Assessing the change in soil water deficit characteristics from farmland to forestland on the Loess Plateau

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Abstract

Soil moisture is an important factor that affects terrestrial vegetation ecosystems and biological growth and development, and water deficit is one of the major environmental factors threatening vegetation restoration in the Loess Plateau. To determine the change in the soil water deficit characteristics from farmland to forestland on the Loess Plateau, in this study, we measured the soil water storage and deficit in abandoned grassland, shrubland, pioneer forestland and climax forestland along with vegetation succession. The results showed that the soil water content and the soil water storage with natural vegetation recovery from the abandoned grassland to shrubland and forestland showed a gradual declining trend, while on the contrary, the soil water deficit was increasing during succession, it was more severe in the deep soil than in the shallow soil layers, and the soil water deficit in July and

September of the rainy season as well as that the vigorous growing period of plants was more serious than that in May and November, which are in the non-rainy season of the Chinese Loess Plateau. The vegetation types, soil texture and soil depth were the key factors affecting the soil water deficiency status in the process of vegetation succession. The results could have great potential in the sustainable development of forestry and provide a theoretical basis for effective water management and reasonable vegetation restoration in arid and semiarid loess regions.

Plain Language Summary

In this manuscript, we measured the soil water status under different land use types along with the vegetation natural restoration from grassland to forestland in different seasons on the Chinese Loess Plateau, and we find that the soil water storage was decreasing, and the soil water deficit was increasing during the succession.

Key words: Soil water deficit, Soil texture, Soil depth, Vegetation types, the Loess Plateau

1. Introduction

According to current climate change models for the 21st century, an increase in average temperature will likely occur in the near future, with more frequent extreme temperature and drought episodes. Soil moisture is an important factor that affects terrestrial vegetation ecosystems and biological growth and development [1], and water deficit is considered one of the major environmental factors limiting plant growth, yield and survival in arid and semiarid regions of the world, where plants are often exposed to drought conditions [2]. Located in the northern part of central China, the Loess Plateau has an arid continental monsoon climate and is one of the regions with the most serious soil erosion and the most fragile ecology in the world. In recent years, the government in China carried out the large-scale implementation of returning farmland to forest and grass [3], which has made remarkable achievements; however, it led to a lower soil moisture content, even though the dry layer phenomenon appeared because of the region with low rainfall and high evaporative conditions and because of the unreasonable distribution of vegetation types in the process of vegetation restoration [4]; additionally, along with vegetation restoration, the soil water deficiency phenomenon has become more severe [5-7]. This phenomenon is very unfavorable to the vegetation restoration and ecological restoration of the Loess Plateau.

Due to the dry climate, scarce precipitation and strong evaporation on the Loess Plateau, water resources have become the key factor in determining the structure and function of the ecological system, and the soil moisture condition is the main factor affecting plant growth and restoration and determining the type and structure of vegetation in ecological construction [8]. Precipitation is the main source of soil moisture and water supply for plants in this area;

however, rainfall has a significant difference in seasonal distribution, which makes the variation in soil moisture closely related to the change in seasonal precipitation [9] and basically consistent with the change trend of seasonal precipitation. On the annual scale, autumn and winter are the slow accumulation stages of soil moisture, late spring and early summer are the intense consumption stages of soil moisture, summer is the fluctuation stage of soil moisture, and soil dry layers occur widely on the Loess Plateau; some vertical soil depths even appear as heavy dry layers [10]. The soil dry layers indicate that severe soil water deficiency exists, and there are many reasons for the formation of dry soil layers, including high plant density, less precipitation, global climate warming and drying and soil erosion; however, the main reason in arid and semiarid areas is intense evaporation, which is attributed to the dry climate. Therefore, scientifically taking advantage of land resources and managing the ecological environment in loess hilly regions is necessary to fully understand the change and utilization of soil moisture under various land-use conditions and to study the spatial change in soil water characteristics during the dry and wet seasons, which is of important scientific value to improve the dry soil layers in the Loess Plateau.

Many studies have been carried out to identify the factors affecting the soil water status. Wang et al. analyzed soil desiccation in artificial forests and found that artificial forests could utilize deep soil water to a threshold [11], resulting in a dry layer that causes the deep soil to completely lose its ability to regulate the soil water status for plant growth. Zhu et al. indicated that soil water deficiency would be aggravated by intense evapotranspiration [12], leading alfalfa to deepen its root distribution in arid and semiarid regions. As a result, soil desiccation was much more serious than before in deep soil; nevertheless, the moisture needed for vegetation evapotranspiration can be supplied by shallow groundwater [13], which would decline with the increasing water demands of plants [14]. Both declining groundwater and aggravating soil desiccation can mitigate the ability to resist drought and adversely affect the soil water balance [15]. Soil water storage is the foundation of vegetation planting, and it is consumed through transpiration and evaporation. The latter mainly expends the soil water stored at the 0-60 cm soil depth [16], and root water uptake is the key mediator of plant transpiration [17]. The soil water consumption may be higher where the roots are denser. Thus, denser roots and sparser land coverage will increase transpiration and evaporation. With rising global temperatures, evapotranspiration is increasing, which inevitably aggravates soil desiccation in arid and semiarid regions [18]. A study in alfalfa grassland by Huang et al. showed that the soil water deficit was severe in the 0~150 cm soil depth, and the deficit degree was significantly different in alfalfa grasslands of different ages [19]. Soil water deficit has been serious during vegetation restoration on the Loess Plateau, which imposes great obstacles to ecological restoration and vegetation construction on the Loess Plateau. Only by fully understanding the characteristics of soil moisture and its deficiency on the Loess Plateau can we provide a theoretical basis for vegetation restoration. However, little is known about the difference in the soil water deficit and the seasonal water storage characteristics in the deep soil layers in different vegetation types during vegetation restoration.

