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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:

$$\theta_v = \theta_m \cdot \rho \quad (1)$$

where θ_v is the volumetric SMC (%), ρ is the soil bulk density ($g\,cm^{-3}$), and θ_m is the gravimetric SMC (%).

The soil water storage (SWS) was calculated using Eq. (2) based on the volumetric SMC:

$$SWS = h \cdot \theta_v \cdot 10^{-1} \quad (2)$$

where SWS is the soil water storage (mm), θ_v is the volumetric SMC (%), and h is the soil layer thickness (cm).

The soil water storage compensation index (SWSCI) was calculated using Eq. (3) based on Yang et al. (2011):

$$SWSCI = \frac{SWS_v - SWS_{cv}}{SWS_{cv} - h \cdot M_w \cdot 10^{-1}} \quad (3)$$

where SWS_v is the soil water storage (mm), SWS_{cv} is the soil water storage of the control sample plot (mm), h is the soil layer thickness (cm), and M_w is the wilting moisture (%).

Water use efficiency (WUE) was calculated using Eqs. (4) and (5) according to Timmons et al. (1966):

$$WUE = B \cdot ET^{-1} \quad (4)$$

where WUE is the water use efficiency ($g\,m^{-2}$), B is the amount of the increase of dry aboveground biomass ($g\,m^{-2}$) during the observation time and ET was estimated following the water balance equation of Hillel (1998):

$$ET = P + U + I - D_w - R - \Delta_w \quad (5)$$

where P is the total precipitation during the observation time and I is the total irrigation (here I = 0 since no irrigation was supplied after grass survival), U is the total upward capillary flow into the root zone, D_W is the total downward draining-out root zone, R is the total runoff (here I = 0 because the experimental field was flat), ΔW is the total change in soil water storage (mm) in the upper (0–300 m) layer of soil during the observation time. The groundwater table is very deep (approximately 80–90 m), so U was assumed to be negligible. There was no waterlogging during the time of observation, so deep drainage was assumed to be insignificant.

Soil relative aridity (SRA) was calculated using Eq. (6) of Ma et al. (2015):

$$SRA = \frac{M_s - M_w}{M_{cs} - M_w} \quad (6)$$

where M_s is the volumetric SMC (%), M_{cs} is the volumetric SMC of the control sample plot (%), and M_w is the wilting moisture (%).

2.3. Statistical analyses

Statistical analyses were performed using SPSS 22.0 (IBM, Montauk, New York, USA). The SMC data of the soil profile were analysed to determine the mean and standard deviations of various soil depths at each site (n = 3). A one-way analysis of variance (ANOVA) was used to compare the mean SMC and SWS among different cropland types, and followed by post-hoc multiple comparisons using the least significant difference (LSD) at $p < 0.05$.

3. Results

3.1. Soil bulk density and plant properties

Soil bulk density exhibited significant ($P < 0.05$) differences with increasing stand age (Table 1). Soil bulk density was the lowest in the cropland of *M. sativa* (1.34 $g\,cm^{-3}$) in the fourth year, followed by that of *P. virgatum* (1.39 $g\,cm^{-3}$) and *M. sinensis* (1.43 $g\,cm^{-3}$). Generally, the vegetation coverage and height exhibited significant differences between the two energy crops (*P. virgatum* and *M. sinensis*) and *M. sativa* ($P < 0.05$). Compared with *P. virgatum* and *M. sativa, M. sinensis* had a lower vegetation coverage and greater height. Moreover, AGB increased with increasing stand age under both energy crops and *M. sativa* (Fig. 1). The AGB of the energy crops was higher approximately five times than that of *M. sativa* in the fourth year. Meanwhile, the rate of BGB at a depth of 0–30 cm under *P. virgatum* and *M. sinensis* was approximately 95.4–98.0% and 92.6%–98.5%, respectively. In contrast, the rate of BGB at a depth of 0–30 cm decreased from 85.4% to 76.8% under *M. sativa* with corresponding increases in stand age. The differences in the rate of BGB suggested that the roots of energy crops were mostly distributed in shallow soil layers, whereas those of *M. sativa* were mainly distributed in deep soil layers.

