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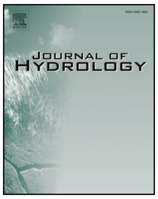

Research papers

Soil water depletion and restoration under inter-conversion of food crop and alfalfa with three consecutive wet years

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ABSTRACT

With the implementation of the "Grain-for-Green" program, artificial vegetation was introduced on the Loess Plateau, which resulted in high soil water content (SWC) depletion. Currently, lack of soil water recharge is one of the most serious challenges on the Loess Plateau. Soil drying and wetting processes are critical for the sustainability of soil water recycling, but this has not been well studied. There is also a lack of physical definition of the upper bound SWC of dried soil layers (DSL). In this study, soil water dynamics – the change of SWC affected by precipitation and vegetation transpiration – were studied under converted vegetation. In-situ SWC measurements from the 0–5 m or 0–8 m deep profile over consecutive wet years (from 2016 to 2018 with an average precipitation of 660.9 mm) were analyzed to understand soil water depletion and restoration processes. Results showed distinct differences in soil water dynamics in the soil profiles and soil water balances under different vegetation types. SWC under continuous perennial alfalfa (*Medicago sativa*) had greater fluctuations between 0 and 300 cm than below 300 cm, and a DSL was observed below 300 cm. After converting from alfalfa to soybean (*Glycine max*), SWC increased greatly during the three wet years. Soil water storage (*S*) increased at an average rate of 35.8 mm $year^{-1}$ m^{-1} within the top 500 cm of the soil profile, average evapotranspiration (*ET*) was 482.0 mm $year^{-1}$, and maximum restoration depth of soil water extended to 660 cm. However, SWC gradually decreased over time after replacing food crop with alfalfa. *S* declined at an average rate of 21.4 mm $year^{-1}$ m^{-1} within the top 500 cm of the soil profile, average *ET* was 680.4 mm $year^{-1}$ and the maximum depth of soil water depletion extended to 360 cm. These results suggest that SWC in deep layers can be depleted and replenished quickly, and the processes were dominated by vegetation types and precipitation. Taking vegetation types and soil texture into consideration, the calculation of upper bound SWC of DSL was redefined. Given the long-term effects of high water demand from vegetation such as alfalfa on the soil water balance, *ET* of vegetation should be reduced through conversion to less water-intensive vegetation types or biomass control (i.e. reduced planting density appropriately) in arid areas of the Loess Plateau.

1. Introduction

Soil water content (SWC) is a vital element of terrestrial systems that can limit vegetation growth in semi-arid regions (Gao and Shao, 2012; Wang et al., 2012a; Zhang et al., 2016). Since the initiation of the "Grain-for-Green" eco-project in 1999, affected areas have experienced an increase in vegetation coverage, and soil and water loss has declined due to the introduced artificial vegetation (Shao et al., 2018). However, artificial vegetation consumes high amounts of soil water deep in the soil profile and this has led to soil desiccation in semi-arid and semi-humid areas on the Loess Plateau, and dried soil layers (DSL) have been widely observed (Shangguan, 2007; Shao et al., 2018; Wang et al., 2011b; Wang et al., 2009).

The phenomenon of DSL formation is a phenomenon related to soil desiccation; DSLs form as a result of excessive soil water depletion from perennial plants below the average precipitation infiltration depth (Chen et al., 2008; Shao et al., 2018). Dried soil layers affect tree growth, survival and natural regeneration, and are a potential threat to plant succession and afforestation efforts (Wang et al., 2010). Deep DSLs may also have other negative effects on the water cycle. For

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example, precipitation may not infiltrate deeply enough to recharge shallow groundwater, or introduced vegetation may not survive during severe dry seasons. Previous studies have investigated factors that control regional-scale distribution of DSLs under forests, meadows and agricultural fields that grow corn (including field capacity, bulk density, slope gradient, slope aspect, capillary water content, sand content, altitude, vegetation coverage, and evaporation), and they have analyzed the negative effects of DSL on ecosystems (including poor vegetation growth, induced degeneration of vegetation, drying microclimate and degrading soil quality), and the potential reasons for their formation (including low precipitation, high evaporation, improper selection of vegetation types, and high-density of trees planted) (Jia et al., 2017; Shangguan, 2007; Wang et al., 2012b; Zhao et al., 2007). However, the occurrences of DSL have become increasingly common and are widely distributed throughout arid and semiarid regions around the world, including Russia, southern Australia, eastern Amazonia, and China's Loess Plateau (Christina et al., 2017; Jipp et al., 1998; Robinson et al., 2006; Shangguan, 2007; Zhao et al., 2007).

Soil water depletion under different vegetation was observed across south-west Western Australia where within 7 years of planting, eucalyptus roots reached at least 8–10 m to exploit soil water (Robinson et al., 2006). On the Loess Plateau of China, DSL depths have been known to exceeded 10 m (Cheng and Liu, 2014; Shao et al., 2018; Wang et al., 2008). Soil water depletion depth of 7-year-old alfalfa (*Medicago sativa*), 23-year-old *Caragana* shrub and 23-year-old pine forest were up to 15.5 m, 22.4 m and 21.5 m, respectively, around the central Loess Plateau (Wang et al., 2009). Cheng and Liu (2014) studied SWC in the 0–15 m soil profile under four land uses, and found that persistent DSLs developed under perennial vegetation. Other studies in the Liudaogou watershed showed that perennial alfalfa and *Caragana* consumed SWC within the top 6 m of a soil profile, and a 40-cm thick DSL was observed under a 2-year-old alfalfa and 4-year-old *Caragana*, but the DSL extended to a depth of 580 cm under alfalfa and *Caragana* after 7 and 8 years of growth, respectively (Fan et al., 2016; Jia et al., 2019). Zhang and Wang (2017) investigated soil water dynamics in apple orchards of various ages on the Changwu Tableland of the Loess Plateau and found that the most severe DSL occurred in the 19-year-old apple orchard.

Soil desiccation has been observed in almost all artificial forests, shrub lands, apple orchards and perennial alfalfa on the Loess Plateau (Chen et al., 2008; Wang et al., 2011a; Zhang and Wang, 2017). To achieve sustainable use of soil water, it is recommended that alfalfa only be cropped for less than eight consecutive years in areas where annual precipitation is 600 mm (Li and Huang, 2008; Ren et al., 2011). Other studies have shown that natural restoration is a better option than artificial replanting with respect to maintaining the sustainability of water resources in arid and semi-arid regions, and the optimal land use in semi-arid regions is grassland (Deng et al., 2016; Wang et al., 2015). A large number of studies about the restoration of SWC in DSLs found that deep SWC can be recharged in fallow land and unfertilized cropland (Cheng and Liu, 2014; Huang and Gallichand, 2006; Jia et al., 2019; Liu et al., 2010; Wang et al., 2011a). A previous study showed that the recovery depths under bare soil and soybean (*Glycine max*) crop were greater than the observation depth (5 m) after 5 years of monitoring in the Liudaogou watershed (Fan et al., 2016). Resulting from many years of intensive cropping, a persistent DSL has been found to form between 2- and 3-m depths in cropland, which was fully replenished after one wet year (Liu et al., 2010). A one-dimensional simulation model "SHAW" was used to evaluate soil water restoration in apple orchards in the gully region of the Loess Plateau, and the simulation results showed that the average recovery time was 7.3 years for 0–3 m soil depth, and an average of 13.7 years for the 0–10 m soil profile (Huang and Gallichand, 2006).

