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Soil Water Depletion in Planted Alfalfa Pastures in an Alpine Pastoral Area

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Abstract: Alfalfa (*Medicago sativa*) has strong stress resistance, high nutritional value, good palatability for cattle, high yield and a drought tolerance mechanism, but long-term planting leads to soil desiccation. This research was carried out to examine the soil water conditions of alfalfa pastures with different planted ages, and determine the optimum time for alfalfa rotation in a plateau area of a sub-alpine monsoon climate. Soil water depletion, soil compaction and vegetation characteristics of alfalfa pastures of different ages (i.e., two, four and seven years) were assayed and compared with those of a cornfield which served as the control crop. Three 20 $\times$ 20 m plots and five random quadrats per plot were established at each field. Soil water contents at 0–400 cm depth and plant biomass were compared among different vegetation types, soil transects and planting years. The results showed that at the 250–400 cm depth, the soil water storage of the four- and seven-year-old alfalfa pastures was much lower than in the two-year-old alfalfa pasture and in the cornfield. Moreover, the degree of soil water storage deficit of the four- and seven-year-old alfalfa pastures was much higher than in the other fields. Soil compaction of alfalfa pastures increased with increasing planting age and reached a peak value in the seven-year-old alfalfa pasture. The highest above-ground biomass was observed in the four-year-old alpine alfalfa pasture. Thus, the best cultivation period for alfalfa pastures was four years from the perspective of higher yield and lower soil water consumption in pastoral sub-alpine areas. This study provided a basis for sustainable alfalfa pasture cultivation, timely harvest, rotation and water management measures to be implemented in alpine grazing lands.

Keywords: alfalfa; soil water storage; soil water deficit; planting ages; Tibetan Plateau

1. Introduction

Soil moisture is an important limiting factor for vegetation growth, seedling establishment and crop production [1,2]. How to increase the utilization efficiency of soil moisture has gradually become a research hotspot in recent years [3,4]. Alfalfa (*Medicago sativa*) is known for its high biomass yield, excellent grass quality and high nutritional value among forage species [5,6]. The rhizobia of alfalfa have a significant effect on soil nitrogen-fixing and soil quality improvement. Because the alfalfa's root system reaches deep soil horizons, it can fully absorb the water stored along the soil profile causing soil desiccation [7]. Rainfall infiltration also affects the soil water recharge and lower rainfall infiltration would lead to soil desiccation and a decrease in pasture productivity [8]. In recent years, the shortage of water resources has become an urgent issue worldwide. Moreover, it is expected that global climate change, particularly changes in temperature and precipitation patterns, will have a significant impact on the productivity and water balance of terrestrial ecosystems [1]. Low economic input, low water consumption, high water efficiency and the maintenance of favorable forage production are among the current focus for achieving sustainable agriculture and animal husbandry [9].

Several studies on water use efficiency and plant growth of alfalfa and some common bean plants have been carried out in the grasslands [7,10]. Some studies indicated that the productivity of alfalfa is related to the irrigation volume, deep root distribution, precipitation and temperature, and concluded that long-term cultivation of alfalfa leads to soil desiccation under arid and semi-arid climatic conditions [11]. In Australian pasture lands, Ridley et al. [12] observed that alfalfa demands more water than other forage plants and its deep root system extracts moisture from deeper soil horizons, thus resulting in dry layers in deeper soil and long-term lower crop yields. Jia et al. [13] reported that the improvement of soil moisture and temperature and the use of deep soil water are conducive to increasing yield and water use efficiency of alfalfa. Many crops present better adaptability to controlled drainage and subsurface irrigation systems. For instance, Lothar et al. [14] highlighted that water requirements strongly rely on the water control level and the type of crop. Alfalfa may cause declined shallow groundwater and increased soil compaction after several years' cultivation [15].

Some authors have studied the biomass and yield of alfalfa, for example, Lamb et al. [16] reported that biomass management systems had a 37% increase in cell wall polysaccharide yield in all alfalfa germplasms compared with hay management systems. To reduce harvesting costs and to extend the crop's shelf life, low-harvest biomass management systems can help increase the economic efficiency. Zhang et al. [17] indicated that intercropping grains with beans allows increases in crop yield and land use efficiency. Alfalfa accumulates greater above-ground biomass carbon, and continuous root growth can increase carbon sequestration and soil biological activity in dry soil compared with annual vegetation [18].