3.2. Soil moisture variation

The CV of soil moisture under energy crops and *M. sativa* varied with soil depths (Fig. 2). Higher CV of *M. sativa* was found in 0–200 cm soil layers, with the lowest and highest value observed at the depth of 40–50 cm and 90–100 cm, respectively. The CV of energy crops were higher in the 0–50 cm soil layer. In contrast, the CV of both energy crops and *M. sativa* were relatively low in the deep soil layers below 200 cm.

The SRA of the soil under both energy crops and *M. sativa* decreased with increasing stand age and soil depths (Fig. 3). The soil under *M. sativa* was mildly desiccative, although with some spots having no desiccation at a soil depth of 0–100 cm. However, the soil under the two energy crops exhibited no desiccation at a depth of 0–100 cm. Additionally, the soil under *M. sativa* was moderately and severely desiccative at depths below 100 cm, even extremely desiccative in the fourth year (Fig. 4). Soil dry layers occurred at depths below 200 cm and tended to increase with increasing stand age. In contrast, the soil under energy crops were mildly desiccative at depths below 100 cm, although exhibiting some points with no desiccation.

3.3. Vertical distribution of soil water

The SMC of *M. sativa* decreased with increasing soil depths, ranging from 16.9% to 13.8% (Fig. 5). In contrast, the SMC of *P. virgatum* and *M. sinensis* were found to increase at a decreasing rate and tended to be stable in the 140–300 cm soil layers, ranging from 18.0% to 22.9% and 20.2%–22.8%, respectively. Generally, energy crops had a higher SMC than *M. sativa*. The soil water storage of *P. virgatum* and *M. sinensis* grasslands were higher approximately 37.89% and 40.17% than that of *M. sativa* grassland.

The SWSCI of energy crops exhibited significant differences in different soil layers ($P < 0.05$, Fig. 6), with that of *P. virgatum* and *M. sinensis* varying from 49.3% to 198.8% and 42.3%–249.3%, respectively. In general, the values of SWSCI in deep soil layers were higher than those in shallow soil layers. The SWSCI of *P. virgatum* and *M. sinensis* were the smallest in the 40–80 cm layer.

3.4. Water-use efficiency

In terms of water use efficiency (WUE), there were significant differences among *P. virgatum*, *M. sinensis* and *M. sativa* ($P < 0.05$, Fig. 7). Energy crops had obviously higher WUE than *M. sativa* ($P < 0.05$). The WUE of *M. sinensis* was the highest (13.03 $g\,kg^{-1}$), being approximately three times that of *M. sativa* (4.53 $g\,kg^{-1}$).

4. Discussion

In this study, we studied the biomass yield of energy crops (*P. virgatum* and *M. sinensis*) and *M. sativa* over long-term cultivation. The results indicated that energy crops were significantly more productive, producing approximately five times the biomass of *M. sativa* in the fourth year. Previous studies found similar results that energy crops had

Table 1
Precipitation, evaporation, vegetation coverage, and soil bulk density at the investigated sites.