There is little field data that simultaneously captures soil drying and wetting processes during the creation and reversal of DSLs, and having this data could help indicate whether DSLs could be reduced or fully remedied. There is a lack of a physical definition for the upper bound SWC of DSLs, which is affected by soil texture and vegetation types.

In our study, the soil water dynamics in the 0–5 or 0–8 m soil profile were observed under three combinations of vegetation types, which included alfalfa to soybean, perennial alfalfa, and planted alfalfa following food crops, from 2016 to 2018 in semi-arid water-wind erosion crisscross region. Soil water storage (*S*) of three treatments and the depth of soil water depletion and restoration were studied. The objective of this study was to determine the rate and depth of soil water depletion and restoration in the observed soil profile depth following vegetation inter-conversion. A new method to calculate the upper bound SWC of the DSL under associated vegetation types and soil texture factors is proposed. The results of this study will improve our understanding of the importance of plant choice under dry land farming.

2. Materials and methods

2.1. Study site

This study was conducted at Shenmu Erosion and Environmental Experimental Station in the Liudaogou watershed (110°21′–110°23′E, 38°46′–38°51′N, altitude is 1094–1274 m, and catchment area 6.9 km^2) located in Shenmu city, Shaanxi Province, China. This location is in the water-wind erosion crisscross region, which is a transitional zone from the Loess Plateau to Mu Us Desert, and at the transitional zone from the loess hilly region of flowing water erosion to the Ordos Plateau. The climate is semi-arid continental monsoon and is characterized by severe changes in temperature and precipitation. The winter is dry and droughts often occur in the spring, which results in wind erosion and sandstorms in this area. In contrast, the summer is wet, characterized by heavy precipitation and rainstorms, which leads to water-induced soil erosion. The mean annual precipitation in the Liudaogou watershed from 2003 to 2018 was 469.0 mm. There were great differences in interannual precipitation ranging from 280.5 mm in 2005 to 704.3 mm in 2016. More than 85% of the total annual precipitation falls between May and October. During this study, total precipitation in 2016, 2017, and 2018 was 704.3 mm, 651.1 mm, and 627.4 mm, respectively (Fig. 1), which is higher than mean annual precipitation. Therefore, each year was considered a "wet year". The sum of the total precipitation in July and August were 426.7 mm in 2016, 375.0 mm in 2017, and 375.3 mm in 2018. This accounted for 60%, 57%, and 73% of the total precipitation in 2016, 2017, and 2018, respectively. The mean annual temperature is 8.4 °C and mean annual evaporation is 785.4 mm. The terrain is characterized by typical deep gullies and undulating slopes and hills.

2.2. Field experiment

The trial had three treatments: a soil water restoration treatment (alfalfa to soybean), a control check treatment (CK, with perennial alfalfa, as the CK of restoration treatment) and a soil water depletion treatment (food crops to alfalfa). In April 2016, three 10-year-old alfalfa plots (alfalfa planted in May 2007, on land with a slope of zero, with 20 m^2 (5 m × 4 m) for each experimental plot) were selected. This treatment was planted with soybean after removing alfalfa, ploughing and fertilizing prior to carrying out the soil water restoration experiment. At the same time, another three 10-year-old alfalfa plots located 5 m from restoration treatment plots (with the same conditions as described for the restoration treatment) were selected as the CK treatment. A 5-m-wide buffer zone was planted with a mix of alfalfa and grass to prevent alfalfa in the CK treatment from absorbing SWC under the soybean crop in restoration treatment. A 5-m long aluminum tube was installed in the center of each plot in the restoration and CK treatments, and after July 25, 2018, the 5-m measuring tube was lengthened using an 8-m long aluminum tube. To study soil water depletion processes, farm land cultivated for 15 years with soybean or

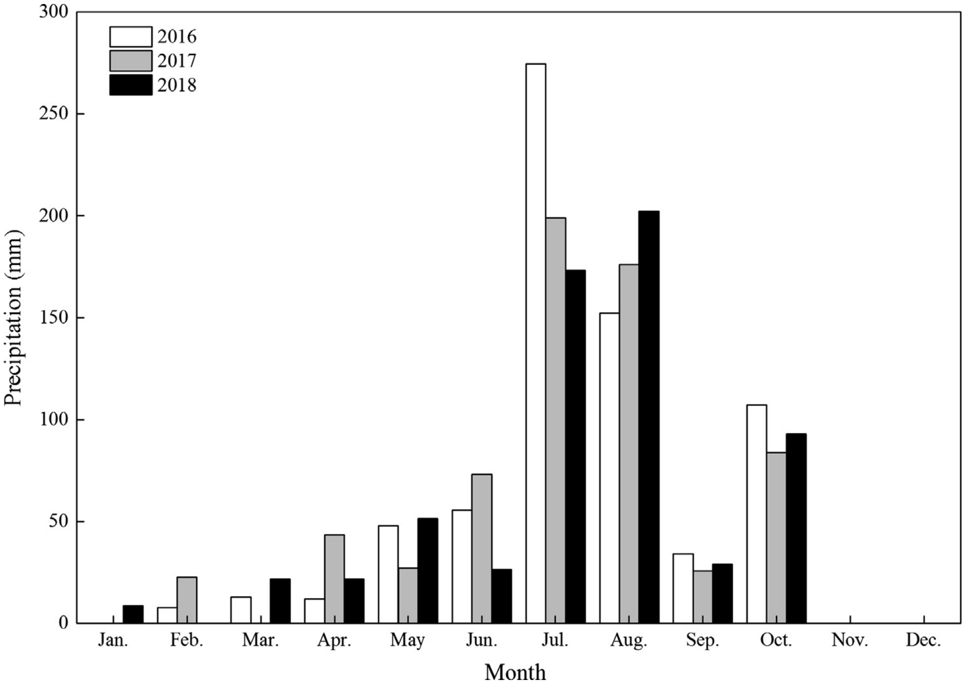

Fig. 1. The monthly precipitation distribution during 2016–2018.

Table 1

General information of restoration (R), CK, and depletion (D) treatments showing the soil bulk density (BD, g cm^{-3}), soil organic matter (SOM, g kg^{-1}), and soil total nitrogen (g kg^{-1}) in the profile of 0–200 cm.