In this study, we aimed to assess the spatial and temporal variation characteristics of soil water storage and deficits in deep soil layers in different vegetation types in the process of vegetation restoration; additionally, we aimed to determine how the soil water deficit changes in the dry and wet seasons during a year. Our findings could have great potential in the sustainable development of forestry and provide a theoretical basis for effective water management and reasonable vegetation restoration in arid and semiarid loess regions.

2. Materials and methods

2.1 Experimental site

The study area is located in the Lianjiabian forest farm of the Ziwuling forest area in Heshui County, Gansu Province, the central part of the Chinese Loess Plateau, between 36°03' and 36°05' N and 108°31' and 108°32' E, which belongs to the temperate continental monsoon climate zone. The annual precipitation is 560~590 mm, mainly from July to September, and the altitude is 1211~453 m. The region's soils are largely loessal having developed from primitive or secondary loess parent materials, which are evenly distributed 50–130 m deep above red earth consisting of calcareous cinnamon soil, and soil pH ranged from 7.92 to 8.31. In this study, soil moisture was measured in the abandoned grassland (AG), secondary *Hippophae rhamnoides* Linn. forestland (HF), *Populus davidiana* Dode. forestland (PF), and *Quercus liaotungensis* Koidz. forestland (QF) to determine the soil water storage and water deficit in May, July, September and November, respectively. The status of the vegetation types is shown in Fig. 1.

Figure 1

2.2 Sampling and measurements

From May to November 2018, soil samples were collected by soil drilling at the beginning of each month. Standard wood was selected from each sample plot, and the soil samples were drilled at a distance of 2/3 m from the tree canopy edge. The sampling soil depths were 0~500 cm, with 10-cm intervals in the 0~100 cm layer and 20-cm intervals in the soil layers below 100 cm. The soil moisture content was measured by the drying method. Under the high temperature of 105℃, the soil was dried for 6~8 h until a constant weight was reached.

The main vegetation in the study area is broad-leaved forest and coniferous forest, and the top community is *Quercus liaotungensis* Koidz, with community coverage of 80%~95%. In the Ziwuling forest area, historical records show that natural secondary forest began to develop on abandoned farmland in the 1760s [20]. Therefore, this study mainly selected AG, HF, PF and QF as the research objects. Five quadrats were set in each community, with five replications, including 20 m×20 m for QF and PF, 5 m×5 m for HF, and 2 m×2 m for AG. Community information is shown in Table 1.

Table 1

Soil water storage (SWS) refers to the absolute amount of water in the soil and was calculated from Eq. (1) [21]:

$$SWS_i = SWC_i \times BD_i \times \mathrm{h} \times 10 \div 100 \qquad (1)$$

where $_i$ represents the sequence of soil layers, SWS_i is the soil water storage (mm), BD_i is the soil bulk density (g/cm^3), h is the soil depth (cm), and SWC_i is the soil water content (%).

The degree of relative soil water deficit was calculated using Eq. (2) [21]:

$$PD=\frac{\sum_{i=1}^{k}\frac{SwS_{ci}-SwS_i}{SwS_{ci}-SwS_m}}{k} \qquad (2)$$

where PD represents the soil water relative deficit index, SWS_i is the soil water storage (mm) in soil layer i of the sample lands, SWS_{Ci} represents the soil water storage (mm) in soil layer i of the control lands, i.e., the AG, SWS_m is the soil water storage (mm) corresponding to the wilting coefficient; and k is the number of soil layers in the sampled lands.

2.3 Statistical analysis

Microsoft Excel 2010 (Microsoft Corporation, USA) was used to process experimental data. Analysis of variance (ANOVA) was performed with the statistical software package SPSS 20.0 (International Business Machines Corporation, USA). The least significant difference (LSD) was at the 0.05 probability level. The graphics were created with Origin software (OriginLab V8, USA).

