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Natural Hazards and Earth System Sciences
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Discussions

Research on Occurrence and Development of Pasture Drought Events in Alpine Grassland using the Drought Threshold

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Abstract. Pasture is vital to livestock husbandry development in Qinghai and even in North China. Drought is the primary meteorological disaster that affects pasture, but insufficient soil moisture is the most prominent cause of pasture drought. Timely and accurate determination of the soil moisture threshold of pasture is important for objective recognition and monitoring of the occurrence and development of pasture drought. This study aims at investigating pasture responses to soil drought as well as quantitative expression of soil drought degree and drought threshold. Test plots were selected from the pasture test station. Five testing groups were set according to coverage rate (0-100%) at the initiation the pasture growth period. The impacts of profile moisture characteristics, drought threshold, and precipitation on duration of pasture drought were studied. Research results have demonstrated that moisture in the soil profile below 20 cm decreases slightly throughout drought events in alpine grassland. Changes of soil moisture in the 0-20 cm layer can generally reflect drought stress of the pasture. In the process of a drought event, the relationship between soil water storage and cumulative relative water loss can be expressed via a logarithmic linear equation. Quantitative expression of drought degree in grasslands can be realized by transforming the slope of this equation into the index *D* with an interval of [0, 1]. The occurrence rates of mild drought, moderate drought, and severe drought were 0.36, 0.45, and 0.70, respectively. The duration of severe drought was closely related with initial soil moisture. The relationship between duration of drought and the necessary minimum precipitation can be expressed by an exponential equation. Values of the *D* index can express soil drought intensity and pasture drought intensity. The durations for different grades of drought events were correlated with both initial soil moisture and previous precipitation. The conclusions of this study can provide scientific references for the objective understanding on occurrence, development, monitoring, and early warning of pasture drought.

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Highlights

- The change of soil volumetric water content under different rainfall conditions were investigated through control experiments.
- Changes of soil moisture in the 0-20 cm layer can generally reflect drought stress of the pasture.
- Dynamic drought index (D) can effectively represent the characteristics of dynamic development and long-term accumulation of drought.
- The duration of severe drought was closely related with initial soil moisture. The relationship between duration of drought and the necessary minimum precipitation can be expressed by an exponential equation. Values of the D index can express soil drought intensity and pasture drought intensity.
- The durations for different grades of drought events were correlated with both initial soil moisture and previous precipitation.

1 Introduction

Grassland has important ecological and productive functions in Qinghai Province and even in the north of China. Animal husbandry is the pillar of the development of the source area of the Three Rivers Sources and the area around the lake in Qinghai Province. Since the underground water level of grassland in this region is generally below 2 m, soil moisture in grassland mainly depends on natural precipitation (Qi et al.,2009;Qin et al.,2015;CMA,2016;Shi et al.,2017). Precipitation changes may directly influence pasture growth. Drought is the primary natural disaster that affects pasture, and severe drought in grassland can cause total pasture failure in the region(Xu et al.,2008;Avramova et al.,2015;Nam et al.,2015;Panda et al.,2016;Quiroga et al.,2016).Given predictions of future climatic changes, the climate in the study area may be become "warm and dry." This would increase the frequency and intensity of extreme weather events, such as drought, high temperatures, and strong precipitation (Stocker et al.,2013;Gholipoor et al.,2013;Field et al.,2014;Myers et al.,2017) .These pasture areas may become more significantly influenced by drought, and handling pasture drought may become a key area of government administration and academic studies.

Meteorological drought may eventually cause the decrease of soil moisture, and the decrease of soil moisture represents the primary cause of crop drought. Therefore, soil moisture is the key metric for assessment of soil-crop systems. In particular, it is an important drought index in regions without

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irrigation measures(Qi et al.,2009;Chen et al.,2007a).Among existing drought indices, Idso et al.(1977)and Jackson et al.(1977)proposed the Crop Water Stress Index (CWSI) is based on canopy-air temperature difference, With the advantages, CWSI has been widely applied to drought research due to climate change (Cai et al., 2000;Alderfasi et al.,2001;Yuan et al.,2004;Anda,2009;Zhao et al.,2013;Wang,Z.,2018). However, CWSI emphasizes crop response to drought and cannot reflect the drought accumulation process. Moreover, Shi et al(2017) and Ma et al.(2017) carried out a simulation test of continuous reduction in soil moisture and identified a soil moisture threshold for plant growth. This implies that when soil moisture is lower than a critical value, crop growth would change significantly. Chen et al.(2007b),Ma et al.(2017)pointed out that a dynamic drought index (soil drought degree) centered on the soil volumetric moisture content can effectively characterize the dynamic development and long-term accumulation characteristics of droughts.