Stand age (year)	Cropland types	Annual precipitation (mm)	Annual evaporation (mm)	Vegetation coverage (%)	Height (cm)	Soil bulk density (g cm^{-3})
1	*M. sativa*	515.40	831.82	65.00 ± 2.89b	38.33 ± 4.41a	1.46 ± 0.01a
	P. virgatum			75.00 ± 2.89b	114.67 ± 8.11b	1.47 ± 0.00a
	M. sinensis			46.67 ± 4.41a	179.33 ± 11.89c	1.47 ± 0.01a
2	*M. sativa*	571.30	749.54	88.33 ± 4.41b	48.33 ± 4.41a	1.42 ± 0.01a
	P. virgatum			88.33 ± 3.33b	132.00 ± 7.02b	1.45 ± 0.00b
	M. sinensis			66.67 ± 3.33a	306.00 ± 8.54c	1.46 ± 0.01b
3	*M. sativa*	520.00	765.00	95.00 ± 2.89b	48.67 ± 5.21a	1.39 ± 0.02a
	P. virgatum			96.67 ± 1.67b	143.00 ± 5.77b	1.44 ± 0.01b
	M. sinensis			73.33 ± 1.67a	353.33 ± 5.78c	1.45 ± 0.00b
4	*M. sativa*	556.00	753.00	97.33 ± 1.20b	49.33 ± 4.33a	1.34 ± 0.02b
	P. virgatum			98.33 ± 1.67b	146.00 ± 7.57b	1.39 ± 0.01b
	M. sinensis			79.00 ± 2.08a	388.00 ± 7.57c	1.43 ± 0.01c

Note: The values represent the mean ± SE. Means in a column and same year followed by different letters are significantly at P < .05.

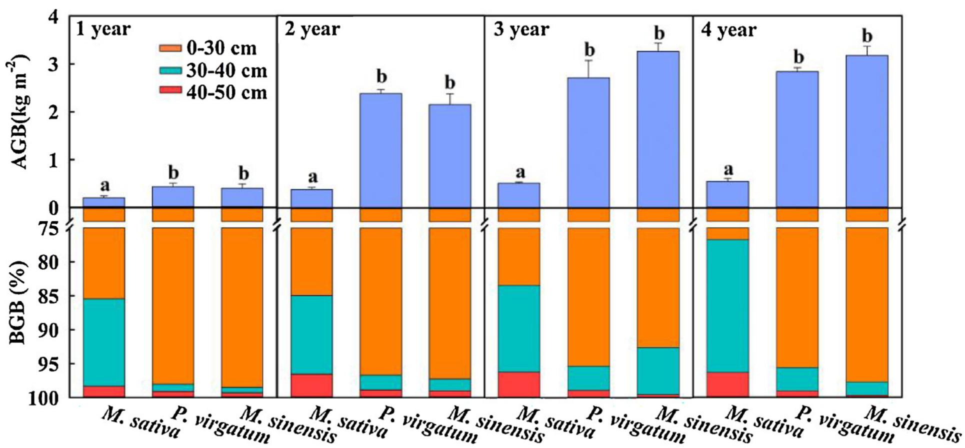

Fig. 1. Aboveground biomass and proportionate distributions of the belowground biomass under three croplands in different stand ages. The proportion of belowground biomass in different soil layers is labelled with different colours. The bars denote the standard deviation of the mean (n = 3). Significant differences in the aboveground biomass among different grassland types at each measurement site are labelled with different lowercase letters (P < 0.05).

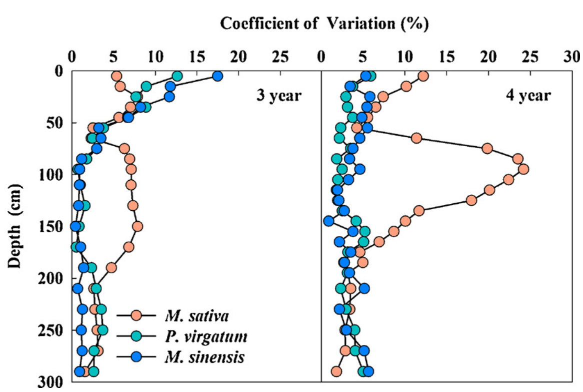

Fig. 2. The vertical distribution of coefficients of variation of soil moisture (CV) for three croplands in different stand ages.

potential biomass yields and associated yields which could reach the maximum production as early as three years after establishment (Lewandowski et al., 2003; Engbers, 2012; Marsal et al., 2016). Therefore, growing energy crops may be beneficial for carbon sequestration and soil erosion control in semi-arid areas (Galati et al., 2016; Mekonnen et al., 2017). Differences in the biomass yields between energy crops and *M. sativa* might reflect differences in plant properties and water use efficiencies.