3. Results

3.1 SWC in different vegetation types during vegetation restoration

As shown in Fig. 2, the SWC first increased and then slowly decreased with increasing soil depth in the HF, PF and QF, while it showed an unstable state in the AG. However, all the forestlands exhibited an upward trend with increasing soil depth, and the SWC in the QF was the lowest. This phenomenon was more obvious in the non-rainy season in May than in the other months, and the peak value of the SWC of the three forestlands in May was mostly concentrated in the soil depth of 160 cm, ranging from 15~25%. The SWC was significantly higher in July of the rainy season than in May of the non-rainy season, and the peak distribution was different. The soil depth where the peak appeared in the HF was 140 cm and was 100 cm and 80 cm in the PF and QF, respectively, ranging from 17~30%. In the rainy season, the SWC in July, after passing the peak point, decreased obviously with increasing soil depth. In the rainy season, the SWC content in September was the most stable and the highest among the months from May to November. The SWC of the non-rainy season in November decreased compared with that of the rainy season in September. In addition to the QF, the average SWC of the 0~500 cm soil layer in rainy September and non-rainy November was approximately 25%. When the soil depth was below 300 cm, the SWC in the AG was significantly higher than that in the other three forestlands. Overall, from the perspective of the four months above, the SWC in the AG was always at a high level, followed by that in the HF, and then the PF, and the SWC in the QF was the lowest among the four vegetation types during natural vegetation restoration.

Figure 2

3.2 SWS in different vegetation types during vegetation restoration

As shown in Fig. 3, the variation trend of the SWS with soil depth in the three forestlands is consistent with that of the SWC. With the increase in soil depth, the SWS in the three forestlands first increased and then slowly declined, while it was unstable and increased with soil depth in the AG. Among the four vegetation types during natural vegetation restoration, the AG had the highest SWS, followed by that in the HF, and then the PF, and the SWS in the QF was the lowest, which is consistent with the SWC. It can be seen from the SWS per meter depth in different vegetation types that the SWC in the AG increased with soil depth in both the rainy season and the non-rainy season (Fig. 4), but this phenomenon was more significant in the non-rainy season than in the rainy season, and the SWS per meter below 300 cm was the highest in the AG. In the five soil layers of 0~500 cm, with vegetation recovery, there was a significant decline from shrubby (the HF) to arbor forest in the initial stage (the PF) and then to arbor forest in the top stage (the QF); furthermore, the SWS in the QF was the lowest except in the 0~100 cm soil layer in May, i.e., when it was not the rainy season. Over 400 cm, the SWS in the HF in the rainy season and non-rainy season was the highest, followed by that in the PF among the three forestlands. In general, the SWS during the rainy season was higher than that during the non-rainy season.

Figure 3

Figure 4

3.3 The PD in different vegetation types during vegetation restoration

The soil water relative deficit index (PD) varied significantly in different vegetation types and in different seasons (Fig. 5). Regardless of rainy season or non-rainy season, the PD in the QF was the highest, which meant that the soil water deficit phenomenon was most obvious and the scarcity of water was most severe; PF ranked second, and the lowest PD occurred in the HF. This result was inversely proportional to the SWC and SWS in the different vegetation types shown in Figs. 2 and 3. The PD in May and November of the non-rainy season was higher than that in July and September of the rainy season, indicating that the soil deficit in May and November was more serious than that in July and September of the rainy season, i.e., when the vigorous growth period of vegetation occurred. Compared with the AG, the soil deficit in the QF was in a continuous state from May to November, but the deficit situation changed during the whole growth period; from May to July, the deficit increased, and it slowed from July onwards. However, in the HF and PF, the soil water was only slightly deficient in the soil layers below 300 cm in July and September, and the PD was negative in the soil layers above 300 cm in all months, indicating there was no deficit.

Figure 5

Fig. 6 shows the difference in the PD per meter soil depth in different vegetation types from May to November. In the 0~100 cm soil layers in May of the rainy season, the PD in the PF was significantly higher than that in the HF and QF, and no deficit phenomenon was observed in the QF; however, in the soil layers under 100 cm, the PD was significantly higher in the QF than in the HF and PF. In the 100~300 cm soil layers, the PD was significantly lower in the HF than in the PF, while in the 400~500 cm soil layers, the PD was significantly higher in the HF than in the PF. In July and September of the rainy season and November of the non-rainy season, the PD in the QF was significantly higher than that in the HF and PF in all soil layers of 0~500 cm, while it was significantly lower in the HF than in the PF in the 100~300 cm soil layer except for September, and it was obviously higher in the HF than in the PF in the 400~500 cm soil layer.

Figure 6

4. Discussion

4.1 Effects of vegetation on soil water deficit characteristics

Due to the difference in root density and depth, different vegetation types consume soil water with different intensities and at different soil depths, resulting in differences in soil water under forests with different vegetation types [22]. In our study, the SWC and SWS with natural vegetation recovery from abandoned grass to shrubland and forestland showed a gradual declining trend, possibly because the aboveground biomass increased gradually, the foliage became more lush, and the tree body gradually enhanced its transpiration capability precipitation interception and trunk runoff with vegetation restoration. In addition, the increased root system underground, the augmented distribution, and the increased absorption and consumption of soil water led to the overall decline of the SWC and SWS [10, 11]. Regarding the soil water deficiency phenomenon in this study, compared with the AG, the PD in the QF, which was in the climax of the natural vegetation restoration process, was significantly higher than that in the HR and PF, which were both in the intermediate stage of natural vegetation restoration, and the soil water deficit was more severe in the deep soil than in the shallow soil layers in both the rainy and the non-rainy season in all three vegetation types. This result was due to the interaction between vegetation growth and soil moisture, the QF consumed more water than the HR and PF, and due to its stronger canopy intercept and lower amount of precipitation recharge, the ability of precipitation resources to ease the degree of soil water deficit was greatly reduced and more unable to supplement the deeper soil moisture, resulting in the deterioration of the soil water deficiency phenomenon in the deep soil. This result was consistent with the results of previous studies [23, 24]. Gao et al. indicated that plants could consume a large amount of soil water storage due to the amount of water consumed by the plants, which was higher than the precipitation balance in different regions of the Loess Plateau, which would lead to the water storage deficit [22]. The research results of Chen et al. also showed that the soil depth where the negative compensation of SWS occurred would reach approximately 300 cm [25]. The research results of Wang et al. showed that the soil water deficiency phenomenon caused by the water consumption being greater than the recharge was widespread on the Loess Plateau [26], and the soil properties and the meteorological factors were the determinants of the soil water deficiency of determinants, which were not caused by bio-utilization.