Since soil moisture in alpine grassland depends on natural precipitation, soil drought directly affects forage yield. and the time scale of soil moisture data used in most previous studies is ten days and the research on droughts in alpine grasslands have basically focused on atmospheric drought and drought characterization has been based on static soil moisture. There have been few studies concerning the soil drought threshold of pasture.

To address the abovementioned problems in existing studies of drought events in alpine grassland, this primary objectives of this study was as follows:(1) to quantify soil drought intensity and grade via the rate of change in soil volumetric moisture content based on simulation tests of precipitation changes;(2) to determine the soil drought threshold in the growth period of pasture and combined with the soil moisture data;(3) to investigate the influences of precipitation and soil moisture on development of drought were. This study will hopefully provide references for the research on the occurrence, monitoring, prediction, and mitigation of pasture drought in alpine grassland.

2 Study area and research methodology

2.1 Study area and experimental design

The experiment was carried out at Haibei Animal Husbandry Meteorological Test Station (36° 57′ N, 100° 51 ′E) from April to September,2017. The experiment was divided into three stages of grass growth and development: turning green stage, vegetative growth stage and yellow withering stage. five testing groups were set according to precipitation coverage rate in order to simulate influences of drought intensity on pasture. Coverage rates were set at 20%, 30%, 40%,60%and 100%,

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respectively. The testing group with a 20% coverage rate is set up so that the total precipitation was reduced by 20%. The other groups follow this same pattern. The five testing groups were recorded as Group 1, Group 2, Group 3, Group 4, and Group 5. In addition, four control plots were set up, and the control observation was carried out during the whole experiment period (Fig.1), but only the second stage experiment was selected for the stage of drought occurrence and development. The sample plot unit is 2.4 m×3 m, and the water-shielding material is highly transparent polycarbonate material; the sample plot unit is made of rust-proof iron sheet, 20 cm above ground and 20 cm below ground; there is no rain-collecting facilities (because there is no possibility of large-scale irrigation in the natural grassland), and the water collected by the rain-shielding grid of the precipitation unit flows into the sample plot naturally. Interval zone. The grid arrangement is consistent with the prevailing wind direction during precipitation in the field observation site. The study area is a parcel of typical alpine grassland. Physical properties of different soil layers are listed in Tab.1. Precipitation and volumetric soil water content were observed at 10 min intervals each day.

2.2 Research methodology

2.2.1 Soil drought

Soil drought is a progressive process that can be quantified by the average drought intensity (I) and drought degree (D) (Zargar et al.,2010;Chen et al.,2017b).

Drought intensity refers to the degree of water deficiency for crops at a certain moment, and it can be expressed by soil water loss and soil water supply. The drought intensity (I) of a certain soil layer can be expressed as follows:

$$\mathrm{I} = 1 - f(\text{soil moisture changes}) = 1 - e^{(1+a)} \quad (1)$$

where, a is the empirical regression parameter and can be calculated via reservoir capacity and relative water loss. The specific calculation process is as follows. The water yield of a soil layer under no water stress is defined as x_0 (mm, the field capacity minus wilting moisture content) and the initial water yield of the soil layer is denoted as x_1 (mm). After the occurrence of drought, the daily water loss of the soil layer is denoted as w_i (mm) and the residual water content of soil layer referred to as x_i (mm). Therefore, the daily relative water loss is $r_i=w_i/x_i$, and the cumulative relative water loss up to that day is $y_i = \sum r_i$. On the n^{th} day of the drought, two sequences that change with drought time could be obtained. The surplus available water storages were X (x_1,x_2,……,x_n) and Y (y_1,y_2,……,y_n). The regression coefficient is a.