Precipitation and evapotranspiration jointly control soil moisture in semi-arid regions, where precipitation is the only source of soil moisture (Wang et al., 2012). Global climate change results in temperature rise, which would increase potential evapotranspiration and further aggravate drought in semi-arid regions (Muluneh et al., 2015; Huang et al., 2018). Vegetation generally results in differences in evapotranspiration and rainfall recharge that influences soil moisture (Fu et al., 2003; Huang et al., 2013; Jia et al., 2015, 2017; Huang et al., 2018). The CV of energy crops and *M. sativa* were higher in shallow soil layers, whereas they were relatively lower in deep soil layers below

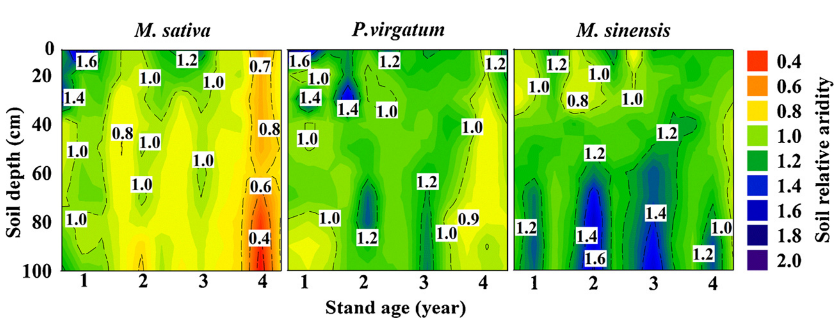

Fig. 3. The vertical distribution and temporal dynamics of soil relative aridity (SRA) for plots under *M. sativa, P. virgatum*, and *M. sinensis*. SRAs of different cropland types are labelled with Arabic numerals. On the basis of soil dryness SRA values, the soil relative aridity is divided into five levels: 1) SRA ≥ 1, non-desiccation; 2) 0.8 ≤ SRA < 1.0, mild desiccation; 3) 0.6 ≤ SRA < 0.8, moderate desiccation; 4) 0.4 ≤ SRA < 0.6, severe desiccation; and 5) SRA < 0.4, extreme desiccation.

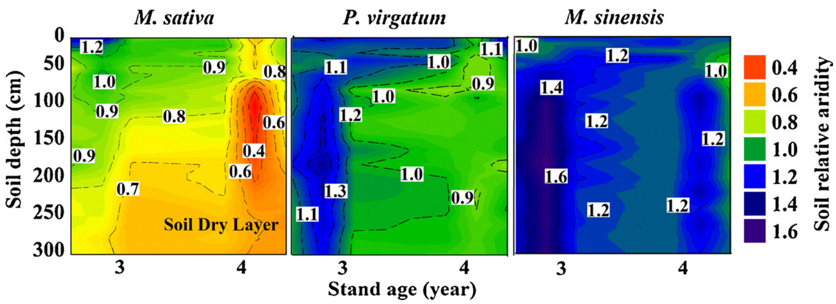

Fig. 4. The vertical distribution and temporal dynamics of soil relative aridity (SRA) for plots under *M. sativa, P. virgatum* and *M. sinensis*. SRAs of different cropland types are labelled with Arabic numerals. On the basis of soil dryness SRA values, the soil relative aridity is divided into five levels: 1) SRA ≥ 1, non-desiccation; 2) 0.8 ≤ SRA < 1.0, mild desiccation; 3) 0.6 ≤ SRA < 0.8, moderate desiccation; 4) 0.4 ≤ SRA < 0.6, severe desiccation; and 5) SRA < 0.4, extreme desiccation.