4.2 Effects of soil properties on soil water deficit characteristics

Soil moisture is affected not only by vegetation type but also by soil depth, particle composition, infiltration and season. The research of Yang et al. showed that SWC decreased significantly with vegetation restoration, with no significant difference in the soil water in the soil surface in the different vegetation types [27], while it was significantly different in the deep soil, and the soil water in the deep soil showed temporal stability to a certain degree, which was consistent with the results of this study. The vertical SWC and SWS in the AG showed a gradual increasing trend, which might have been because, as the soil layer deepened, the grass root density decreased, and the water consumption correspondingly decreased. However, the SWC and SWS in the HR, PF, and QF showed a trend that first increased and then decreased, and the inflection point was at the 150 cm soil depth, which may be because in the 150 cm soil layer, the root system gradually became dense, and its infiltration depth was limited; thus, it cannot be replenished in a timely manner to the subsoil, causing the SWC in the lower layer to continue to decrease and even the dry soil layers appeared. In addition, the SWS in the rainy season was significantly higher than that in the non-rainy season in this study, but compared with the abandoned grassland, the shrubland and forestland had more evident soil water deficit phenomena in the rainy season than in the non-rainy season, which suggested that the increased precipitation resources in the rainy season led the SWS in the topsoil to increase to a certain extent and relieved the water deficit. Nevertheless, the infiltration depth was not enough, and although precipitation was greater in the rainy season, which was also the vigorous growing period, the water consumption was greater than that in the non-rainy season; thus, there was no significant improvement in the water deficit in deep soil, and the soil water stored in the deep soil was lower in the rainy season than in the non-rainy season. In addition, in the same soil layers, the SWC in the abandoned grassland was higher than that in the shrubland and forestland, which agreed with the previous study of Yang et al. [28]. This result may be because of the high proportion of clay content in the abandoned grassland, while the proportion of sand content was higher in shrubland and forestland, and the clay can absorb more moisture than sand [29]. This process may be another leading cause of the soil water deficit being higher in the shrubland and forestland than in the abandoned grassland. Therefore, vegetation type, soil texture and soil depth were the key factors affecting soil water deficit during vegetation succession.

Conclusions

We found that the SWC in the HF, PF and QF first increased and then decreased slowly with increasing soil depth, while it presented an unstable state in the AG. In general, it showed an increasing trend with increasing soil depth. In both the rainy and the non-rainy seasons, the SWC in the AG was the highest, followed by that in the HF, that in the PF, and finally, that in the QF, which had the lowest SWC. From the non-rainy season to the rainy season, the soil depth which the peak value of the SWC occurred in gradually increased from the abandoned grassland to the shrubland and forestland. Compared with the AG, the soil water deficit in the QF was most serious, with a constant deficit from May to November, followed by the PF and the HF. In addition, the soil water deficit in July and September of the rainy season and the vigorous growing period of plants were more serious than those in May and November, which are in the non-rainy season in the Chinese Loess Plateau. The vegetation types, soil texture and soil depth were the key factors affecting the soil water deficiency status in the process of vegetation succession. This result can provide a reference for the government to make policies on the rational utilization of water resources and the sustainable development of vegetation restoration.

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Table and Figure captions:

Table 1 Geographical information and vegetation types in the sample plots during the vegetation restoration. Note: AG represents the abandoned grassland, HF stands for the shrubland, PF represents the pioneer forestland and QF stands for the climax forestland. And the restoration ages after cropland abandonment were 10, 50, 100 and 160, respectively.

Fig. 1. The status of the vegetation types in the study area.

Fig. 2. Vertical SWC change at different time in different vegetation types during the restoration.

Fig. 3. Vertical SWS change at different time in different vegetation types during the restoration.

Fig. 4. The difference of the SWS in the per meter soil layers at different time in different vegetation types during the restoration. Values are in the form of Mean ± SE and the sample size n=5. Different uppercases above the bars mean significant differences in the different soil layers in the same vegetation types, and different lowercases above the bars mean significant differences in the same soil layers in the different vegetation types ($P < 0.05$).

Fig. 5. Vertical PD change at different time in different vegetation types during the restoration.

Fig. 6. The difference of the PD in the per meter soil layers at different time in different vegetation types during the restoration. Values are in the form of Mean ± SE and the sample size n=5. Different lowercases above the bars mean significant differences in the same soil layers in the different vegetation types ($P < 0.05$)

Table 1 Geographical information and vegetation types in the sample plots during the vegetation restoration.