The drought degree (D) is the cumulative function of drought intensity (I) with duration of drought:

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$$D = \sum_{t=1}^{n} I_t \quad (2)$$

2.2.2 Soil relative humidity

The calculation method of soil relative humidity is:

$$R = \frac{W_g}{f_c} \times 100\% \quad (3)$$

$$W_v = W_g \times \rho \quad (4)$$

where, R is the soil relative humidity (%). W_v and W_g are volumetric soil water content (cm^3/cm^3) and soil weight water content (g/g), respectively. ρ is the soil bulk density (g/cm^3), and f_c is the field capacity (g/g).

The pasture growth conditions in alpine regions and regulations in the Qinghai Local Standards (DB63/T372-2011) lead to the conclusion that crop growth in this area is seriously degraded when the soil relative humidity is lower than 20. Crops withered when the soil relative humidity was within the 20%-40% range, and signs of drought occurred when the soil relative humidity was within the range of 40%-50%. However, no signs of drought were observed in crops when the soil relative humidity was higher than 50%.

3. Results and analysis

3.1 Soil moisture changes in different continuous drought processes

3.1.1 Soil moisture changes in different layers

Drought occurs when the soil moisture is reduced to a certain extent. Soil moisture changes in the root layer significantly influence agricultural crop yields(Chen et al.,2017b) For all five groups, soil moisture in different layers decreased continuously over time (Fig. 2).

With the reduction of volumetric soil water content and deepening of soil layers, the amplitude of change in volumetric soil water content among the different groups decreased. Ultimately, significant continuous reduction ceased. At the same time, the moisture gradient among different groups disappeared gradually.the volumetric soil water content gradient In the early period of drought events, The 0-10cm soil layer presents the most significant inter-group difference of soil volumetric water content, followed by the 10-20cm layer and 20-30cm layer successively.and these differences were present but diminished in the 10-20 cm layer and likewise in the 20-30 cm layer. As time progressed after the onset of the drought event, volumetric soil water content in the 0-10 cm layer decreased the most quickly. The inter-group difference in the 10-20 cm layer narrowed the most rapidly, and this

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trend was followed by fluctuations. The volumetric soil water content in the 20-30 cm layer changed slowly over all time-intervals, and the inter-group difference began to decrease early in the drought period.

3.1.2 Balance characteristics of soil moisture

Soil drought could be described well by soil water balance. According to a related study(Ma and Zhou,2017), the numerical value of soil water balance is equal to crop-soil evapotranspiration loss when the soil moisture yield is 0 mm under continuous soil drought.

Since the soil moisture yield of Group 5 is 0 mm, water moisture changes of Group 5 can generally represent the water changes of other groups. Daily water losses of Group 5 in major soil layers are shown in Fig3. Soil water storage in all layers was higher than 0 mm and water loss was present for a majority of the study period. Daily soil water loss generally fluctuated within 0-0.4 mm. In the drought stage of 1-7 d, daily soil water loss rate was high and basically presented a declining trend. The soil water balance was negative. This is the consequence of the combined factors of high soil moisture and its large differential with atmospheric humidity as well as the strong pasture-soil evapotranspiration. In the drought period of 7-35 d, soil evapotranspiration is composed of constant evaporation and secondary evaporation. Soil water loss still remained higher. However,

such soil water loss is relieved slightly as the drought continues. soil moisture changes were relieved slightly as soil drought continued in relative with that before. In the drought stage of 35-49 d, soil water balance was generally negative. However, these were accompanied with a few positives values for soil water balance. Some soils gained water which indicates that the upward migration rate of soil water in deep layers began to increase and secondary water distribution among different soil layers was triggered. As a result, water content in some soil layers increased. The surface layer of 0-10 cm was mostly affected by the aboveground environment and water loss was high. However, the degree of influence that the aboveground environment asserted on the soil water loss rate decreased with the increase of soil layer depth. The daily soil water loss of the 0-20 cm layer was 0-0.21%in 1-7 d stage, low as -0.09-0.09% in the 7-36 d stage, and is -0.04-0.15% in the 35-49 d stage. The ultimate water losses of the 0-10, 0-20, 0-30, 10-20, and 20-30 cm soil layers were 2.7%, 3.18%, 3.12%, 3.66%, and 2.98%, respectively. The soil water balance of the 20-30 cm layer changed slightly. The cumulative water loss of the 20-30 cm layer reached a maximum value at 3d (0.4%), but it obtained higher water

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yields than other soil layers in the late stage of drought. Based on the above analysis, it can be seen that soil water balance changes and water dynamic changes of the 0-20 cm layer can represent water changes of the whole pasture root system.