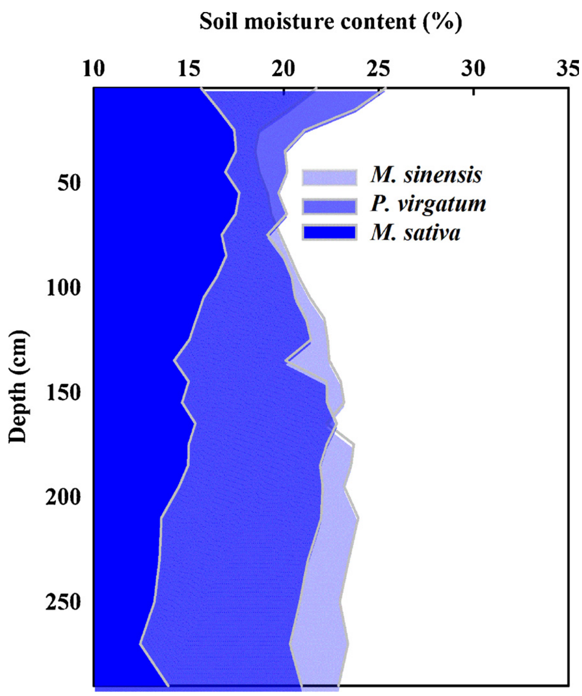

Fig. 5. The vertical distribution of soil moisture content under different cropland types in the fourth stand age.

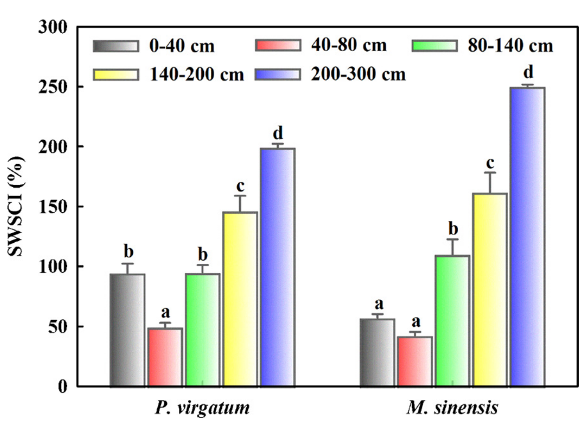

Fig. 6. Soil water storage compensation index (SWSCI) for plots under *P. virgatum* and *M. sinensis* compared with *M. sativa* croplands. The bars denote the standard deviation of the mean (n = 3). Significant differences in SWSCI between different soil layers at the measurement sites are labelled with different lowercase letters (P < 0.05).

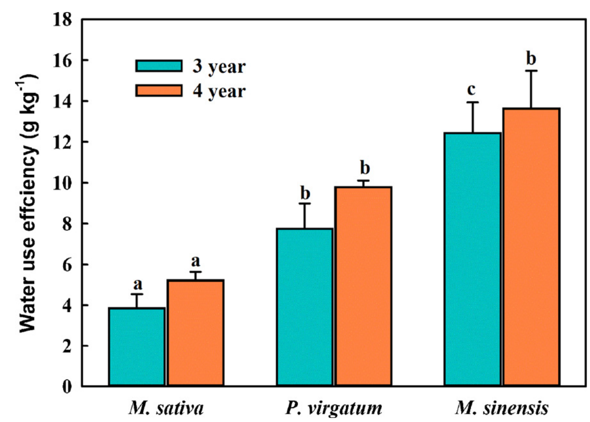

Fig. 7. Water use efficiency under different cropland types in different stand ages. The bars denote the standard deviation of the mean (n = 3). Significant differences in water use efficiency among different cropland types at the measurement site are labelled with different lowercase letters (P < 0.05).