Vegetation types	Latitude (N)	Longitude (E)	Altitude (m)	Aspect	Slope (°)	Coverage (%)	Main plant species
AG	36°5′4″	108°31′37″	1348	NE	14	85	*Lespedeza bicolorr*
HF	36°4′14″	108°32′1″	1354	NE	18	90	*H. rhamnoides* Linn.
PF	36°2′16″	108°31′32″	1450	NE	12	85	*P. davidiana,* Dode.
QF	36°2′57″	108°32′13″	1449	NE	18	95	*Q. liaotungensis* Koidz.

Note: AG represents the abandoned grassland, HF stands for the shrubland, PF represents the pioneer forestland and QF stands for the climax forestland. And the restoration ages after cropland abandonment were 10 a, 50 a, 100 a and 160 a, respectively.

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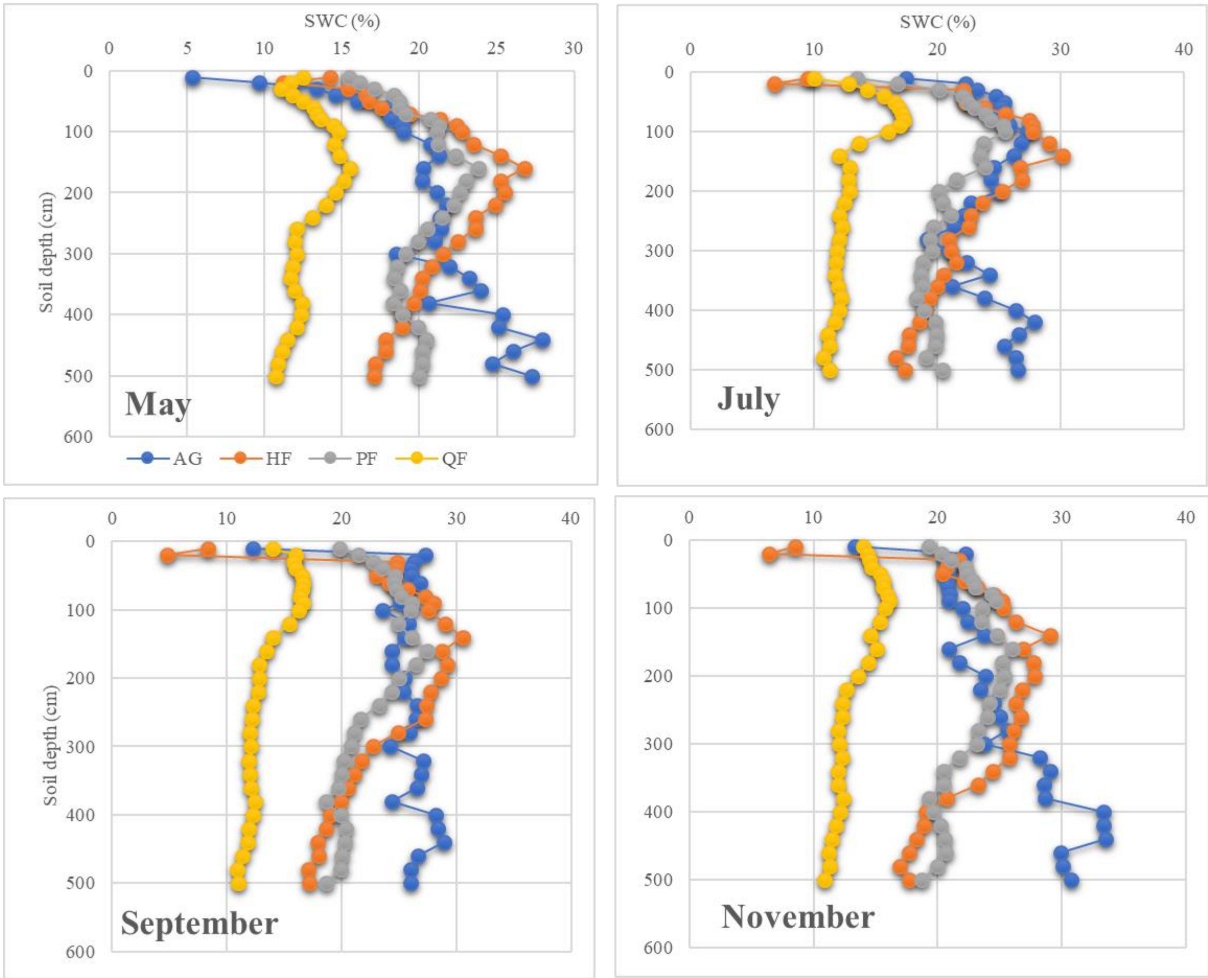

Fig. 2. Vertical SWC change at different time in different vegetation types during the restoration.