Alfalfa consumes large quantities of soil water; therefore, continuous planting of alfalfa could cause soil desiccation and ground water depletion. Soil water deficit caused by long-term planting of alfalfa and the feasibility of soil moisture recovery have not been explored sufficiently and require more attention and specific research studies. The decrease in groundwater recharge may cause water scarcity at the regional level in the near future [19]. Large amounts of grasses have been consumed in pastoral areas and will have a significant impact on soil water consumption. In order to maintain the high pasture yield of alfalfa, it is necessary to determine the optimal cultivation period based on the soil water deficit index, the soil water storage performance and the productivity level of alfalfa in pastoral areas.

Due to specific geographical and climatic constraints, grasslands in pastoral areas are dominated by species of the Gramineae and Cyperaceae families. The dominance of single pasture species at a specific site, insufficient forage legumes, lack of forage and a lag in the development of cultivated grasslands cause the reduction of grass storage, which can be very prominent and seriously restricts the development of local animal husbandry and economy. Continuous cultivation of alfalfa affects the soil water storage and the grassland's productivity [20]. Soil water compensation potential refers to the potential to mitigate the negative impact induced by water-intensive activities in water-scarce lands. It was observed that plant growth with increase age of revegetation, particularly below-ground biomass, absorbed more soil water and caused soil desiccation [20]. Therefore, it is important to assess the soil water compensation potential of the planted species and develop specific soil water conservation techniques for proper management of the groundwater in Tibetan pastoral areas. The objectives of this study were to: (1) examine the effects of alfalfa pastures of three different ages on the soil water storage at a Tibetan Plateau study site by using a cornfield as the control crop; and (2) to determine the optimum time for alfalfa rotation. The results of this study will provide evidence for sustainable soil hydrology of alfalfa cultivation on the Tibetan Plateau and other alpine pastoral areas.

2. Materials and Methods

2.1. Experimental Sites

The experimental site is located in Milin County (93°25′ E, 29°50′ N, 2900 m a.s.l.) near Nyingchi City in the Tibet Autonomous Region, Southwestern China (Figure 1). This region belongs to the alpine area and has a typical sub-alpine, temperate, semi-humid, monsoon climate with an average annual temperature of 8.2 °C. The average temperature of the coldest month (January) is −14.0 °C, while the average temperature of the hottest month (July) is 19.2 °C. The annual precipitation is ca. 641 mm $year^{-1}$, with 85% of the rainfall occurring from June till September. The average annual frost-free period is 170 days and the annual total solar radiation ranges from 5460 to 7530 MJ m^{-2} in Milin. The forest ecosystem of Nyingchi City is relatively complete from south to north, and comprises several species such as *Picea abies*, *Cupressus funebris* and *Rhododendron simsii*. The soil type in this area is leached cinnamon soil which is young in origin and does not exhibit different soil horizons. The contents of silt, clay and sand are 17.2%, 23.5% and 59.3% respectively in the soil surface layer and the pH value is 6.7.

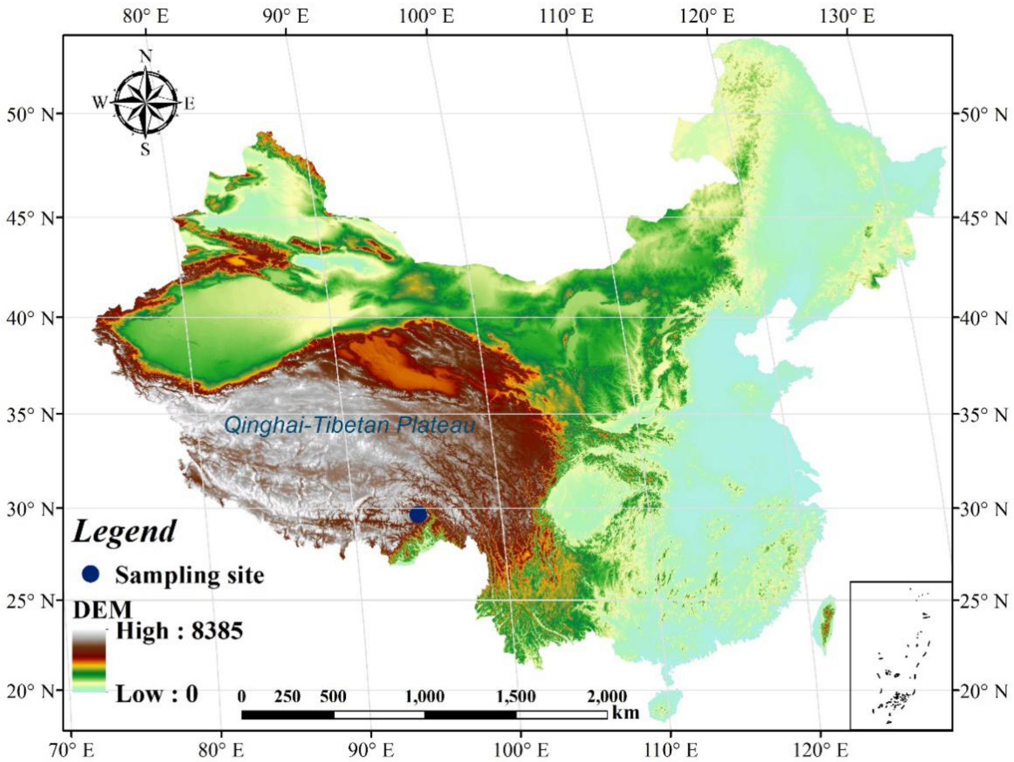

Figure 1. Location of the study site in Milin County (93°25′ E, 29°50′ N, 2900 m a.s.l.) near the Nyingchi City, the Tibet Autonomous Region, China.

2.2. Experimental Field Measurements

Alfalfa pastures of two, four and seven years old were chosen as the three treatment groups, and a field cultivated with corn as a supplementary feeding crop was selected as the control site near the pastures. The field experiment was conducted in mid-July 2017 before harvest. For each treatment and control, three parallel plots (50 × 50 m) were established; the distance between each plot was more than 100 m. The soil samples in each plot had three parallel sampling points. Five 1 × 1 m quadrats were randomly selected at each plot to record the number of species. The species richness of all treatments was the mean value of species in each quadrat. All above-ground plant parts of each individual species were harvested and collected. Then, biomass was dried at 75 °C to constant weight. Below-ground biomass was measured by using root auger (9 cm in diameter), and the samples were taken from 0–50 cm soil layers, at 10 cm intervals. In each plot three root samples were taken and each root sample was a mixture of the three root auger samples in identical layers. The roots were separated from the soil by rinsing, and brought back to the laboratory to be oven dried at 75 °C to constant weight. The natural growth, i.e., the plant height of the cornfield and the alfalfa pastures, was measured with a tape measurer. The species richness (R) was calculated using the following equation:

$$R = S \tag{1}$$

where S is the number of species.

Soil compaction was measured at 2.5 cm intervals from the soil surface to 50 cm depth by using the instrument SC-900 (Spectrum Technologies Inc., San Antonio, TX, USA). Gravimetric soil water content in 0–400 cm soil profiles (at 10 cm intervals) was measured by using a soil drilling method. Each plot had three parallel samples which added up to 360 soil samples. The soil samples were collected in aluminum boxes and immediately weighed, then oven-dried at 105 °C to constant weight. The soil water content at field capacity (Fc) of the top (0–10 cm) soil layer was measured by using the indoor cutting ring (5 cm long and 5 cm diameter) method. We considered the field capacity to be the same throughout the soil profile. The soil water storage (SWS) was calculated as follows:

$$SWS = h \cdot r_{\mathrm{b}} / r_{\mathrm{w}} \cdot q_{\mathrm{g}} \times 10^{-2} \tag{2}$$

where SWS is the soil water storage (mm), h is the soil layer thickness (mm). r_{b} is the soil bulk density (g cm^{-3}), r_{w} is the water density (g cm^{-3}) and q_g is the gravimetric soil water content (g g^{-1}).

The soil water storage deficit (Da, mm) and degree (DSW, %) were calculated as follows:

$$DSW = (Da/Fc)\ 100 \tag{3}$$

$$Da = Fc - SWS \tag{4}$$

2.3. Statistical Analyses

The statistical analyses were performed using SPSS 18.0 software (IBM, Montauk, New York, USA). One-way ANOVA was used to analyze the differences in the above-ground and below-ground biomasses, and species richness among the cornfield and the three alfalfa pastures. All data are presented as mean ± standard error. A standardized process was conducted with SPSS to analyze the comprehensive performance of the above-ground biomass, soil compaction, soil water storage and plant height among the cornfield and the three alfalfa pastures. All data were auto-standardized with SPSS. The figures were plotted using SigmaPlot 12.5 software (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Soil Water Changes and Soil Compaction

At the depth range of 0–30 cm, SWS in the seven-year-old alfalfa pasture was about 5%, 30% and 20% higher than in the cornfield, and the two- and four-year-old alfalfa pastures, respectively. SWS in the four- and seven-year-old alfalfa pastures at the depth range of 100–350 cm was much lower than at the 0–100 cm depth. Fluctuations of SWS in the alfalfa pastures with different growth years was minor at the 0–100 cm depth; however, in the cornfield, the SWS increased at the 30–40 cm depth, but sharply decreased in the 40–200 cm layer, then gradually increased and reached a stability at 300 cm depth. The SWS of the two-year-old alfalfa pasture was higher than that of the other alfalfa pastures at the soil depth of 250–400 cm (Figure 2).