3.2 Soil drought degree and drought threshold

According to the formula of drought degree, drought degree shall present a linear relationship with drought intensity and duration when the assessment period N is given. However, our results also demonstrate that soil water loss rate and drought degree were relieved when the drought continued. Therefore, the negative indexation of the drought degree was carried out by combining previous research methods:

$$D = 1 - e^{-\sum I} \quad (3)$$

This change was made because $e^{\sum I}$ changes in the interval of [0, 1]. For the convenience of distinguishing drought degrees of different groups, Eq. (3) can be multiplied by one parameter (x_1/x_0, initial soil water storage/filed capacity precipitation of soil layers). Hence, the drought degree (D) can be expressed as:

$$D = 1 - \frac{x_1}{x_0} e^{-\sum I} \quad (4)$$

When D value falls in the interval of [0, 1]. The high D value implies stronger soil water stress and more serious damage to crops.

3.2.1 Relationship between surplus available water storage and cumulative relative water loss

Our analysis indicates that there is an extremely significant negative correlation between available water storage and cumulative relative water loss throughout the soil. This relationship can be described by the logarithmic linear equation Y=*a*ln*X*+*b* (Tab.2). The regression coefficient (*a*) has the following characteristics. If a<0, then │a│>1 indicates the process of water loss and │a│<1 indicates the process of water gaining. The regression coefficient *a* increased continuously with increase in soil layer depth. For the same soil layer, the regression coefficient *a* was negatively related with precipitation. Obviously, *a* could properly reflect the drought rate for the whole process.

3.2.2 Effects of duration on drought degree and drought threshold

It can be seen in Fig.4 that the drought degree (*D*) for the same layer displays parabolic growth with the duration of drought and gradually approaches 1. *D* was kept at 1 if the drought continued. Pasture cannot normally survive if the level of *D* stays at 1 for a long time without decreasing. On the

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contrary, the growth rate of drought intensity (*I*) was higher in the early stage, but it was lower in the late stage. Among the different soil layers, water loss rate was high in the early stage of drought in the 0-10 cm layer. This is attributable to the high soil moisture in the 0-10 cm layer. The *I* value for the 0-10 cm layer was three times that of the 10-20 cm layer, showing a relatively higher growth rate. However, the *D* value of the 0-10 cm layer was relatively low and no soil drought had yet occurred. In the late stage of drought, volumetric soil water content was small. It decreased gradually in the 0-10 cm layer and increased gradually in the 10-20 cm layer. Severe soil drought occurred under these circumstances. The *I* value reflects soil development speed toward the drought condition, while *D* reflects the existing drought situation in soil layers. A higher *D* value implies stronger influences of drought stress on pasture growth. Given continuous drought without precipitation, a higher I value would more rapidly bring about a high D value. Such changes conformed to the actual situation of soil drought. According to preliminary judgment, these two indices are reasonable choices to express drought situations.

For comprehensive considerations, D values were calculated according to water contents in the root layer, and it therefore is superior for monitoring drought in pasture soils.

Considering pasture growth conditions in alpine regions and regulations in the Qinghai Local Standards (DB63/T372-2011), crop growth is seriously destroyed when the soil relative humidity is lower than 20%. Crops withered when the soil relative humidity ranged within 20%-40%, and signs of drought occurred when the soil relative humidity was 40%-50%. However, no signs of drought were observed in crops when the soil relative humidity was higher than 50%. The drought degree threshold was calculated as 0.36 by fitting the multi-sample data for the volumetric soil water content of the five groups in the 0-20 cm layer. The drought intensity thresholds at the occurrence of different drought grades are shown in Table 3.

3.3 Effects of precipitation on duration of drought

In Fig.5, it can be seen that volumetric soil water content can directly influence the duration of drought. Group 1, Group 2, and Group 3 witnessed more days of moderate drought, while Group 4 had more days of severe drought compared with that of moderate drought. In different groups, duration of mild drought and moderate drought first increased and then decreased with the continuous reduction of soil volumetric water content, whereas the duration of severe drought achieved exponential growth. These trends revealed that duration of pasture drought was related with the initial volumetric soil water content as well as previous precipitation events. Natural precipitation, the only water resource for pasture growth in alpine regions, may indirectly influence duration of

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drought. Hence, the relation between cumulative precipitation and duration of different grades of drought during the growth period of pasture could be calculated according to the transitive relation of precipitation, soil volumetric water content, drought intensity, and duration: $y = 1.7928e^{0.1029x}$ (R^2 =0.6537). On this basis, the time of transition among different drought grades could be estimated by combining the current drought degree and forecasting of precipitation (hourly, daily, and monthly) for a certain period in the future. These estimates provide a strong basis for reasonable pasture management in alpine grasslands.