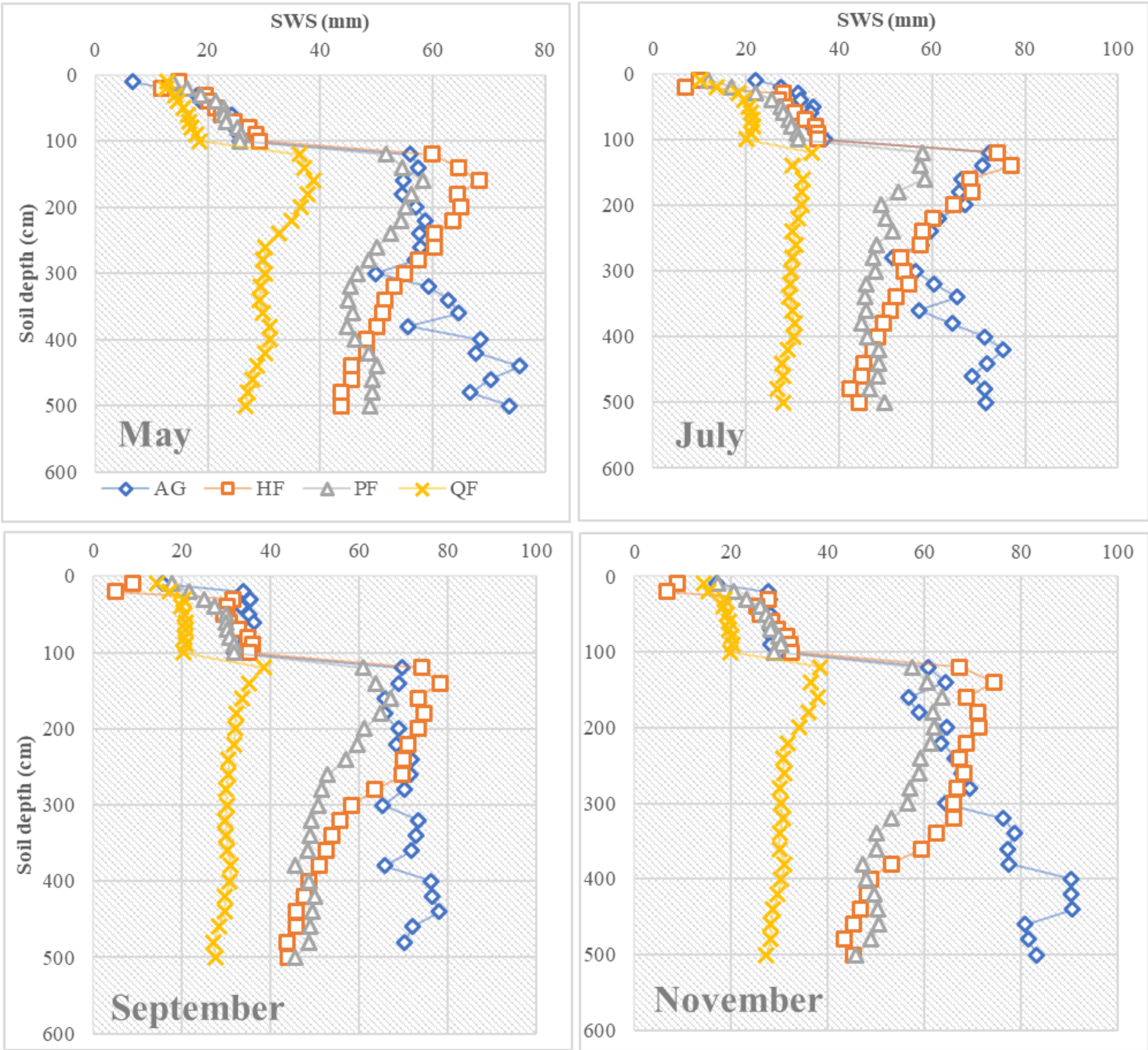

Fig. 3. Vertical SWS change at different time in different vegetation types during the restoration.

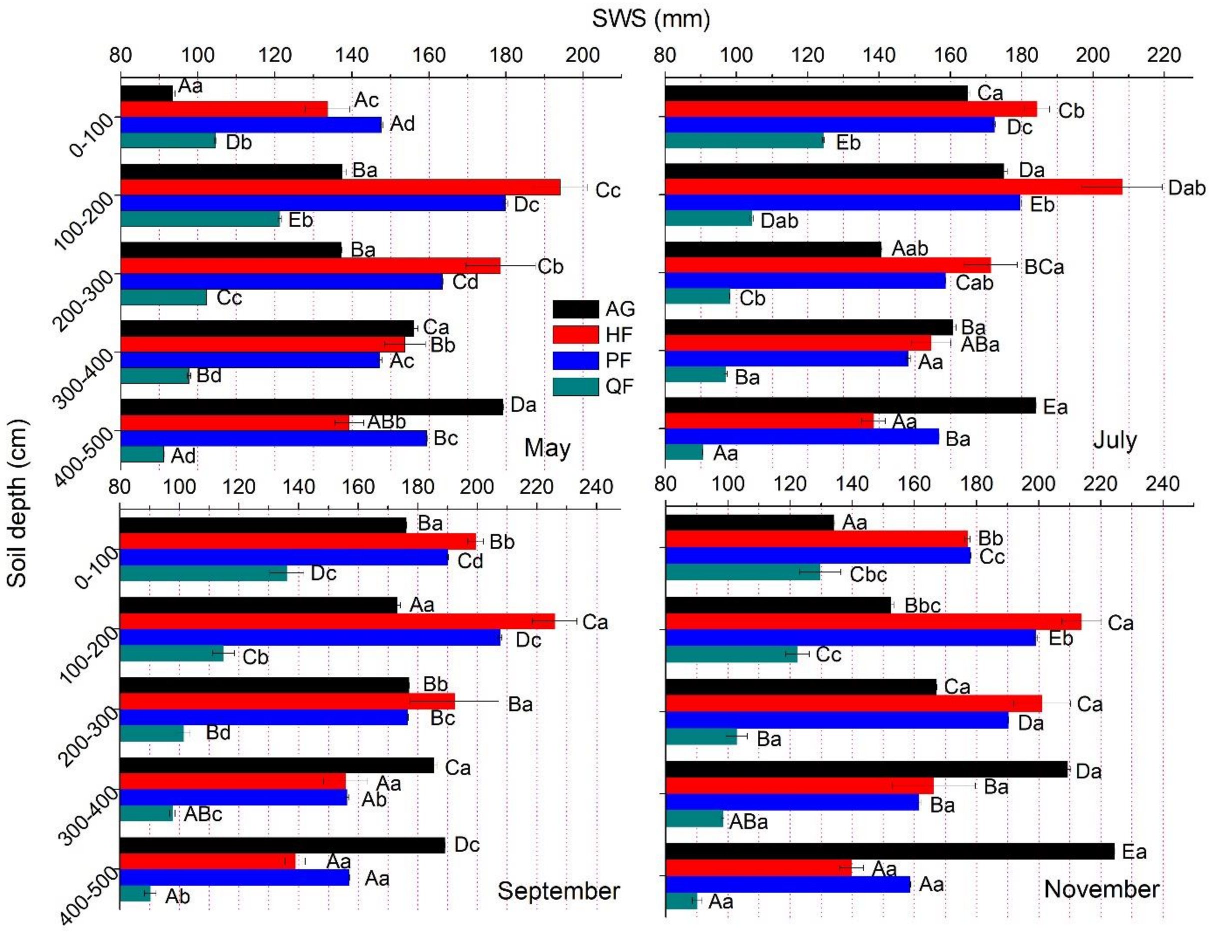

Fig. 4. The difference of the SWS in the per meter soil layers at different time in different vegetation types during the restoration. Values are in the form of Mean ± SE and the sample size n=5. Different uppercases above the bars mean significant differences in the different soil layers in the same vegetation types, and different lowercases above the bars mean significant differences in the same soil layers in the different vegetation types (*P* < 0.05).

