* are the dominant energy crops in the study region. Three replicate plots (3 m × 5 m) were constructed on each type of herbaceous energy cropland and farmland. Seeding of *M. sativa* and *P. virgatum* was carried out with a row spacing of 25 cm and at a sowing rate 1.5–2.25 $g\,m^{-2}$ and 0.4–1.0 $g\,m^{-2}$, respectively. Seeding of *M. sinensis* was carried out with a row spacing of 40 cm and with a column spacing of 25 cm. The three grasslands were established at the same time, and plants were irrigated to ensure survival at the beginning of the restoration period. Later, grass growth depended entirely on rainfall, without any human intervention such as irrigation and fertilization, and, to ensure that the conditions in all plots were similar and that any difference was solely due to the cropland type. Therefore, it could be assumed that any difference in soil moisture content (SMC) could be attributed to the cropland type.

From the beginning of the growing season, three parallel 1 m × 1 m quadrats in each of the plots were randomly selected at two-month intervals. The aboveground biomass (AGB) was harvested from each quadrat by cutting the plant stems at the soil level, and then sealed in an envelope. Each envelope was weighed while the plant material was fresh and then re-weighed after drying at 65 °C for 48 h. Roots of the species studied were mainly distributed in the 0–50 cm soil layer in the region, and the depth of rainfall infiltration was approximately 50 cm (Liu et al., 2015). Therefore, we investigated the roots in the 0–50 cm soil layer. To measure the belowground biomass (BGB), a 9-cm diameter root augur was used to obtain three soil samples from each soil depth of 0–10, 10–20, 20–30, 30–40, and 40–50 cm, then the three samples collected from the same layer were pooled. A 2-mm sieve was used to separate most of the roots from the soil. No attempt was made to distinguish between living and dead roots. The separated roots were oven dried at 75 °C for 48 h and weighed. The measurements were conducted in September 2012, May and September every year from 2013 to 2016.

Surface soil samples were collected at the depth of 0–50 cm at 10-cm intervals. In each plot, three samples were randomly collected, and three soil cores were randomly taken with a steel cylindrical ring of 100-cm^3 volume for laboratory assays of soil bulk density. A drill (5 cm in diameter) ensured that differences in the mean soil moisture at the same depth among plots could only be attributed to the effect of vegetation. At each plot, three sampling profiles were randomly chosen to obtain the average soil moisture content at two-month intervals from July to September 2012, and from May to September every year from 2013 to 2016. Soil moisture was relatively stable outside the growing season due to limited precipitation and evapotranspiration, so data for soil moisture was only collected during the growing season. Soil moisture content in the 0–100 cm was measured from 2012 to 2014, and soil moisture content in the 0–300 cm layers was measured from 2015 to 2016. The depth interval was 10 cm for the upper 100 cm of the soil and 20 cm for layers deeper than 100 cm. A total of 20 soil samples were collected from each sampling profile. Soil samples were sealed immediately in air-tight aluminium cylinders after they were taken, and brought to the laboratory to measure the gravimetric soil moisture content. Soil moisture content was determined using the oven-drying method (24 h at 105 °C). All of the field sampling and laboratory work was completed within five days. Soil moisture content was measured gravimetrically and expressed as the ratio of soil water to dry soil mass. We calculated the coefficient of variation (CV, the ratio of the standard deviation to the mean) for the temporal-averaged soil moisture at each depth in each plot. Volumetric SMC was calculated using Eq. (1) based on the measured bulk density: