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Soil water storage deficit of alfalfa (*Medicago sativa*) grasslands along ages in arid area (China)

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A R T I C L E I N F O

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A B S T R A C T

Alfalfa (*Medicago sativa*) is a high-yield and high drought-tolerant perennial forage crop, which take up water from deep soil layers by its deep root system. Long-term cultivation of alfalfa without a sufficient water supply aggravates soil water storage deficits, which are not conducive to plant succession. In this study, we studied the above-ground biomass and the degree of soil water storage deficit at different alfalfa stands of different planting ages. The experiment was conducted in six alfalfa grasslands of different ages. Soil water content of the 0–300 cm soil layer in each grassland was measured for the calculation of soil water storage deficit. The results showed that soil water storage increased gradually along the soil profile. The degree of soil water storage deficit was the highest in all six alfalfa grasslands at the depth of 0–150 cm. The deficit degree of the one- and six-year-old alfalfa grasslands was significantly higher than that at the grasslands that had been cultivated for two to five years ($P < 0.05$) at the depth of 0–100 cm. The deficit degree of the four- and five-year-old alfalfa stands was less than 10% below the depth of 200 cm. The above-ground biomass reached a peak value in grasslands that had been cultivated for three and four years, and then gradually decreased. In summary, based on its relatively high yield and low soil water consumption intensity, the optimal cultivation age for alfalfa grasslands was four years. Thus, irrigation should be increased after five years' cultivation of alfalfa. Moreover, more water should be supplied to the upper soil layer of one-year-old alfalfa grassland stands. This study provides the basis for water management measures of alfalfa grasslands in arid areas.

1. Introduction

Global climate change results in temperature rise, and such rise can increase potential evapotranspiration, and further aggravates the drought in semi-arid regions (Muluneh et al., 2015). Soil water content is the key limiting factor for crop growth in arid regions. Higher water consumptions by crops aggravate soil drought and lead to the decline of crop productivity (Brookshire and Weaver, 2015). Araya et al. (2012) reported that the decline of crop yields was mainly due to drought. As population increases, the demand for crops also increases (Sharma et al., 2017). To meet the ever-increasing demand for food, many artificial grasslands were built to increase pasture yield. Legumes are generally used for grassland planting, and alfalfa (*Medicago sativa*) is one of the most popular species in arid and semi-arid regions. Alfalfa is a high-yield perennial forage crop which can rapidly regenerates many new stems after harvest, and it can be harvested multiple times during the growing season (Lamm et al., 2012; Brink et al., 2015). Alfalfa is widely grown around the world, especially in water-limited regions, due to its capacity to take up water from deep soil layers via its deep roots system (Zhu et al., 2016; Sim et al., 2017). However, due to its high-yield and extensive taproot system, it consumes much more soil water than other forage grasses (Ren and Huang, 2016), thus aggravating soil desiccation and creating adverse conditions to vegetation succession in arid regions.

Many studies have indicated that the high productivity and deep root distribution of alfalfa results in high levels of evapotranspiration, and planting of alfalfa results in increased soil water storage deficits and aggravates soil desiccation over time in arid regions (Li et al., 2008; Zhu et al., 2016). Some studies had indicated that shallow groundwater can supply plenty of water for vegetation evapotranspiration (Ramos

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et al., 2017; Xue et al., 2017). Successive planting of alfalfa with increasing water demands may cause declines in the shallow groundwater (Zheng et al., 2012). Soil desiccation and the decline in groundwater have negative effects on soil water balance, leading to reductions in the drought-resistance ability and growing rates of alfalfa and causing adverse effects on the growth of subsequent crops (Wu et al., 2015; Zheng et al., 2012; Chen et al., 2008). The cultivation time of alfalfa has significant influences on the aboveground productivity and belowground soil water storage. It is feasible to restore the soil water content after long-term planting of alfalfa, but a longer recovery time is required for better soil water conditions (Jia et al., 2009). Wang et al. (2012) suggested that when the age of alfalfa stands reached 10 years, the desiccation of the 0–6 m soil layer reached the extreme degree and was difficult to recover. Du et al. (1999) reported that alfalfa that had been planted for eight years almost needed four or five years to restore the soil water conditions. Soil water properties and forage quality of alfalfa gradually degrade with time (Ren et al., 2011). Li and Huang (2008) indicated that soil water storage of alfalfa grassland decreased by 33.5 mm $year^{-1}$ in the 0–500 cm soil layer, and the yield decreased with time by 0.629 t ha^{-1} $year^{-1}$ in semi-arid regions. Therefore, to avoid over-consumption of soil water and maintain a high yield, it is essential to determine the best cultivation ages for alfalfa based on the trade-off between soil water storage and crop productivity in water-limited regions. Furthermore, the degree of water storage deficit under different cultivation ages of alfalfa grasslands is an important indicator for irrigation. Proper use of soil water resource is in the favour of the sustainability of agriculture, especially in arid and semi-arid regions (Keesstra et al., 2016).

It is urgent to balance the soil water storage and productivity of alfalfa grasslands in arid regions, and the cultivation ages of alfalfa is a key determining factor for such balance. However, few studies have focused on the feasibility of alfalfa cultivation ages based on the perspective of increasing of soil water deficit, which varies with the increasing growing ages. The characteristics of soil water consumption along alfalfa profiles in shallow groundwater areas warrants further investigation. Therefore, the aim of this study was to examine the characteristics of soil water storage deficits of alfalfa grasslands along cultivation ages, and to ascertain the optimal age of alfalfa grasslands in order to avoid excessive consumption of soil water. The results of this study can provide a basis for soil water management of alfalfa profiles with different cultivation ages.

2. Materials and methods

2.1. Description of the study site

The study was conducted in an alfalfa farm at the Helan Mountain, which is located in Yinchuan City of the Ningxia Hui Autonomous Region in China (38°30′ N, 106°02′ E). The altitude of the study region is 1135 m. The area has a moderate temperate continental monsoon climate, the annual mean temperature is 8.4 °C, the minimum and maximum temperature is −20 °C and 38 °C, respectively. The mean annual precipitation is 200 mm, and the annual evaporation is approximately 2250.0 mm. The average annual hours of sunshine is 3075.5 h. The mean annual frost-free period is approximately 160 d. The soil type is light sierozem. The water table is shallow and approximately 4–5 m.

2.2. Field experiments

The alfalfa grasslands of the study site were planted from 2012 to 2017, so we studied alfalfa grasslands that had been growing for one-six years. The row space of the alfalfa grasslands was 25 cm. The aboveground parts of alfalfa were harvested four times a year. The first harvest was at the end of April, and subsequent harvests occurred every 30 days. The six grasslands were close to each other. The status of alfalfa growth is shown in Fig. 1. The cultivation conditions and management measures of the studied sites were the same. Soil and plant samples were collected from July 20 to 26, 2017, before plants were mowed.

Fig. 1. Growth status of alfalfa (*Medicago sativa*) in the study regions.

2.3. Sampling and measurements

Gravimetric soil water content of the 0–300 cm soil depth range was measured at 10-cm intervals by using a soil auger of 4-cm diameter and 20-cm height. Each alfalfa grassland had three parallel samples, and total 540 soil samples were taken. The collected soil samples were weighed immediately, dried at 105 °C for 24 h, and then weighed again. The auger samples were taken at each grassland site, and the soil water storage was calculated as follows (Gao et al., 2014):

$$W = h \cdot \rho \cdot \theta \cdot 10^{-1} \quad (1)$$

where W is the soil water storage (mm), h is the soil depth (cm), ρ is the soil bulk density (g cm^{-3}), and θ is the gravimetric soil water content (%).

The soil water storage deficit degree (DSW) was calculated as follows (Wang et al., 2004):

$$DSW = Da/Fc \times 100\% \quad (2)$$

$$Da = Fc - W \quad (3)$$

where Da is the soil water storage deficit (mm) and Fc is the field capacity (mm).

Five 1 × 1 m^2 quadrats were taken at each site to represent the average growth conditions. The above-ground parts of plants in each quadrat were harvested, dried at 75 °C for 72 h, and then the dry mass was weighed. The above-ground biomass was measured before the fourth harvest. The growing rates were calculated by the follow equation:

$$R_A = A/D \quad (4)$$

where R_A is the growing rate ($g\,m^{-2}\,yr^{-1}$), A is the amount of the increase of the dry, above-ground biomass ($g\,m^{-2}$) (calculated by the current biomass minus the biomass of the previous year), and D is the year of plant growth (yr), which was one in this study.

Collection of the below-ground biomass samples was performed by digging a soil profile (1 m × 1 m × 1.2 m), and there were three parallel profiles in each alfalfa grassland. Below-ground biomass samples from the 0–100 cm soil layer were taken at 10-cm intervals, and the sample volumes were 20 cm × 20 cm × 10 cm. After bringing the samples to the lab, roots were separated from the soil using a 2-mm sieve. The separated roots were dried at 75 °C for 48 h, and then their dry mass was weighted. The growing rates of the below-ground biomass were calculated by the follow equation:

$$R_B = B/D \quad (5)$$

where R_B is the growing rate ($g\,m^{-2}\,yr^{-1}$), B is the amount of the increase of dry below-ground biomass ($g\,m^{-2}$) (calculated by the current biomass minus the biomass of the previous year), and D is the year of plant growth (yr), which was one in this study.

2.4. Statistical analyses

Data pre-processing was performed using Excel 2010. One-way ANOVA and tests of significance were conducted by using SPSS 18.0. The figures were plotted using SigmaPlot 12.5. Significant differences were determined at the 0.05 significance level.

3. Results

3.1. Vertical distribution of soil water storage

Soil water storage of all alfalfa grasslands studied increased with soil depth in the 0–300 cm soil layer (Fig. 2). The differences in soil water storage among the six alfalfa grasslands of different ages were the greatest at the depth range of 50–150 cm. Soil water storage of the six-year-old alfalfa grassland was the lowest in the 20–100 cm soil layer. In contrast, soil water storage of the one-year-old alfalfa grassland was the lowest in the 50–100 cm soil layer.

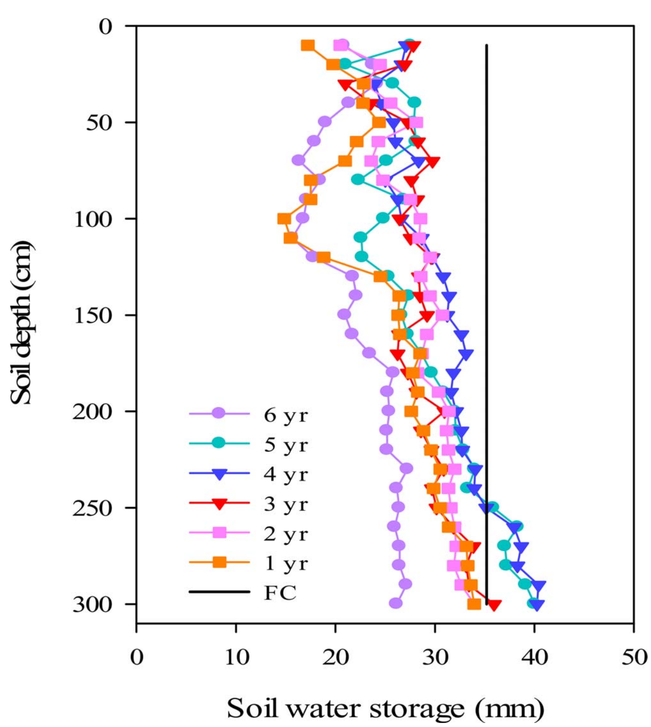

Fig. 2. Soil water storage in the 0–300 cm layer at 10-cm intervals in alfalfa grasslands of different stand ages. 1 yr denotes the one-year-old stand, 2 yr denotes the two-year-old stand, and so on. Fc denotes the field capacity.

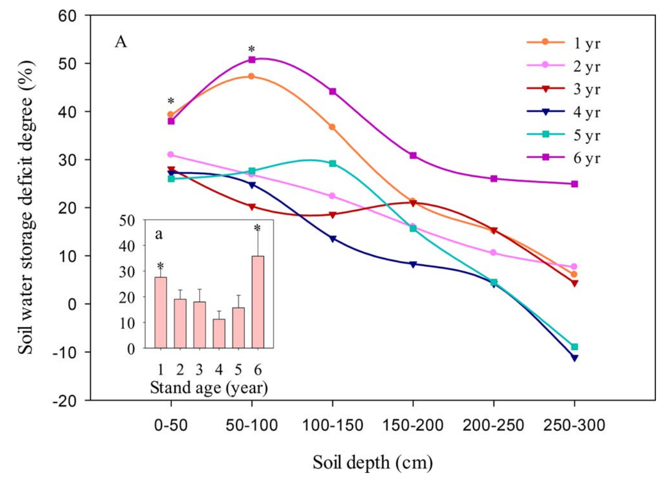

Fig. 3. Soil water storage deficit degree of different soil layers (A) and the whole 0–300 cm soil layer (a). 1 yr denotes the one-year-old stand, 2 yr denotes the two-year-old stand, and so on. *Indicates that the soil water storage deficit degree is significantly different at the 0.05 significance level.

3.2. Soil water storage deficits

Soil water storage deficits of the one-year-old and six-year-old alfalfa grasslands were significantly higher than those of the two- to five-year-old alfalfa grasslands at the depth range of 0–300 cm ($P < 0.05$, Fig. 3). Along the soil profile, soil water storage deficit of all alfalfa grasslands studied was the greatest at the depth range of 0–150 cm and then decreased with increasing soil depth. Soil water storage deficit at the depth ranges of 0–50 cm and 50–100 cm of the one- and six-year-old alfalfa stands were significantly higher than those in the two-five-year-old alfalfa stands ($P < 0.05$). Soil water storage deficit was the greatest at the depth range of 50–100 cm (44%) and 100–150 cm (50%) after six years' alfalfa cultivation. For the one-to five-year-old alfalfa grasslands, the deficit degree was higher at the depth range of 0–50 cm and 50–100 cm than at other soil depths. Below the soil depth of 200 cm, soil water storage deficit of the four- and five-year-old alfalfa grasslands was less than 10%, and soil water storage exceed the field capacity ($35.2\,cm^3\,cm^{-3}$) below the soil depth of 250 cm.

3.3. Above- and below-ground biomass

The above-ground biomass of the one-year-old alfalfa grassland was significantly lower than that of the two-six-year-old alfalfa grasslands ($P < 0.05$, Fig. 4). The three-year-old ($313.16 \pm 95.77\,g\,cm^{-2}$) and four-year-old ($312.33 \pm 28.95\,g\,cm^{-2}$) alfalfa grasslands had the highest above-ground biomass, which was approximately 21.4%, 16.3%, and 8.6% higher than the values at the six-, five- and two-year-old alfalfa grasslands, respectively. The growing rate of the above-ground biomass was the highest in the two-year-old grassland, and then it decreased sharply with years. The above-ground biomass showed a downward trend after the 4th year ($-0.8\,g\,m^{-2}\,yr^{-1}$). The below-ground biomass increased with increasing stand age, and the growing rate was the highest in the 2nd year, being $340\,g\,m^{-2}\,yr^{-1}$, a peak value which was 77% higher than that in the 3rd year. The growing rate gradually decreased after the 3rd year.

4. Discussion

Alfalfa is a high-yield forage crop, but it also shows a high water consumption, because it can take up water from the deep soil layers.

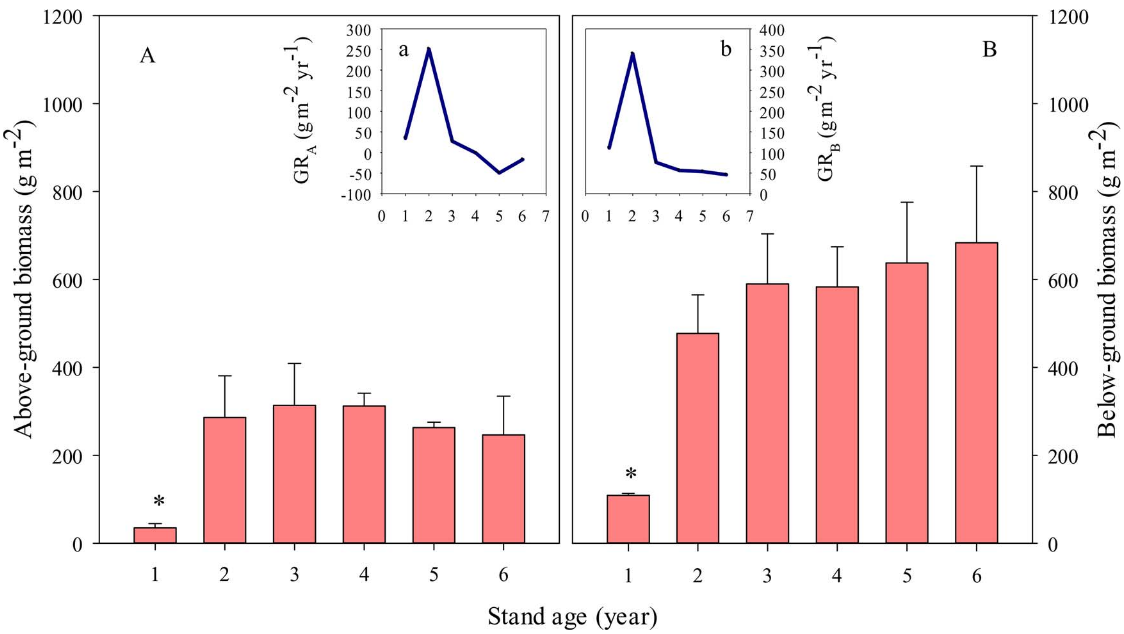

Fig. 4. Above-ground biomass (A), below-ground biomass (B), growing rate of above-ground biomass (GR_A) (a) and below-ground biomass (GR_B) (b) in alfalfa grassland stands cultivated for one to six years. *Indicates that the biomass values are significantly different at the 0.05 significance level.

Previous studies have found that the soil storage water consumption depth gradually deepens as the age of the alfalfa grasslands increases (Ren et al., 2011). The consumption of stored soil water may result in serious soil water deficits. Our study indicated that the degree of soil water deficit was different in alfalfa grasslands of different stand age and also varied with soil depth. Many studies have indicated that planting perennial alfalfa leads to the desiccation of deep soil layers in arid and semi-arid regions (Li et al., 2008; Jia et al., 2009; Ren et al., 2011), which restricts the growing rate of alfalfa (Zhang et al., 2017). Therefore, long-term planting of alfalfa is adverse to its productivity, and make it difficult to meet the future sustaintable forages demand. Our study found that the growing rate of alfalfa decreased when the stands were more than two years old. The vertical distributions of soil water may be different in areas with and without groundwater recharges at a shallow groundwater level. Groundwater is an important water source for alfalfa growing in areas with a shallow groundwater table (Zhu et al., 2016). In the study region of the present study, shallow groundwater has a great influence on soil water distribution, and over-consumption of soil water may cause the decline of the groundwater table (Zheng et al., 2012). Prudent water management is necessary to maintain a high yield and better soil water conditions.

Soil water storage is a critical indicator of water resources, which are the foundation of vegetation planting, especially in water-limited areas (Zhao et al., 2017). In this study, soil water storage of one- and six-year-old alfalfa grasslands decreased with increasing soil depth at the depth range of 30–100 cm. Soil water consumption intensity of the one- and six-year-old alfalfa grasslands was higher than that of the two-five-year-old alfalfa grasslands. Soil water was consumed by two ways, evaporation and transpiration. Evaporation mainly consumed the stored soil water at the depth range of 0–60 cm (Liu et al., 2015; Zhang and Shangguan, 2016). Root water uptake is the key mediator of plant transpiration (Zhang et al., 2016; Schenk and Jackson, 2002). The one-year-old alfalfa grassland had the lowest above-ground biomass, the lowest land coverage and the highest amount of soil water consumed through evaporation. In addition, the roots of alfalfa were mainly distributed in the depth range of 0–100 cm (Li et al., 2003; Fu et al., 2012), where soil water consumption intensity was higher. Therefore, plants with lower land coverage and higher root biomass will consume more soil water. As global temperature rises, the evapotranspiration will also increases, thus aggravating drought in arid regions (Muluneh et al., 2015).

The study region had shallow groundwater (4–5 m), which can supply part of the water used for alfalfa growth by capillary rise (Wu et al., 2015). The degree of soil water storage deficit varied, it decreased first and then increased with grassland age. The deficit degree was lowest for the four-year-old alfalfa grassland, and it reached the highest value after six years' cultivation. Both soil water consumption intensity and the deficit degree were higher at the depth range 0–150 cm than at other depths measured. Further, the deficit degree was higher in the one- and six-year-old alfalfa grasslands than in the two-five-year-old alfalfa grasslands. Moreover, the deficit degree of the six-year-old alfalfa stand was higher than that at the younger alfalfa stands along the 0–300 cm soil profile, and the more extreme deficit were showed at the depth of 50–150 cm. Our study demonstrated that, due to the shallow groundwater in study area, soil water deficit was greater in the upper soil layers than in the lower ones, especially in the 1st growing year. In addition, the six-year-old alfalfa may have caused a serious water deficit. The introduction of high water-consumption vegetation can result in the decrease of available groundwater (Zheng et al., 2012), which would lead to the decline of water table, if there is not adequate water recharge from other ways. In this study, the deficit degree increased with the cultivation time of the alfalfa grasslands. To reduce the degree of soil water storage deficit and prevent the decline of the water table in alfalfa grasslands, for grasslands with a stand age of one year, soil water must be supplied to the upper layer of the soil. Moreover, as the time since the planting year increases, the deeper soil layer needs increased amounts of soil water replenishment. For the development of sustainable agriculture, it is urgent to design a proper irrigation scheme to mitigate soil dessication and reduce excessive consumption of groundwater (Keesstra et al., 2018).

Soil water storage and productivity decrease with the stand age of alfalfa (Ren et al., 2011). Du and Qu (1994) indicated that the life of an alfalfa stand should be less than three years in arid regions, due to decreases in the yield after the 3rd year. Moreover, a higher degree of soil water storage deficits occurred after six years' alfalfa cultivation compared to earlier years (Ren et al., 2011). Our study indicated that the highest growing rates of the above- and below-ground biomass of the alfalfa grasslands both appeared in the 2nd year of growth and then decreased with increasing stand age. The above-ground biomass reached its peak value during the three- and four-year stand age. After

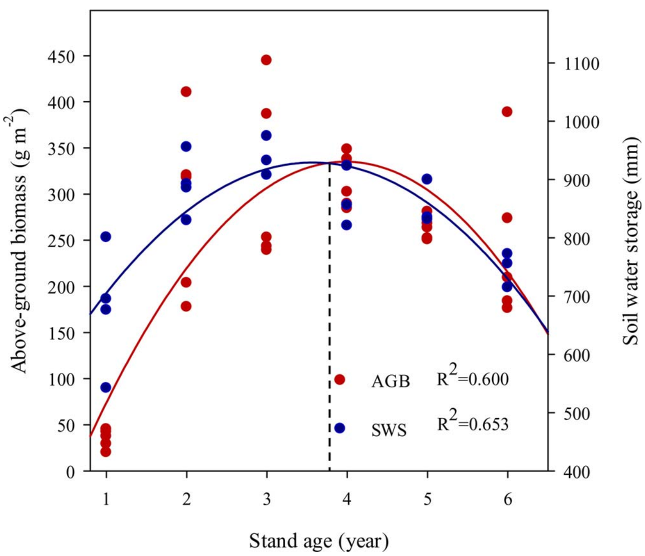

Fig. 5. Relationships between the above-ground biomass (AGB) and soil water storage (SWS) in the 0–300 cm soil depth range of stands of different ages. The black dashed line indicates the fit growing year (3.8 years) of alfalfa grasslands, determined by the peak values of above-ground biomass and soil water storage that occurred at this age.

the 3rd year, the below-ground biomass of the stands gradually increased. Increases in root biomass and length can aggravate the consumption of soil water and increase the consumption of stored deep soil water (Li et al., 2010). The increased dryness could also drive a decline in grassland productivity (Brookshire and Weaver, 2015). Severe reduction of crop yields in arid and semi-arid regions due to long-term dryness has been reported (Muluneh et al., 2015).

For maintaining better soil water conditions and higher productivity, our results suggest that the best planting age for alfalfa is four years in arid areas with shallow groundwater (Fig. 5). After four years' planting of alfalfa, the productivity and soil water storage both decreased, and the degree of soil storage water deficit reached a significant level after five years' planting of alfalfa. Hence, the maximum stand age of alfalfa should not be longer than five years, from both soil moisture condition and economic perspectives. Less precipitation and severe soil desiccation caused by alfalfa make it difficult to restore soil water conditions (Wang et al., 2012), and it is not favourable for the sustainable development of agriculture in arid regions. Timely crop rotation when the stand age of alfalfa reaches five years will help restore the soil water conditions, and groundwater can provide water for crops when the precipitation is not sufficient (Wang et al., 2012). It is essential to take land management for achieving the goal of developing sustainable agriculture (Keesstra et al., 2016).

5. Conclusion

Long-term planting of alfalfa could aggravate soil water deficits and produce further reductions in the yield. The results of this study indicate that the soil water storage deficit is higher in the 0–150 cm soil layers. Moreover, the deficit degree was greater in one- and six-year-old stands of alfalfa grasslands. The growing rates of above- and below-ground biomasses were higher for the two-year stand age than others, and the above-ground biomass reached its highest value at the three- and four-year-old stands, and then decreased. Compared to other grasslands, the four-year-old alfalfa grassland had the highest yield and maintained the best soil water conditions. To maintain high crop productivity and improve soil water storage conditions, crop rotation is needed after five years' alfalfa cultivation. In addition, the upper soil layer of one-year alfalfa grassland stands may need a greater soil water supply than that of other stands.

Conflict of interest statement

The authors declare that there is no conflict of interest.

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