200 cm, indicating that the variation in deep soil moisture was quite low in a short period of time. This result was consistent with previous studies (Yang et al., 2014), in which soil moisture content was found to be temporally stable in deeper soil layers. Wang et al. (2009) found that soil moisture in semi-arid areas varied seasonally and inter-annually in shallow layers, depending on the precipitation. Vertical distribution and temporal variations of deep soil moisture differed from those of the shallow soil moisture, due to the thickness of the loess-covered soil (Wang et al., 2009; Yang et al., 2012; Jia et al., 2015, 2017). In general, soil moisture content below the rainfall infiltration depth was relatively more stable than that in shallow layers under artificial grasslands (Chen et al., 2008b; Chen et al., 2010). However, the soil moisture under *M. sativa* obviously decreased under long-term cultivation. *Medicago sativa* was mildly and moderately desiccative to the topsoil, while it became severely, even extremely desiccative to the deep soil layer with increasing stand age. (Huang et al., 2018). In contrast, energy crops were mildly desiccative, and there were even some areas showing no desiccation. Such differences were very likely due to *M. sativa* had deep root systems and consumed more deep soil moisture than energy crops. Root water uptake is an important process determinining soil moisture dynamics in semi-arid areas, where precipitation is the only source of soil moisture (Wang et al., 2012). The root systems of *M. sativa* in this study were mainly distributed in deep soil layers. The vast deep root systems below the rainfall infiltration depth generally consumed more deep soil moisture, leading to serious soil desiccation (Chen et al., 2010; Yang et al., 2014; Jia et al., 2015, 2017; Huang et al., 2018). In contrast, energy crops had much fewer root systems below the rainfall infiltration depth. Due to the excessive depletion of soil moisture by deep root systems and long-term insufficient rainfall infiltration, the deep soil moisture of *M. sativa* was significantly lower than that of energy crops, even led to soil desiccation. The vertical distribution of soil moisture varied significantly. A relatively higher soil moisture was usually observed on sites covered with energy crops at each transect, whereas lower values was observed on *M. sativa* site (Fig. 5). The values of SWSCI for energy crops roughly showed an increasing trend with increasing soil depths (Fig. 6). One possible reason was that the soil under *M. sativa* had higher evapotranspiration than precipitation

recharge (Jian et al., 2015). Furthermore, the annual rainfall infiltration depth in revegetated lands can hardly reach 1 m, according to long-term field soil moisture observations (Yang et al., 2014). The deep root systems of *M. sativa* consumed abundant deep soil moisture, which was not sufficiently supplemented. Therefore, the differences in soil moisture between *M. sativa* and energy crops were obvious with increasing soil depths.

The value of SWSCI for *P. virgatum* was much higher than that for *M. sinensis* in the 0–40 cm soil layer, possibly due to the relatively lower potential evapotranspiration of *P. virgatum* compared with that of *M. sinensis*. In addition, the vegetation coverage of *P. virgatum* was relatively higher than that of *M. sinensis*. A high vegetation coverage reduced the evaporation of surface moisture, and resulted in a relatively higher soil moisture in the shallow layers (Hamerlynck et al., 2012). Energy crops had significantly higher water use efficiencies compared with *M. sativa*. As an important source of water for vegetation, deep soil moisture is mainly supplied by rainfall (Chen et al., 2008b; Jia et al., 2015). Land productivity is seriously restricted by shortages of soil moisture in semi-arid regions. Thus, improvement of crop yields with less water resources is a key issue that needs to be addressed (Wang et al., 2018). *Medicago sativa* with a high consumption of deep soil moisture can lead to soil drought. In contrast, energy crops with a lower consumption of deep soil moisture and higher biomass yield are more suitable for long-term cultivation. Furthermore, energy crops having a good potential for soil water storage compensation are also good choices for crop rotation in agricultural management.

5. Conclusions

The biomass yields and soil moisture in different soil layers under energy crops and *M. sativa* were compared and analysed over long-term cultivation. The vegetation types determined the conditions and the vertical distribution of deep soil moisture. *Medicago sativa* drastically decreased the deep soil moisture and even induced soil dessication over long-term cultivation. In contrast, energy crops with a higher soil water storage compensation potential, based on the higher biomass, are more suitable for cropland cultivation in semi-arid regions.

Conflict of interest statement

The authors declare that there is no conflict of interest.

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