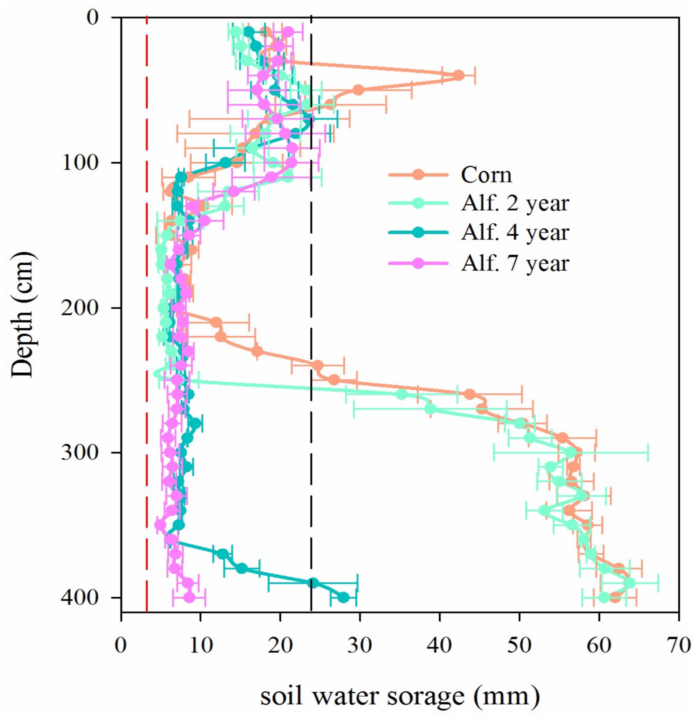

Figure 2. Soil water storage in the cornfield and in the two-, four- and seven-year-old alfalfa pastures in the 0–400 cm soil layers at 10 cm intervals. The black dotted line indicates the soil water content at field capacity. The red dotted line indicates the soil water content at permanent wilting point.

The soil water storage deficit (*Da*) in the cornfield was greatest at the depth range of 130–200 cm (75.2%), then decreased with increasing soil depth and was lower than in the three alfalfa pastures below a soil depth of 200 cm. The greatest *Da* was observed at the depth range of 130–250 cm (79.3%) in the two-year-old alfalfa pasture. However, the soil water storage degrees (*DSW*) of the four- and seven-year-old alfalfa pastures were higher than that of the two-year-old alfalfa pasture below the soil depth of 250 cm (Figure 3).