Depth (cm)	BD (g cm^{-3})		SOM (g kg^{-1})		TN (g kg^{-1})	
	R/CK	D	R/CK	D	R/CK	D
10	1.48	1.43	7.88	11.44	0.50	0.66
20	1.46	1.45	5.11	8.34	0.38	0.50
30	1.48	1.48	2.87	2.75	0.25	0.25
40	1.53	1.57	2.67	2.75	0.24	0.25
50	1.57	1.68	2.21	2.15	0.22	0.21
60	1.61	1.59	2.12	2.15	0.21	0.21
70	1.57	1.57	2.23	1.74	0.20	0.19
80	1.54	1.57	1.89	1.74	0.19	0.19
90	1.54	1.56	1.71	1.75	0.19	0.18
100	1.51	1.62	1.71	1.75	0.18	0.18
120	1.51	1.61	1.60	1.54	0.19	0.14
140	1.52	1.64	1.86	1.47	0.19	0.14
160	1.52	1.61	1.59	1.63	0.16	0.15
180	1.55	1.59	1.54	1.81	0.15	0.17
200	1.61	1.63	1.55	1.56	0.16	0.15

millet under typical local management were selected in April 2017 and three plots were set up. The field had a slope less than 10°, the shortest distance from the restoration treatment field is 561 m. The three plots were planted with alfalfa, and the whole plot of alfalfa was mowed in August and October each year. Each plot area was 80 m^2 (10 m × 8 m). An 8-m long aluminum tube was installed in the center of each plot for the depletion treatment. The dominant soil type was loessial soil, and each of the three fields had similar, almost uniform soil texture. Initial conditions for each treatment are shown in Table 1 and Fig. 2.

2.3. Soil water content measurements and calculations

Each of treatments has three replicate plots, and 5-m or 8-m aluminum tube was installed. Installation holes were drilled manually and access tubes were installed vertically into soil profile. Soil water content (cm^3 cm^{-3}) was measured periodically with neutron probes (model CNC503B, Super Energy Nuclear Technology Ltd., Beijing, China) at 10 cm (0–100 cm) or 20 cm (100–500 or 800 cm) intervals. Measurements were taken in April, July, August, and October 2016. In May, July, August, September, and October 2017, May, June, July, August, September, and October 2018. The oven dry method was used to calibrate neutron probe readings.

S was calculated using the following equation:

$$S = \sum_{i=1}^{n} \mathrm{SWC}_i \cdot h_i \tag{1}$$

where S is the soil water storage (mm), the change in depth is $h_i = 10$ cm for the depth range of 0–100 cm and $h_i = 20$ cm for depth > 100 cm, i denotes the increment of profile depth and S was calculated over the depth range of 0–500 cm.

Run-off was never observed on the terraces due to the high infiltration rate of water in these soils. There was no irrigation on any of the fields and no groundwater replenishment because the groundwater table is more than 50 m below the surface. Generally, the observed maximum infiltration depth is 200 cm in the study area (Fan et al., 2016), although the infiltration depth occasionally reached 660 cm (in the restoration treatment), deep percolation below 500 cm was ignored. The differences value of S was calculated by equation:

$$\Delta S = S_{\text{end}} - S_{\text{start}} \tag{2}$$

where ΔS is the differences value of S between the beginning and the end of growing season (mm), S_{start} and S_{end} are the S at the beginning and the end of the growing season (mm) respectively.

The evapotranspiration (mm, ET) was calculated with the following water balance equation:

$$ET = P - \Delta S \tag{3}$$

where P is precipitation (mm).

Because different treatments were compared at same measured date, only measured data over the growing season were analyzed, the impact of measured SWC before or after precipitation on soil water depletion and restoration over the growing season were the same with different treatments. Soil water depletion and restoration rate were calculated using the following equations:

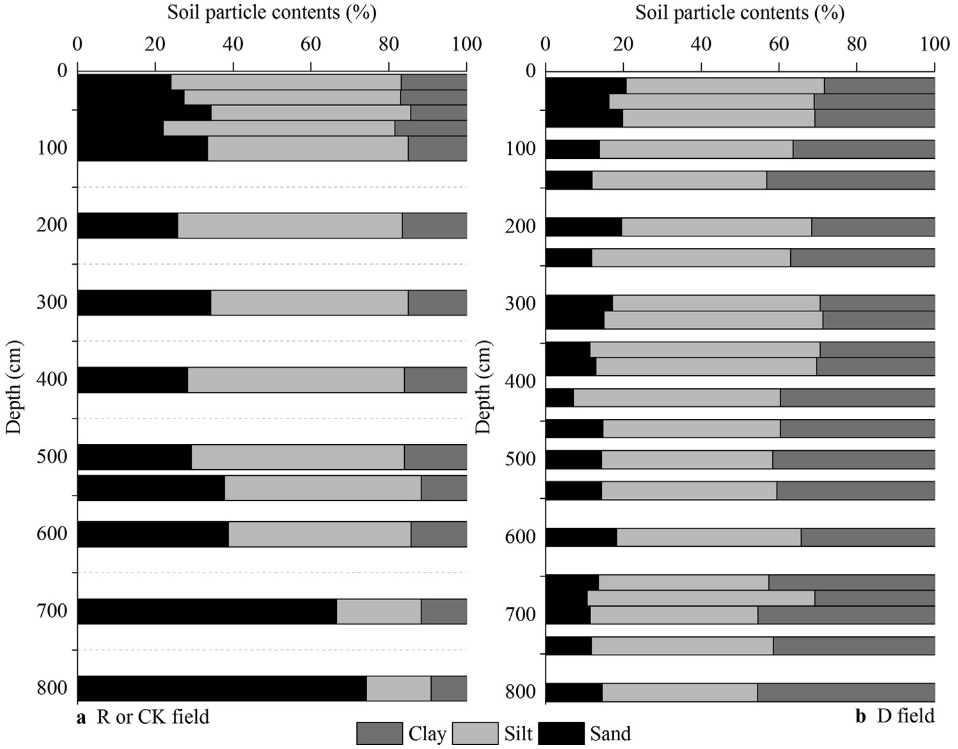

Fig. 2. Soil particle contents in 0–800 cm profile of three treatments. a is restoration (R) or CK treatment, b is depletion (D) treatment.

$$R_{\mathrm{D}} = \frac{S_{\min} - S_{\mathrm{start}}}{\mathrm{T} \times \mathrm{D}} \tag{4}$$

$$R_{\mathrm{R}} = \frac{S_{\mathrm{end}} - S_{\mathrm{start}}}{\mathrm{T} \times \mathrm{D}} \tag{5}$$

where R_{D} is the depletion rate per year per meter (mm year^{-1} m^{-1}), R_{R} is restoration rate per year per meter (mm year^{-1} m^{-1}) during the whole growing season, $S_{\min}$ is amount of S at times of high evapotranspiration during the growing season (mm), T is time (year), and D is soil depth (m).

Soil water depletion depth is the depth of soil water consumed by plants in the current year. According to the SWC curve measured at the beginning of the growing season and strong evapotranspiration curves during the growth season, the corresponding depth of the cross-over point of the two curves is the depletion depth, and the corresponding curve was the depletion curve. If two curves have no distinct cross-over point, the depletion depth exceeds measured depth. Soil water restoration depth is the precipitation infiltration depth in the current year under each vegetation type. By comparing the measured SWC curve at the beginning and end of the growth season, the corresponding depth of the cross-over point of the two curves is the restoration depth. Similarly, if two curves have no distinct cross-over point, the restoration depth exceeds the measured depth (Fig. S1).