4 Discussion

4.1 Soil moisture changes

As drought continued, precipitation directly influenced soil moisture utilization in deep layers. For example, the overall soil moisture of Group 5 did not decrease significantly relative to other groups, which agrees with the research conclusions of other scholars (Zheng et al.,2012). This can be interpreted by following two aspects of the soil hydrology. When there are abundant precipitation events, more water migrates downward and arrives at a certain depth. This assures the moisture continuity of the whole soil layer and induces water in deep soil layers to migrate upward and supplement surface water consumption. When there is insufficient precipitation, the surface soil moisture is lower than the wilting point due to continuous water consumption and capillary moisture is broken. Under this circumstance, surface water consumption can only be supplemented by evaporation of deep soil water, resulting in the low utilization of deep soil moisture (Chen et al.,2017b). Availability of soil moisture is determined by soil moisture content and vertical water distribution. Surface soil water is the most important component of soil water for pasture growth. Based on the above analysis, insufficient surface soil moisture may affect the absorption and utilization of deep soil moisture in pastures. Moreover, the best soil layer for representative monitoring varies with respect to different crops.

4.2 Quantitative characterization of soil drought and crop drought

Previous studies on drought in alpine grasslands (Qi et al.,2009;Chen et al.,2007a) have mainly focused on the influences of meteorological drought on pasture yield and drought index inversion based on remote sensing images. In this study, the influences of precipitation on drought development were analyzed through a numerical simulation test. With reference to previously published research methods used to determine the drought threshold of peanut and corn(Chen et

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al.,2007b), drought intensity (*I*) and drought degree (*D*) were introduced. These indices use dynamic moisture changes in the soil layer to represent the current development speed toward drought conditions and the existing drought conditions. *D* can accurately reflect the influences of drought history on the current drought degree and the whole drought process. Given the same drought speed, the value of *D* is positively related with duration of drought. the value of *D* increases with increasing drought speed given the same duration of drought. Therefore, *D* can reflect pasture drought to some extent based on soil drought degree. For quantitative characterization of soil drought, the combination of *I* and *D* is superior to using either individually. *D* can be calculated easily by testing the soil moisture. It is a simpler and more intuitive index because it further quantizes and integrates soil moisture dynamics, thus significantly increasing the monitoring time scale and spatial scale.

4.3 Time scale of soil relative humidity data

Previous studies(Wang et al.,2013;Daviemartin et al.,2015;Paudel et al.,2015)on soil relative humidity mostly use the observational data of meteorological stations, the data is 3 times a month, 8, 18, 28 days, respectively, and interpolate them to the daily scale by relevant technical methods to form the time series of the daily scale. The research data in this paper is based on the daily observation data every 10 minutes. Compared with the time series of daily scale, the conclusions obtained are more accurate and precise.

In this paper, soil relative humidity was utilized as the soil-pasture drought intensity threshold. This was accomplished according to relevant local standards due to the lack of daily observation data for pasture growth indices. Future studies should adjust the test to further optimize the pasture drought threshold.

5 Conclusions

(1) Soil moisture in the 0-30 cm layer declined continuously in all groups after gradient processing of precipitation. With increasing precipitation, there was an increase in the utilization of deep soil water and an increase in the reduction rate of soil moisture. Inter-group differences gradually disappeared as the drought conditions continued.

(2) The daily soil water balance can properly reflect the soil drought process. Over the time scale of drought development, soil drought rate and daily water loss of pasture are higher during the early stage than the late stage. Spatially, soil water balance in the upper layers changes more quickly than that in the lower layers. Upper layers mainly suffer water loss, while the lower layers are relatively stable. These results all confirm that monitoring or simulating soil moisture dynamics in

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appropriate layers can reflect pasture drought conditions.