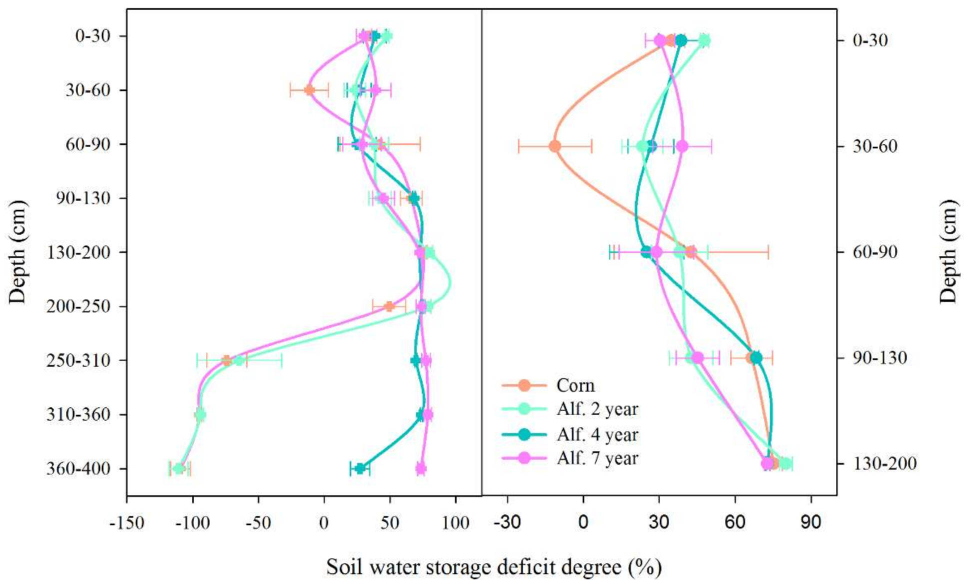

Figure 3. Soil water storage deficit degree of the cornfield and the two-, four- and seven-year-old alfalfa pastures at different soil thicknesses along the 0–400 cm soil layers. The figure on the right shows the detailed soil water storage deficit degree at the 0–200 cm soil layers.

Soil compaction in the cornfield and the alfalfa pastures increased with the increase of soil depth in the 0–50 cm soil layers, but the increased speed gradually reduced below the 27.5 cm soil depth. The average soil compaction of the two-, four- and seven-year-old alfalfa pastures were approximately 15%, 90% and 100% higher than in the cornfield at the 0–15 cm soil depth. Soil compaction in the four- and seven-year-old alfalfa pastures was much higher than in the cornfield and the two-year-old alfalfa pasture at the depth range of 0–25 cm. The seven-year-old alfalfa pasture had the highest soil compaction values at the depth range of 25–40 cm compared with the other fields (Figure 4).

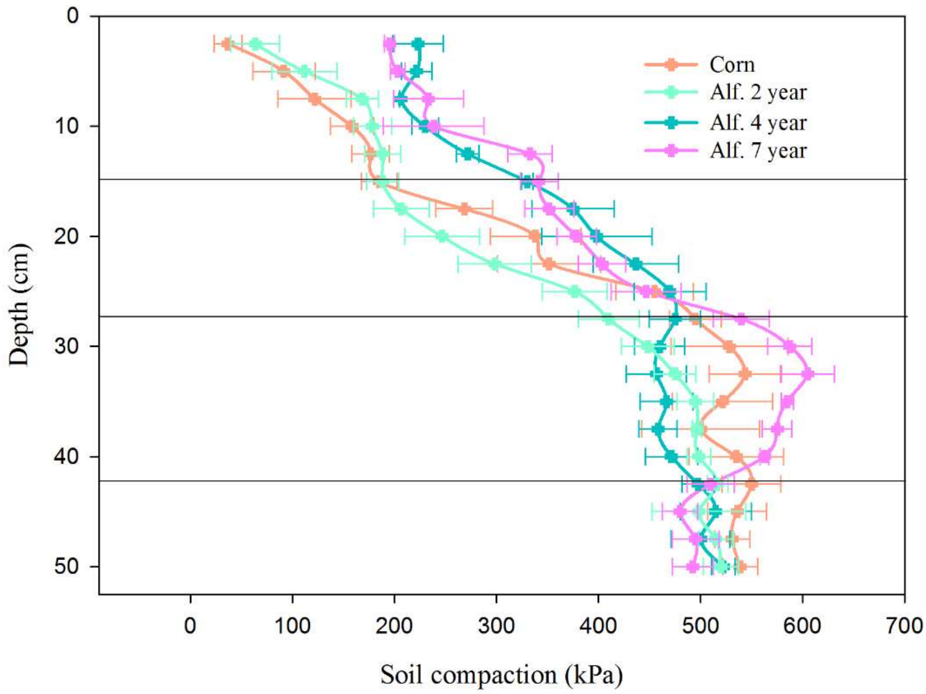

Figure 4. Vertical variation of the soil compaction in the cornfield and in the two-, four- and seven-year-old alfalfa pastures at 0–50 cm soil depth.

3.2. Above- and Below-Ground Biomass and Species Richness

The four-year-old alfalfa pasture achieved the highest above-ground biomass compared with the other two alfalfa pastures (Figure 5). The below-ground biomass of all alfalfa pastures and the cornfield gradually decreased with increasing soil depth. The cornfield had lower below-ground biomass than the alfalfa pasture. The total below-ground biomass of the seven-year-old alfalfa pasture was the highest, though the belowground biomass of the seven-year-old alfalfa pasture was lower than that of the two- and four-year-old alfalfa pastures at 40–50 cm depth (Figure 6). The species richness of the seven-year-old alfalfa pasture was significantly higher than that of the two- and four-year-old alfalfa pastures and that of the cornfield (Figure 7).

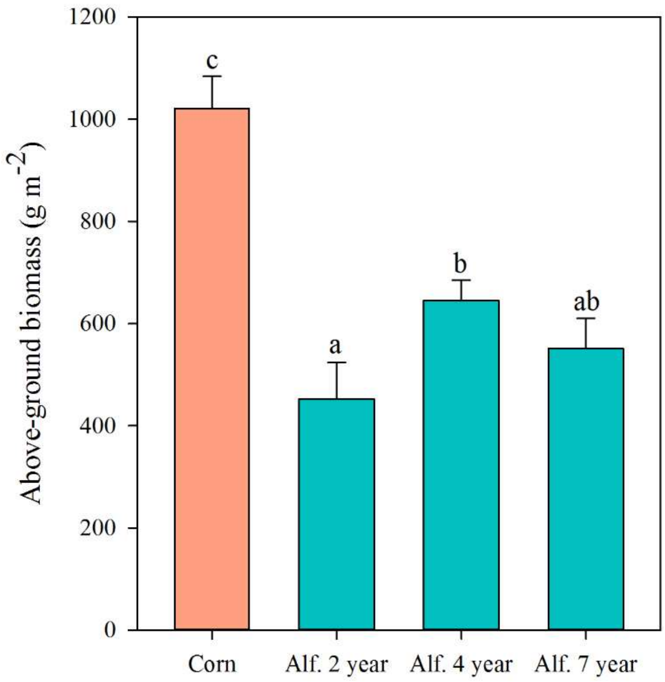

Figure 5. Above-ground biomass in the cornfield and in the two-, four- and seven-year-old alfalfa pastures. Different lowercase letters indicate statistically significant differences at the 0.05 level.

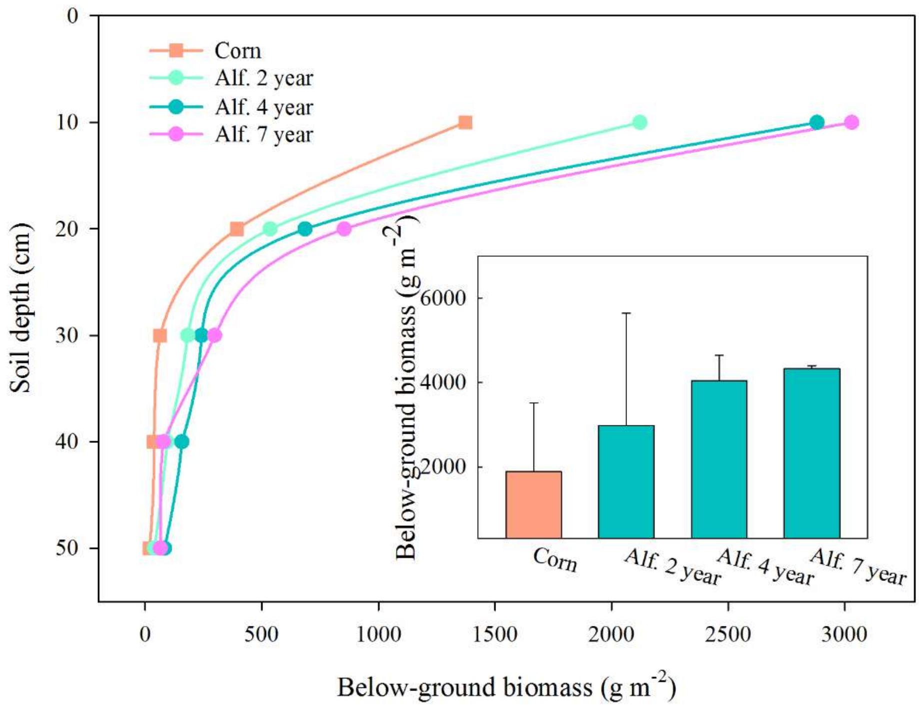

Figure 6. Vertical distribution of the below-ground biomass of the cornfield and the two-, four- and seven-year-old alfalfa pastures. The column chart on the right side shows the total below-ground biomass at 0–50 cm soil depth.