The upper bound SWC of DSL was defined considering vegetation types and soil texture. A DSL begins to form at a specified pressure head, which was calculated as the median between wilting point pressure head and the lowest point of optimal pressure head for root water uptake. According to root water stress response function (Van Genuchten and Nielsen, 1985; Feddes et al., 1978), the specified pressure head represents the pressure head at which root water uptake is reduced by 50%, and then, SWC can be calculated using the soil water retention curve. Root water uptake parameters of alfalfa and soybean were referenced from HYDRUS-1D.

3. Results

3.1. Processes of soil water restoration and depletion

The upper bound SWC of DSL was calculated for two sites with different soil particle composition and different vegetation types. The upper bound SWC of DSL is represented with dashed lines in Figs. 3 and 4. Mean upper bound SWC of DSL was 0.102 cm^3 cm^{-3} in the restoration treatment with soybean (Fig. 3d–f) and 0.083 cm^3 cm^{-3} with alfalfa in the CK treatment (Fig. 3a–c), but was 0.137 cm^3 cm^{-3} in 0–800 cm profile in the depletion treatment due to different soil textures (Fig. 4). The distributions of SWC changed over time and under different treatments. SWC of the restoration treatment increased over the three wet years compared with CK. SWC at 0–360 cm depth in the depletion treatment decreased from 2017 to 2018. SWC dynamics of the CK treatment at 0–300 cm showed greater fluctuations than that at 300–500 cm, especially in the 0–100 cm soil layer where SWC varied between 0.03 cm^3 cm^{-3} and 0.26 cm^3 cm^{-3}. There was a stable SWC layer in the CK treatment in 300–500 cm, which maintained a SWC below 0.10 cm^3 cm^{-3} (0.06–0.10 cm^3 cm^{-3}) over time (Fig. 3a–c), and 92.1% of the SWC measurements were lower than the upper bound SWC of a DSL (0.086 cm^3 cm^{-3}, average value in 300–500 cm).

The changes in SWC were distinct after land-use was converted. Following conversion from alfalfa to soybean land, the dry soil profiles were recharged substantially. The SWC increased to nearly 0.21 cm^3 cm^{-3} at 30 cm depth and at 180–220 cm depth, and was 0.11 cm^3 cm^{-3} at 300 cm soil depth, and then SWC in the 0–300 cm profile was higher than the upper bound SWC of DSL by the end of the growing season in 2016 (Fig. 3d). By the end of the growing season in 2017 (Fig. 3e), SWC was greater than 0.20 cm^3 cm^{-3} at 30–50 cm and 160–260 cm, and SWC was up to 0.20 cm^3 cm^{-3} at 500 cm depth. In addition, SWC did not have a cross-over point in the 400–500 cm soil layer. Therefore, soil water infiltration depth exceeded the observation depth, and SWC at the end of the growing season was higher than the upper bound SWC of DSL in the whole profile. Furthermore, the observation depth was extended to 800 cm in July 2018 (Fig. 3f). The

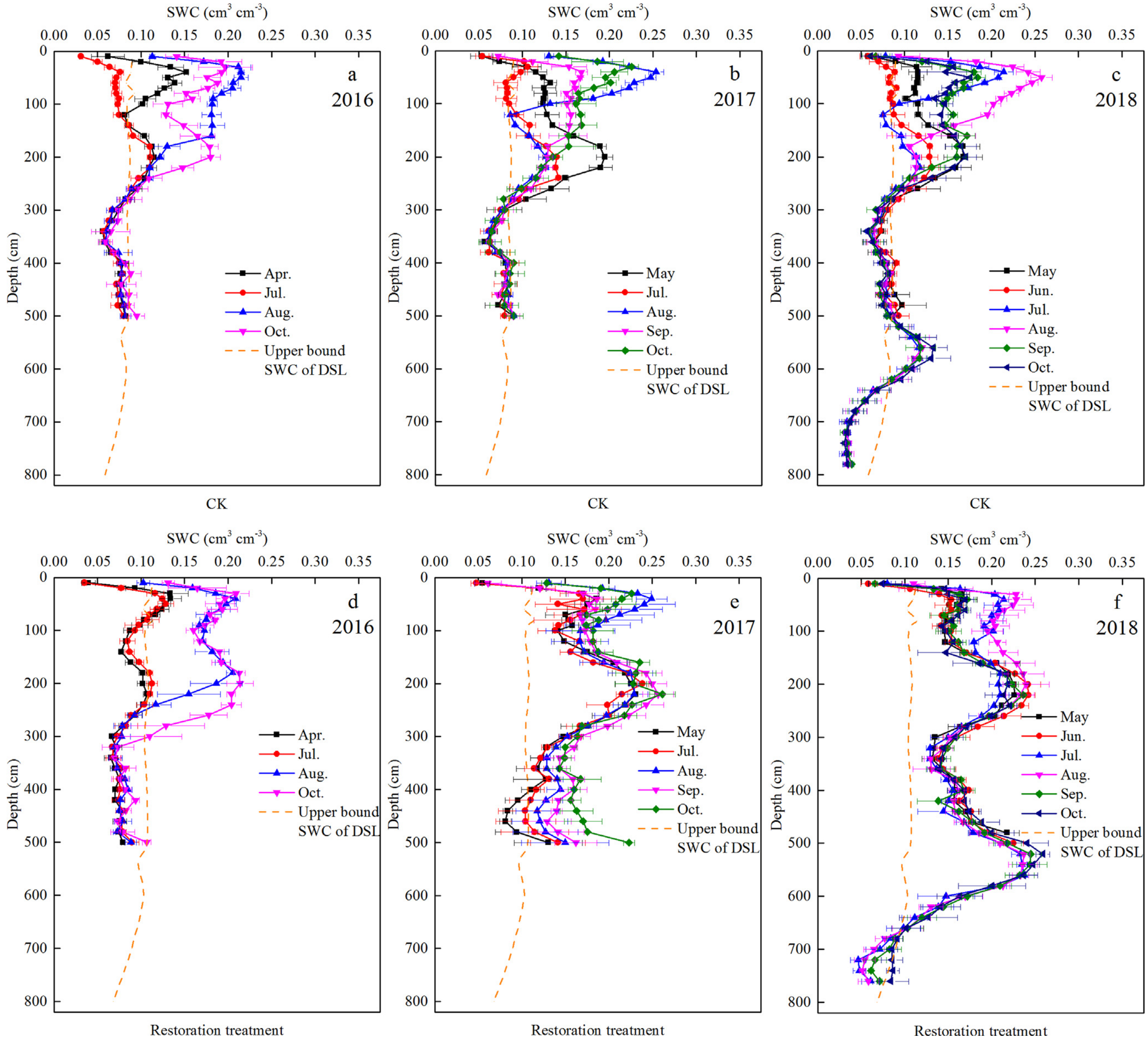

Fig. 3. Soil water content (SWC) dynamics of perennial alfalfa (CK treatment, a, b and c) and alfalfa to soybean (restoration treatment, d, e and f) in 2016, 2017 and 2018 at Shenmu, Shaanxi, China. Dashed line is the boundary SWC on which a dried soil layer (DSL) begins to form under alfalfa and soybean, respectively.