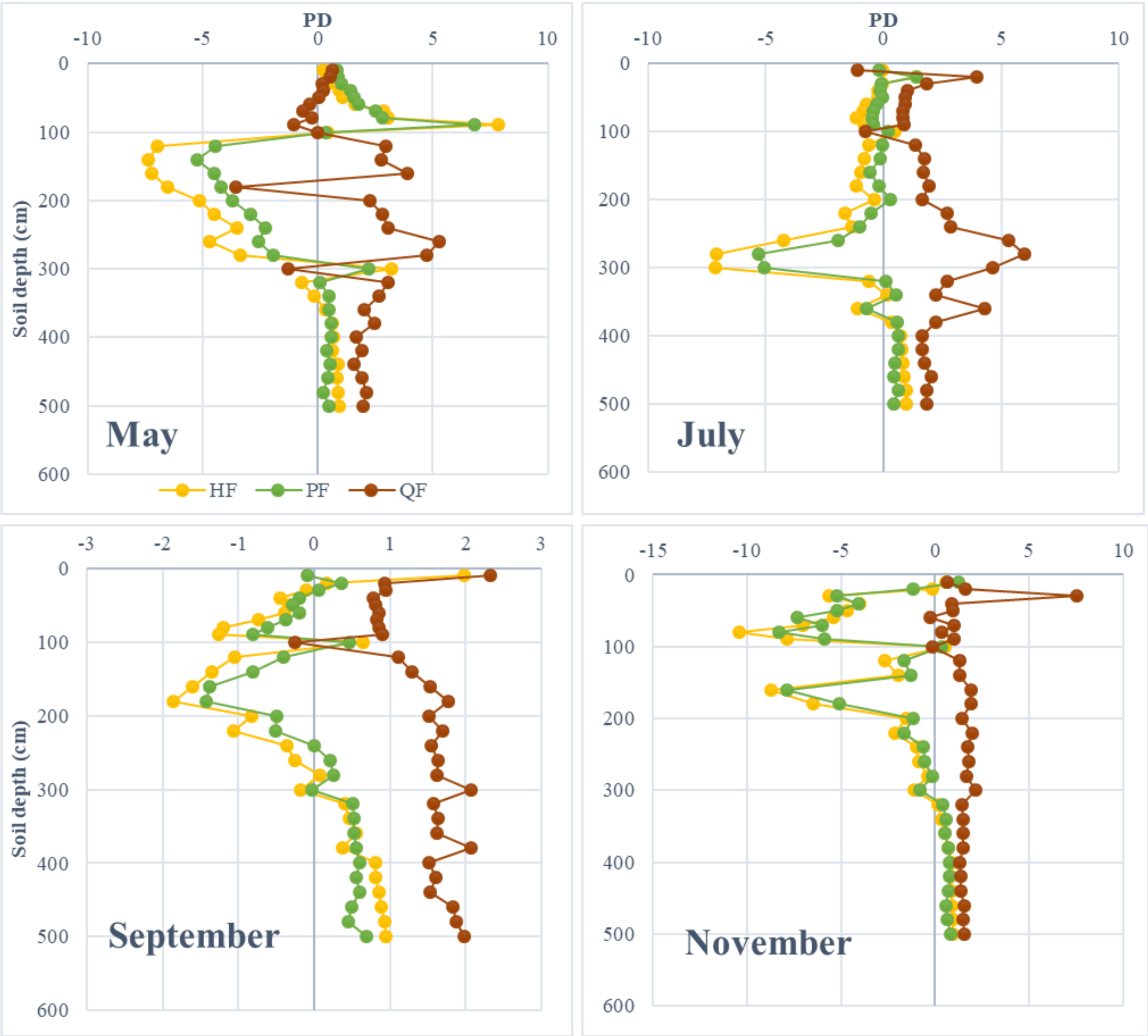

Fig. 5. Vertical PD change at different time in different vegetation types during the restoration.

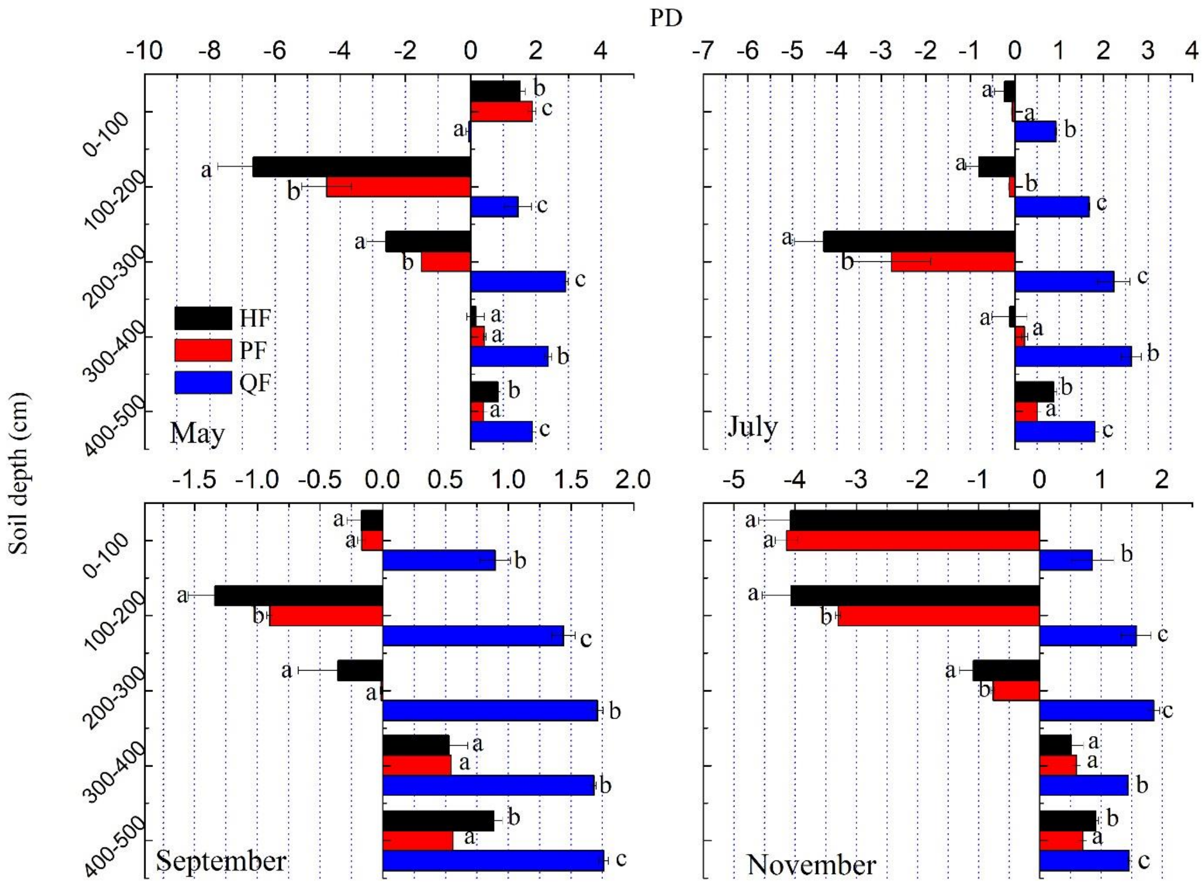

Fig. 6. The difference of the PD in the per meter soil layers at different time in different vegetation types during the restoration. Values are in the form of Mean ± SE and the sample size n=5. Different lowercases above the bars mean significant differences in the same soil layers in the different vegetation types ($P < 0.05$).