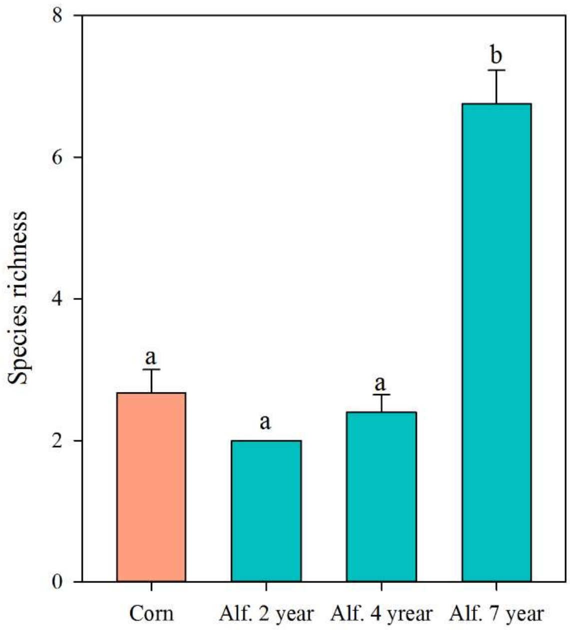

Figure 7. Species richness of the cornfield and the two-, four- and seven-year-old alfalfa pastures. Different lowercase letters indicate statistically significant differences at the 0.05 level.

3.3. The Comprehensive Performance of Above-Ground Biomass, Soil Compaction, Soil Water Storage and Plant Height

The above-ground biomass of the four-year-old alfalfa pasture, the soil water storage of the two-year-old alfalfa pasture, the soil compaction of the seven-year-old alfalfa pasture and the plant height of the two-year-old alfalfa pasture were the highest of all the pastures. Soil compaction of the two-year-old alfalfa pasture and the plant height of the seven-year-old alfalfa pasture were the lowest of all the pastures (Figure 8).

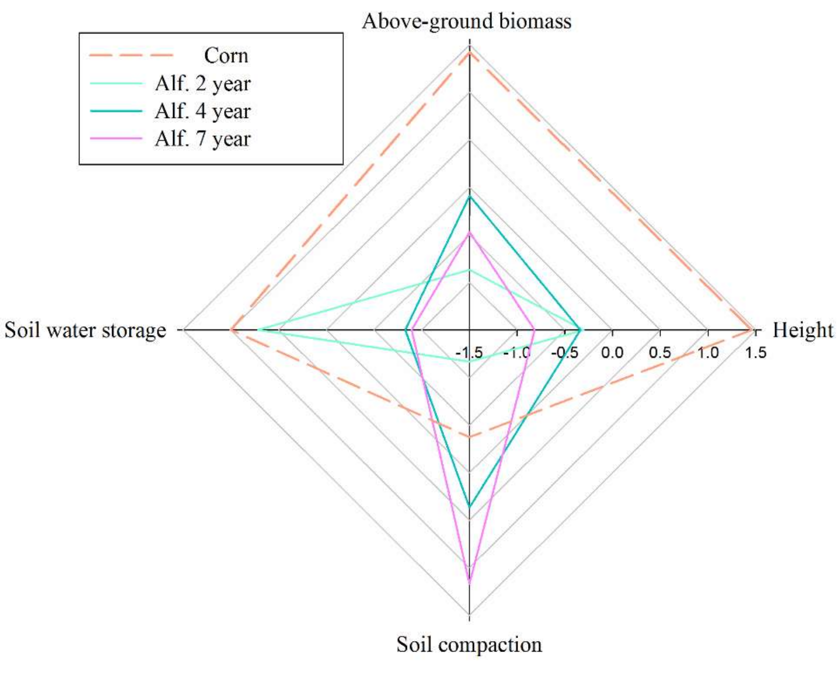

Figure 8. The comprehensive performance of soil compaction, soil water storage, vegetation height of the cornfield and the two-, four- and seven-year-old alfalfa pastures. The values of the four factors were standardized.

4. Discussion

Alfalfa pastures play an important role in the development of animal husbandry and in disaster-restrained livestock in the Tibetan Plateau. However, the results of the present study show that there is relatively higher water consumption and deep soil water deficit in alfalfa pastures. The effects of alfalfa pasture on *SWS* levels mainly depends on the water consumption characteristics of the planting years. This study indicates that the water consumption and deficit of deep soil increased with increasing alfalfa planting years, especially in the four- and seven-year-old alfalfa pastures. *SWS* is a critical indicator for the planting and production of alfalfa pastures in pastoral areas [21]. In this study, *SWS* of the four- and seven-year-old alfalfa pastures decreased with increasing soil depth within the 0–350 cm range. At the 250–400 cm depth, *SWS* of the cornfield and the two-year-old alfalfa pasture was significantly higher than the soil water content at field capacity. Soil water consumption mainly happens through soil evaporation and plant transpiration [22]. On the two-year-old alfalfa pasture, there was less land coverage and greater plant height than on the four- and seven-year-old alfalfa pastures; therefore, the soil evaporation and water requirement for long-distance transportation was higher.

Previous studies have shown that the increase of alfalfa planting years favors soil desiccation in the deep soil horizons under arid and semi-arid climatic conditions, thus limiting the growth and yield of the alfalfa [17]. We found that the soil water deficits in the deep soil horizons (250–400 cm) in the cornfield and in the two-year-old alfalfa pasture were less than those in the four- and seven-year-old alfalfa pastures. Our results agreed with those reported by Gu et al. [23] who found that planting years and groundwater level affected the growth and yield of alfalfa pastures in pastoral areas. Therefore, under long-term cultivation, the SWS of alfalfa pastures is significantly reduced. With the increase of planting years, the deeper soil horizons of the alfalfa fields become severely desiccated, and dry layers appear at 200 cm depth. This result was consistent with the studies of Yang et al. [24] who found that deficits occur in deeper soil as planting years increased. This may relate to the tap-root system of alfalfa. Due to the deep roots of alfalfa, it can pump soil water from deeper soil layers. Thus, alfalfa is widely used in many areas as a more drought tolerant pasture. However, it can also lead to soil water deficit with increased planting years. Our study indicated that below-ground biomass was increased with increased planting years, and the consumption of soil moisture constantly increased. In addition, soil compaction affects root growth and triggers destruction of soil microorganism activity, which results in a loss of yield [25,26]. In this study, soil compaction increased with the planting year but was lower in the two-year-old alfalfa pasture than in the cornfield. This result indicates that two-year-old alfalfa pastures can reduce soil compaction. On the one hand, the traffic and long-term no tillage on alfalfa pastures would create compaction of top soil [27]. On the other hand, the diameter of roots would increase with increased growing years and it would squeeze soil, which would cause soil compaction to increase. Otherwise, higher soil compaction might be detrimental to root respiration and water absorption. Simultaneously, soil compaction of the seven-year-old alfalfa pasture gradually increased with increasing soil depth.

A good forage for legumes, biological nitrogen fixation of alfalfa plays a vital role in the improvement of local soil nitrogen economy and crop biomass [28]. Above-ground biomass is an indicator of the yield of alfalfa pastures. Yu et al. [13] reported that the suitable planting age of alfalfa in the semiarid Loess Plateau should be nine years when considering the highest average yield and the optimal duration of alfalfa stands should not exceed eleven years when only considering the water use efficiency. Due to the differences in temporal and spatial rainfall patterns and anthropogenic activities, the optimal continuous planting time needs to be determined for alfalfa in the Tibetan Plateau. We found that with an increase in planting years, the above-ground biomass of the alfalfa pastures reached a peak value at four years old.

The species richness of the three alfalfa pastures gradually increased with increased planting age. In addition, the species richness of the four-year-old pasture was significantly lower than that of the seven-year-old pasture. It is known that species richness is negatively related to the competition between species [29]. Low species richness indicates a higher competition for resources, which is conducive to the development and accumulation of above-ground biomass [30]. Therefore, for the effective soil water use and sustainable development of eco-economy, the optimum growth period of alfalfa pasture should be maintained at four years in the Tibetan Plateau, and it should be rotated to another crop after the fourth year of plantation. The long-term cultivation of alfalfa as a perennial forage will cause soil water deficit at a local scale, the desiccation degree will be intensified, and the soil compaction will be difficult to recover. Therefore, timely crop rotation will help to restore soil quality and maintain local groundwater stability [31].

5. Conclusions

The biomass yields and soil water storage in different soil layers in a cornfield, as the control field, and three alfalfa pastures were compared and analyzed long-term to evaluate the planting differences among the different fields and planting ages. The planting years determined the soil conditions and the vertical distribution of the deep soil water storage. Long-term cultivation of alfalfa pastures seriously consumed the deep soil water. This process of soil water deficit of alfalfa pastures was obviously aggravated after four years of planting. In addition, the soil compaction was at an appropriate value for alfalfa growth, the above-ground biomass reached a peak value and the soil moisture conditions were better in the four-year-old alfalfa pastures. Therefore, in order to maintain high and sustainable crop productivity and to improve long-term soil water storage in Tibetan alpine pastoral areas, it is necessary to rotate crops after four years of alfalfa planting.

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