SWC distribution indicated that the SWC was greater than 0.15 cm^3 cm^{-3} down to soil depths of 600 cm. The SWC of soybean was similar to that of CK at 660 cm. Therefore, soil water restoration depth was 660 cm, and the SWC was almost higher than the DSL upper bound SWC over the entire soil profile.

Growing alfalfa after food crops in 2017 decreased SWC (Fig. 4). Based on the fact that the SWC at the beginning of the growing season (mean value = 0.24 cm^3 cm^{-3}) was near field capacity (0.26 cm^3 cm^{-3}) (Chen et al., 2008; Wang et al., 2010), and many crops and natural grasses did not cause deep DSL, the deep SWC under these vegetation types has little inter-annual variability (Fang et al., 2016). The changes in average SWC ranged from 0.24 cm^3 cm^{-3} to 0.20 cm^3 cm^{-3} in the 0–200 cm soil layer. Below 200 cm, SWC did not decline in 2017 (Fig. 4a). In 2018, SWC was close to the upper bound SWC of a DSL in the 0–260 cm soil layer (Fig. 4b). At the same time, SWC in 0–360 cm was lower than the SWC at the beginning of the growing season. Therefore, growing alfalfa after food crops decreased SWC, and SWC approached the upper bound SWC of a DSL. Below 360 cm, SWC was stable compared to the beginning of the growing season in 2018 because of the small biomass of alfalfa in the first growing stage.

3.2. Temporal variation of S on depleting and restoring processes

Seasonal variation in the amount of stored water in the 500-cm-deep profiles was evident from 2016 to 2018. The S of the restoration treatment increased compared with the CK treatment (Fig. 5). From the beginning to the end of the growing season, S increased by 62.7% (from 431.5 mm to 702.1 mm) in 2016, and increased by 24.5% (from 755.7 mm to 941.0 mm) in 2017, and increased by 10.3% (from 789.0 mm to 869.9 mm) in 2018. Under the CK treatment, S was stable. On the contrary, S in the depletion treatment constantly declined (Fig. 5). By the end of September 2017, S declined from 1246.1 mm to 1213.4 mm, however, it increased slightly in October 2017. Then S declined until June 2018. In July and August, S increased due to high rainfall, and then decreased as alfalfa biomass increased throughout the growing period.

The soil water balances differed between the three land-use

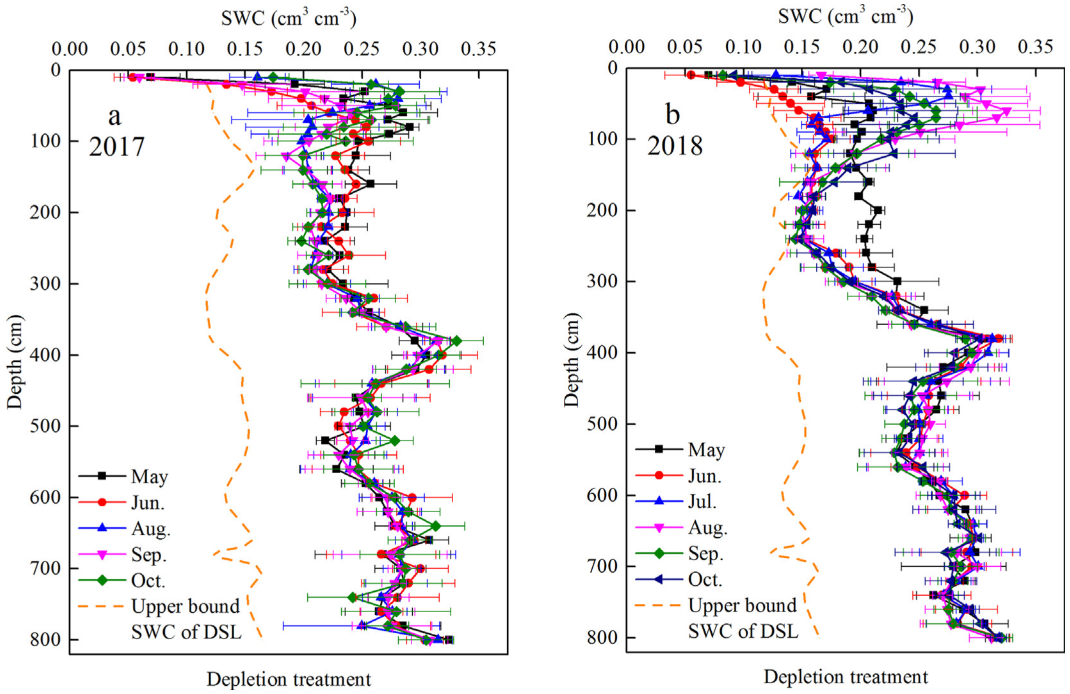

Fig. 4. Soil water content (SWC) dynamics of planted alfalfa following food crops (depletion treatment) in 2017 (a) and 2018 (b) at Shenmu, Shaanxi, China. Dashed line is the boundary SWC on which a dried soil layer (DSL) begins to form.

treatments. The restoration treatment exhibited a large increase in Δ*S* compared with CK from 2016 to 2018 (Table 2). There was 592.1 mm year^{-1} of average *ET* from the CK treatment, which was higher than the restoration treatment (482.0 mm year^{-1}) during the study period. The average Δ*S* was 68.9 mm year^{-1} over the three-year study for the CK treatment, and 178.9 mm year^{-1} for the restoration treatment. In contrast, a net decrease in Δ*S* occurred under the depletion treatment that planted alfalfa following food crops from 2017 to 2018 (Table 2). Alfalfa consumed all of the seasonal precipitation as well as an additional 41.1 mm year^{-1} of soil water.

3.3. Rate and depth of soil water depletion and restoration

Through the comparison of *S* depletion and restoration between the

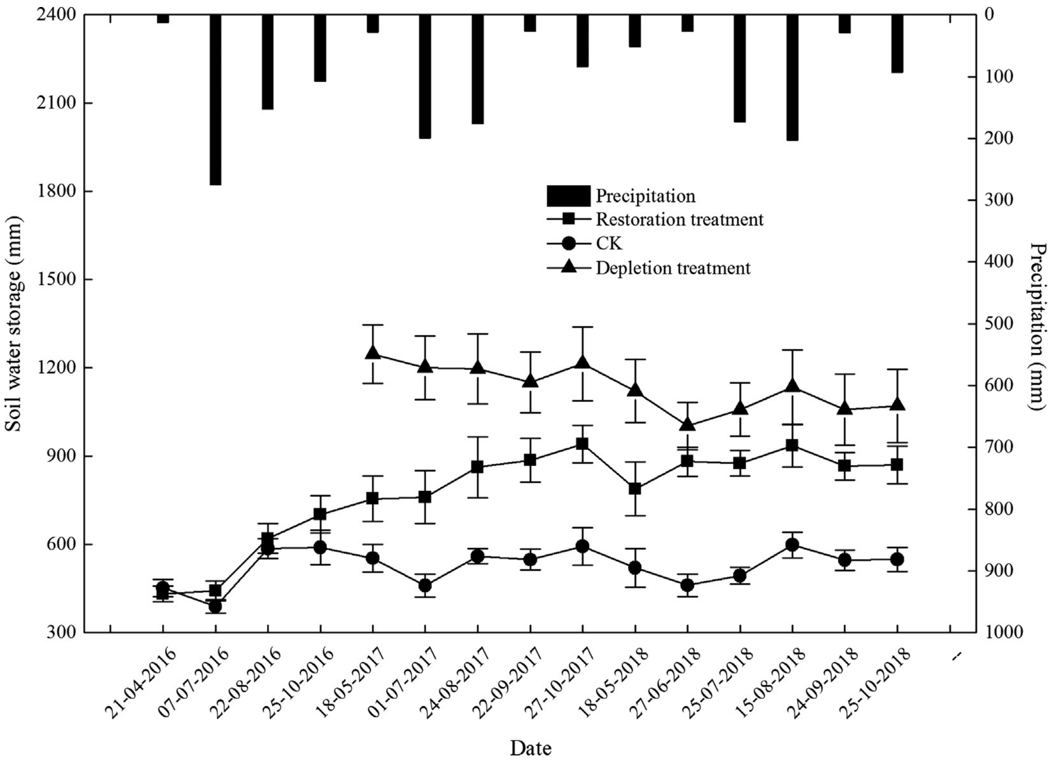

Fig. 5. Seasonal variations in 0–500 cm of soil water storage under vegetation conversion during 2016–2018. The restoration treatment is alfalfa to soybean; CK treatment is perennial alfalfa; depletion treatment is alfalfa following food crops.

Table 2

Soil water balance at 0–500 cm from 2016 to 2018 after converting vegetation types in Shenmu, Shaanxi, China. The restoration treatment is alfalfa to soybean; the CK treatment is perennial alfalfa; the depletion treatment is alfalfa planted following food crops.

	Precipitation (mm)	Restoration treatment	CK treatment	Depletion treatment
[a]S_{start}2016	704.3	431.5 ± 27.3[c]	452.3 ± 29.5	—
[b]S_{end}2016		702.1 ± 62.8	589.8 ± 59.2	—
[d]$\triangle S$		270.6	137.5	—
[e]*ET*		433.7	566.8	—
S_{start}2017	651.1	755.7 ± 76.9	553.2 ± 47.3	1246.1 ± 100.1
S_{end}2017		941.0 ± 63.0	593.2 ± 63.5	1213.4 ± 124.9
$\triangle S$		185.3	40.0	−32.7
ET		465.8	611.1	683.8
S_{start}2018	627.4	789.0 ± 92.0	519.9 ± 65.1	1120.8 ± 108.0
S_{end}2018		869.9 ± 63.4	549.0 ± 41.2	1071.2 ± 124.1
$\triangle S$		80.9	29.1	−49.6
ET		546.5	598.3	677.0
Average precipitation	660.9			
Average $\triangle S$[f]		178.9	68.9	−41.1
Average *ET*[g]		482.0	592.1	680.4

[a] S_{start} = soil water storage at the beginning of the growing season, mm.

[b] S_{end} = soil water storage at the end of the growing season, mm.

[c] ± Standard deviation.

[d] $\triangle S$ = total water storage change, mm.

[e] *ET* = evapotranspiration, mm.

[f] Average $\triangle S$ was the average value of $\triangle S$ within three years, mm year^{-1}.

[g] Average *ET* was the average value of *ET* within three years, mm year^{-1}.

Table 3

Rate of depletion (R_D) and restoration (R_R) among the three treatments in the 0–500 cm profile under vegetation type conversions. The restoration treatment is alfalfa to soybean; the CK treatment is perennial alfalfa; the depletion treatment is alfalfa planted following food crops.

	Restoration treatment	CK treatment	Depletion treatment
R_D/R_R in 2016 (mm year^{-1} m^{-1})	—/54.1	−12.6/27.5	—/—
R_D/R_R in 2017 (mm year^{-1} m^{-1})	—/37.1	−18.7/8.0	−19.1/−6.5
R_D/R_R in 2018 (mm year^{-1} m^{-1})	—/16.2	−11.7/5.8	−23.6/−9.9

three treatments, the rate of water increase in the restoration treatment was always higher than that in the CK treatment, and the rate of water decrease was always highest in the depletion treatment (Table 3). For the CK treatment, in 2016, the rate of soil water storage increased by 27.5 mm year^{-1} m^{-1} from the beginning to the end of the growing season, which was higher than in 2017 (8.0 mm year^{-1} m^{-1}) and in 2018 (5.8 mm year^{-1} m^{-1}). For the restoration treatment, the rate of soil water storage increased by 54.1 mm year^{-1} m^{-1} in 2016, but was lower in 2017 (36.5 mm year^{-1} m^{-1}) and 2018 (16.2 mm year^{-1} m^{-1}). However, the rate of soil water decrease in the depletion treatment was 19.1 mm year^{-1} m^{-1} in 2017 and 23.6 mm year^{-1} m^{-1} in 2018.

Soil water content restoration and depletion processes occurred simultaneously. Under the CK treatment of perennial alfalfa, the restoration depth (240 cm) was greater than the depletion depth (200 cm) in 2016 (Fig. 6). Until 2017, the restoration depth was 200 cm, less than the depletion depth (300 cm). In 2018, the restoration depth (200 cm) was less than the depletion depth (280 cm). For the restoration treatment with the conversion of alfalfa to soybean, the restoration depth was greater than the depletion depth; the restoration depth was down to 320 cm in 2016, and was deeper than the observation depth (500 cm) in 2017. In 2018, after the observed depth was increased, the restoration depth was down to 660 cm and the restoration processes were in progress. For the depletion treatment with the alfalfa planted following food crop, the depletion depth was 200 cm in 2017, and with the SWC continually consumed, the depletion depth was down to 360 cm at the end of the growth season in 2018. This occurred despite the two previous years being wetter than compared to the mean annual precipitation.

4. Discussion

4.1. Formation of DSL

DSLs – based on oure new index of DSL – were found if high water requirements were planted. The upper bound of DSL was defined as a soil layer with SWC that results in root water uptake being reduced by 50% (Van Genuchten and Nielsen, 1985). However, DSL has also been defined in previous studies based on desiccated soil as a soil layer with a SWC lower than 60% of field capacity (Chen et al., 2008; Wang et al., 2010; Wang et al., 2012b). The practicality of using this value should be discussed for different soil textures and vegetation types. Crops and drought-tolerant vegetation have different root water uptake parameters according to the HYDRUS-1D model (Feddes et al., 1978; Lv et al., 2014; Turkeltaub et al., 2018). For example, under the condition of DSL SWC, a crop may not be able to grow due to limited water uptake, but drought-tolerant vegetation may be able to grow. Our definition of DSL considers varied soil texture and vegetation types. For example, according to our definition, for alfalfa, the mean upper bound SWC of DSL was 0.083 cm^3 cm^{-3} in loessial soil (Fig. 3-c), and it was 0.137 cm^3 cm^{-3} in old loessial soil (Fig. 4). For loessial soil with the same texture, it was 0.102 cm^3 cm^{-3} and 0.097 cm^3 cm^{-3} for soybean (Fig. 3d-f) and corn, respectively. However, according to previous definitions (Chen et al., 2008; Wang et al., 2010; Wang et al., 2012b), the upper bound SWC of DSL was 0.156 cm^3 cm^{-3} in loessial soil.

DSLs can quickly form under vegetation with high water requirements. With the implementation of the "Grain-for-Green" project, the vegetation in the local study area has recovered gradually, and soil erosion has been substantially reduced (Fan et al., 2010; Zhang et al., 2018). However, with an increase in vegetation coverage, especially artificial vegetation, the SWC in the soil profile has decreased. This

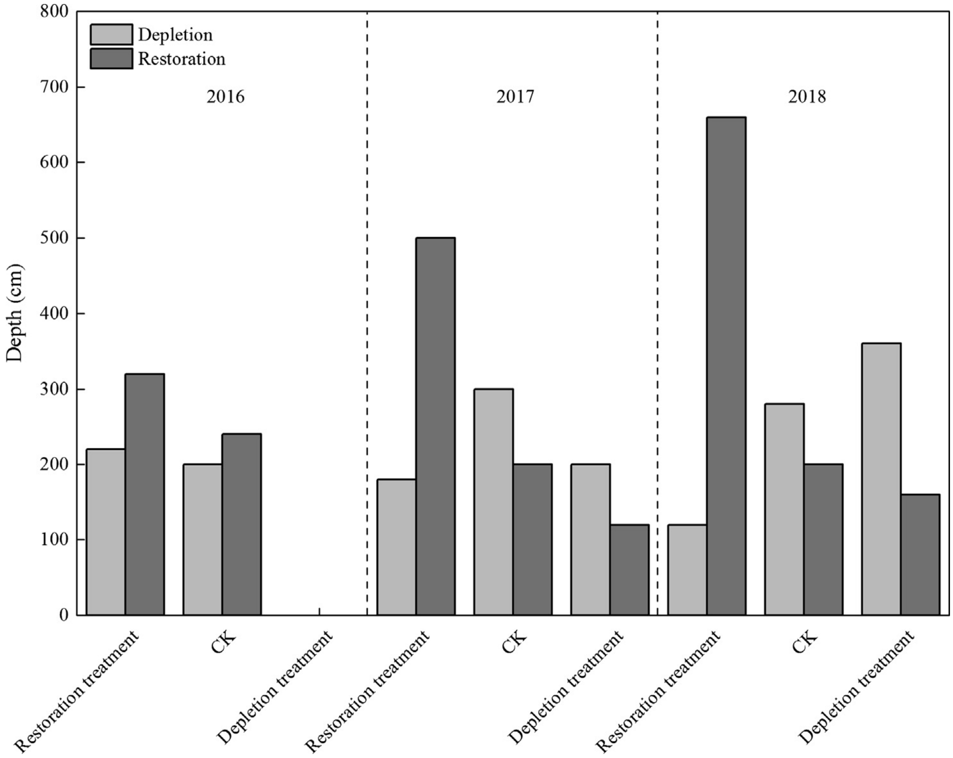

Fig. 6. Comparison of soil water depletion and restoration depths (cm) under vegetation type conversion. The restoration treatment is alfalfa to soybean; the CK treatment is perennial alfalfa; the depletion treatment is alfalfa planted following food crops.

quickly resulted in a DSL forming under vegetation with high water requirements. Wang et al. (2010) reported that a DSL was formed 2 years after planting alfalfa and 3 years after planting *Caragana korshinskii* in the Liudaogou watershed where our experiments were conducted. Cheng and Liu (2014) observed a DSL at a depth of 1–4.5 m under continuous alfalfa, and the DSL continued to extend to a depth of 10 m by 3 years after planting in the semi-arid Changwu Tableland region of the Loess Plateau, where average annual precipitation is 579 mm. Deep stocks of soil water on the Loess Plateau can be buffered against seasonal and inter-annual variation in rainfall, however, DSL occurrence indicated that the soil's buffering capacity has been lost. The deep soil water is also an important resource in many tropical forests. For example, in eastern Amazonia, forests are well buffered against seasonal and interannual variations in rainfall (Christina et al., 2017). However, the seasonally dry forests in Paragominas appears to be growing near the soil's buffering capacity in the severe dry years associated with El Nino Southern Oscillation (ENSO) events (Jipp et al., 1998). In this study, deep-rooted alfalfa depleted deep soil water in prior years and alfalfa biomass was controlled by rainfall.

A DSL formed in deep soil layer which still existed under perennial alfalfa, and a DSL appears to be forming after conversion from food crops to alfalfa in consecutively wet years. SWC under the CK treatment was stable at 0.06–0.09 $cm^3\ cm^{-3}$ at 300–500 cm, lower than the upper bound SWC of a DSL. This indicates a DSL has formed. At the same time, SWC was decreasing rapidly in the depletion treatment during two growing seasons (Fig. 4). In the 100–360 cm soil layer, the maximum reduction of SWC was 24.5% by the end of the growing season in 2018, and was close to the upper bound SWC of a DSL. The speed of DSL formation was slower than the results of Wang et al. (2010) due to relatively abundant precipitation. Soil water depletion depth reached 360 cm within the two wet years, and S declined at a rate of 8.2 $mm\ year^{-1}\ m^{-1}$. Even with the abundant precipitation in wet years 2017 (651.1 mm) and 2018 (627.4 mm), SWC still declined. This result is in accordance with previous studies (Cheng and Liu, 2014; Wang et al., 2010).

The *ET* of artificial alfalfa was nearly equal to or more than precipitation (Table 2). High evapotranspiration rates reduced precipitation replenishment to deep soil resulting in low SWC in the soil profile (Liu and Shao, 2016). This illustrates that alfalfa could rapidly deplete deep soil water with increased in root length, which is consistent with the conclusions of Fan et al. (2014). DSLs generally developed under perennial vegetation. Even after removing the vegetation, DSLs can persist for several decades (Cheng and Liu, 2014). If the precipitation only infiltrates down to shallow soil layers, the DSL will not disappear.

4.2. Δ*S* and restoration of the DSL

Δ*S* and precipitation infiltration depth differed when vegetation type was altered, consistent with previous research (Chen et al., 2008; Yang et al., 2014; Jian et al., 2015). Becasue introduced vegetation depleted SWC in deep soil (Yang et al., 2014), SWC in deep soil layers was lower than SWC in the upper bounds of the DSL (Fig. 3a–c). S of the CK treatment did not show large fluctuations within three wet years, with an average of 526.7 mm (Fig. 5). It indicated that SWC in deep soil layer could not be replenished by precipitation under perennial high-demand water vegetation within consecutive wet years. The infiltration was obstructed by the existence of a DSL and alfalfa in the CK treatment consumed all the water added during rainfall. Under alfalfa converted to soybean, S increased over three growth seasons by a total of 101.6% (from 431.5 mm in April 2016 to 869.9 mm in October 2018) (Fig. 5). Because local food crops (i.e. soybean) have shallow roots and lower water demands (Fan et al., 2016), extra water was able to infiltrate through the soil profile and S in deep soil layers could be recharged. On the contrary, S started to decrease slowly within two wet years; S decreased by 14.0% from May in 2017 (1246.1 mm) to October in 2018 (1071.2 mm) (Fig. 5) in the depletion treatment. This can be attributed to planting alfalfa two years prior and the alfalfa growing at a low water consumption period during the two consecutive wet years. It could be predicated that DSL would develop after alfalfa was grown at high water requirement stage as shown in the CK treatment.

Abundant precipitation could replenish the SWC of a DSL if evapotranspiration of vegetation was substantially reduced. In this study, soil water recharged down to 660 cm under soybean after alfalfa was removed during the continuously three wet years (in 2016, 2017 and 2018 with precipitation of 704.3 mm, 651.1 mm, and 627.4 mm, respectively), and by the end of those three years, SWC of the DSL was similar to the water content before planting alfalfa. This indicated that the SWC of DSL can quickly recover to pre-DSL conditions, and the recovery rate of SWC in the DSL was 35.8 mm $year^{-1}$ m^{-1} in the three wet years. Others have noted that the 3 m recovery time for a DSL was 7.3 years under a normal precipitation of 545 mm in the southern part of the Loess Plateau if apple trees were cut (Huang and Gallichand, 2006).

Food crops such as soybean were not an optimal choice on sloped land because soil erosion occurs on the slope (Wang et al., 2018), which is contrary with the objective of “Grain-for-Green”. Consecutive years of high precipitation rarely happen in the semi-arid region of the Loess Plateau. To balance the sustainable use of soil water resources with precipitation, it is important to consider plant species selection.

4.3. Measures for sustainable water management

Water resource sustainability and ecosystem perseverance should be considered when vegetation is restored, especially in arid and semi-arid regions. Soil water infiltration and root water uptake depth are greatly affected by introduced vegetation in semi-arid regions (Fan et al., 2016). Selecting proper land use types and plant species is important, especially where there is a lack of available water (Liu et al., 2016; Wang et al., 2012c; Yang et al., 2012). Fan et al. (2017) found rooting depth was highly sensitive to local soil profile water content determined by precipitation infiltration depth and groundwater table depth.

The root depth of shrubland and a mix of shrubland-alfalfa, shrubland-orchard, shrubland-grassland have been reported to be up to 1800 cm, 1550 cm, 600 cm, and 560 cm, respectively (Wang et al. 2015). Deep roots of shrubs or trees can increase the volume of soil that could supply water in order to support high evapotranspiration (Asbjornsen et al., 2008; Reader et al., 1993). *C. korshinskii* and *Robinia pseudoacacia* have been highly recommended for vegetation restoration in the Anjiapo catchment which has an annual mean precipitation of 420 mm (Jian et al., 2015). However, *C. korshinskii* and *R. pseudoacacia* have been recognized as vegetation with high water demand (Jia et al., 2017). Deep-rooted and high water-consumption vegetation such as artificial alfalfa, *C. korshinskii*, *R. pseudoacacia* (Jia et al., 2017), and *P. tabuliformis* (Zhang et al., 2015) occupied a large percentage around our study site, and these species would further deplete *S*. However, these species should not be the primary choice in semi-arid loess (Liang et al., 2018). It is essential that the current vegetation recovery strategy be reevaluated with consideration to vegetation sustainability and soil water availability (Wang et al., 2017). In addition, Zhang et al. (2015) provided a reference guide for planting coverage for different precipitation regions according to many quantitative results, and choosing reasonable planting densities based on different precipitation regions could also help to reduce *ET*.

Our study showed that SWC of DSLs can be quickly recovered fully if deep-rooting plants are removed. To avoid the formation of DSLs in semi-arid regions, planting shallow-rooted vegetation instead of deep-rooted plants should be considered. Shallow-rooted vegetation would improve soil and water conservation, similar to natural restoration by succession (Deng et al., 2016; Jia and Shao, 2014; Liu and Shao, 2016; Wang et al., 2015) and artificial grassland. However, a large proportion of natural grasslands have been greatly influenced by shrub encroachment (Li et al., 2019; Zhou et al., 2019) and shrubs consume significantly more water than grass (Su and Shangguan, 2019). Similarly, woody plants and eastern redcedar (*Juniperus virginiana*) have encroach into tallgrass prairie and this has led to greater soil water depletion in the 0–80 cm soil layer, resulting in artificial encroachment becoming a threat to groundwater replenishment in dry sub-humid regions (Acharya et al., 2017).

Some areas with fertile soils were abandoned due to the low income for the farmers in mountain areas of Europe and the Western Mediterranean (Hatna and Bakker, 2011; Macdonald et al., 2000; Romerodíaz et al., 2017). Vegetation recovery after abandonment has been successful, but high erosion and low soil quality were found under semiarid conditions (Romerodíaz et al., 2017). Compared with natural succession, high-diversity grassland artificially planted with C3 and C4 shallow-rooted grass species on abandoned and degraded lands could reduce nitrate leaching, reduce invasive plant species, and increase underground biomass and carbon sequestration (Yang et al., 2019). Herbaceous vegetation with a relatively shallow effective rooting depth that replaces woody plants has been shown to improve biodiversity, reduce erosion and increase deep drainage, replenishing soil storage in southwest Idaho where mean annual precipitation is 550 mm (Seyfried and Wilcox, 2006). Williamson et al. (2005) found that recharge capacity increased due to decreased transpiration rates that followed shrub removal in San Dimas experimental forest which has a mean precipitation of 678 mm. Therefore, proper land management is required regardless of the vegetation. Maybe shallow-rooted grassland should be developed which can achieve ecological and economic development. Future research should explore which vegetation restoration efforts will achieve this goal in the water-wind erosion crisscross region on the Loess Plateau.

5. Conclusions

Conversion of vegetation types along with precipitation impact *S* and infiltration depth. After conversion from food crops into alfalfa, *S* consistently decreased, and the depletion depth consistently increased even during consecutive wet years. On the contrary, after conversion from perennial alfalfa into soybean, the rate and depth of restoration continuously increased over time. SWC was restored at an average rate of 35.8 mm $year^{-1}$ m^{-1}, and the restoration depth was up to 660 cm in three wet years. These results indicated that SWC of DSL could be recovered with consecutive wet years, and altering vegetation types between deep- and shallow-rooted vegetation could play an important role in soil water restoration and depletion. The new standards to define a DSL include soil textures and vegetation types, which may be used to more accurately judge soil water status under different vegetation. Furthermore, vegetation conversion should be considered according to the SWC of DSL.

CRediT authorship contribution statement

Jiamin Ge: Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Jun Fan:** Conceptualization, Methodology, Writing - review & editing, Project administration. **Hongyou Yuan:** Investigation, Supervision. **Xueting Yang:** Investigation. **Mu Jin:** Investigation. **Sheng Wang:** Investigation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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