(3) In the process of drought, there is a significant logarithmic relationship between soil water storage and cumulative relative water loss. The slope can express soil drought and pasture drought degrees. Pasture suffers drought after the soil drought degree exceeds 0.355, which is the soil drought threshold for pasture growth.

(4) Duration of the different grades of droughts is related with the initial volumetric soil water content and previous precipitation levels. The relationship between duration of drought and cumulative precipitation can be expressed by an exponential equation.

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Tables

Table 1. Physical properties of soil in the study area

Soil layer (cm)	Soil bulk density g/cm^3	Field capacity g/g	Wilting humidity g/g
0-10	1.24	31.0	8.8
10-20	1.32	29.3	8.2
20-30	1.30	30.5	7.5

Table 2. Relationship between surplus available water storage and cumulative relative water loss in different soil layers of different groups

Groups	**Regression equation**	**Correlation coefficient**	**n**
	0-10 cm		
Group 1	Y=-1.028ln(x)+3.2624	1	49
Group 2	Y=-1.026ln(x)+2.9010	1	49
Group 3	Y=-1.032ln(x)+2.8367	1	49
Group 4	Y=-1.019ln(x)+2.4879	1	49
Group 5	Y=-1.020ln(x)+1.7615	1	49
	10-20 cm		
Group 1	Y=-1.028ln(x)+2.9524	1	49
Group 2	Y=-1.026ln(x)+2.7576	1	49
Group 3	Y=-1.043ln(x)+2.6702	1	49
Group 4	Y=-1.018ln(x)+2.3602	1	49
Group 5	Y=-1.013ln(x)+2.0791	1	49
	0-20 cm		
Group 1	Y=-1.027ln(x)+3.1144	1	49
Group 2	Y=-1.025ln(x)+2.8272	1	49
Group 3	Y=-1.033ln(x)+2.7474	1	49
Group 4	Y=-1.015ln(x)+2.4168	1	49
Group 5	Y=-1.012ln(x)+1.9254	1	49

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Table 3. Drought degree (D) thresholds of different grades of drought.

Drought grade	The threshold of Drought degree
No drought	D<0.36
Light drought	0.36≤D<0.45
Medium drought	0.45≤D<0.70
Heavy drought	D≥0.70

Figures

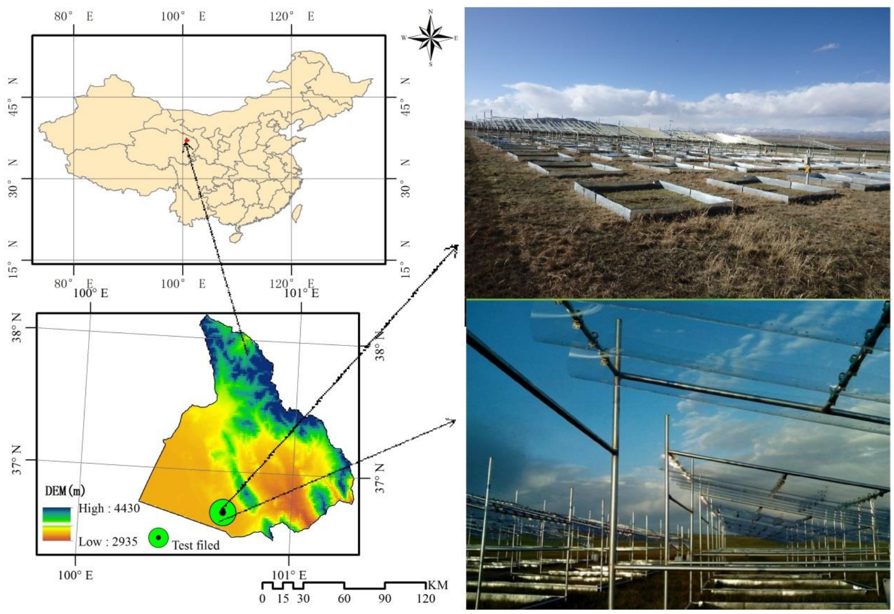

Figure 1.:Arrangement of testing plot and set-up of precipitation coverage rates

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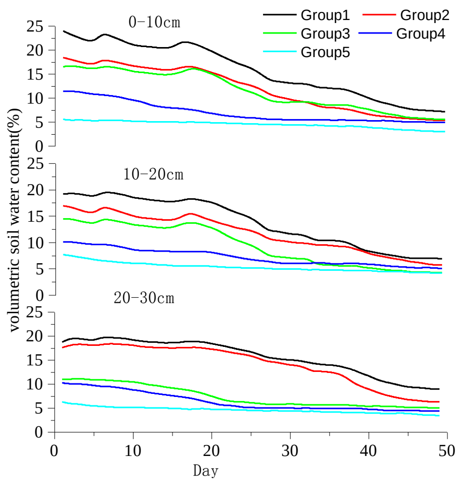

Figure 2:Changes of volumetric soil water content in different layers.

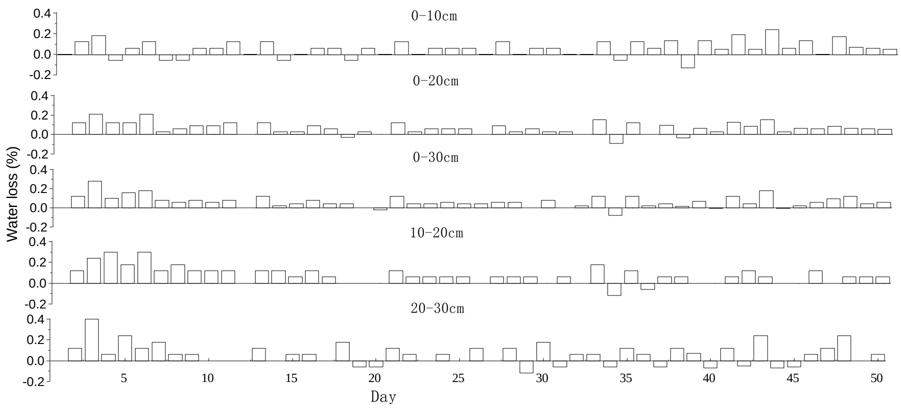

Figure 3:Soil water balance characteristics in different layers under conditions of no precipitation.

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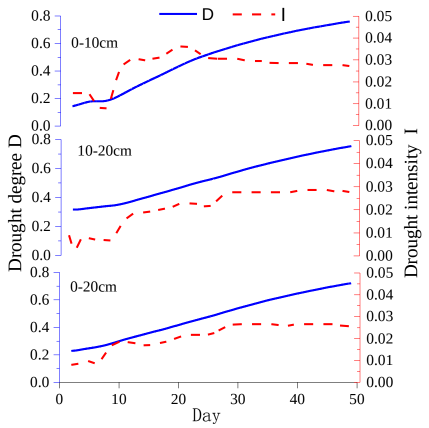

Figure 4.:Changes of drought intensity and drought degree of Group 1 in major soil layers.

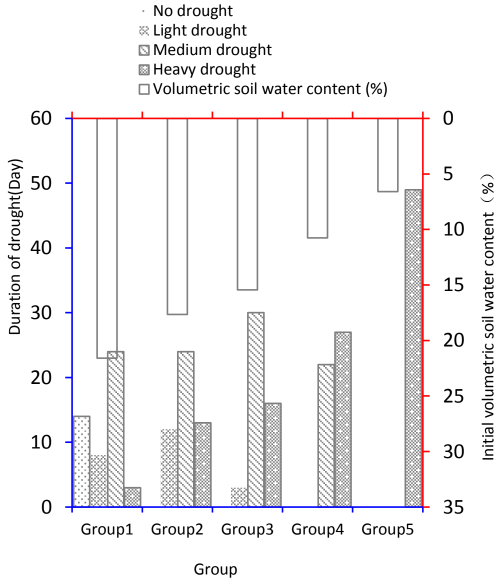

Figure 5:Relationship between duration of drought and volumetric soil water content in different groups.

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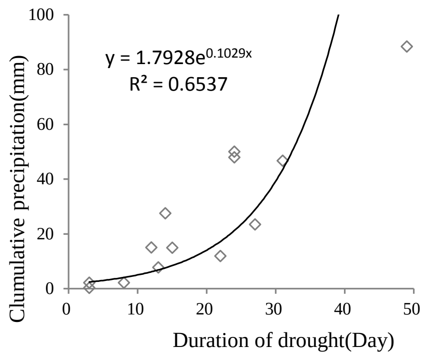

Figure 6:Relationship between duration of drought and cumulative precipitation