The occurrence and development of soil drought in alpine grassland using the drought threshold

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Abstract. Soil and crop drought is not merely a deficiency of rainfall, but a deficiency of water available for the use of growing crops. Based on the water flow and supply in a soil–pasture continuum, an empirical correlation between soil water storage and depletion in a given layer and an index of soil drought intensity (I) and degree (D) was established using the soil water data obtained from a field experiment conducted in Haibei, Qinghai, China. Five testing groups were established according to their vegetation coverage (0–100%) at the initiation of the pasture growth period. It was found that the changes of soil moisture in the 0–20 cm layer generally reflect the drought stress of a pasture. The daily values of I reflected the soil water depletion rates in the drying course and the values of D in different soil layers increased with the progressive soil drying course. The D index in different soil layers not only revealed the drought severity of the layer, but it was also reflected pasture drought inversely when D was more than the threshold values. When D went beyond 0.39, the soil will appear drought. The durations of different grades of drought s were correlated with both the initial soil moisture and previous precipitation. Based on soil water changes, the index D is the comprehensive result of antecedent soil water condition, soil properties, and potential atmospheric evaporation. The results suggest that soil drought degree D, together with I, can be an index for monitoring and evaluating soil–crop drought.

Highlights

- Changes of relative soil moisture in the 0-20 cm layer can generally reflect drought stress of the pasture.

- Soil drought degree 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.

1 Introduction

The term agricultural drought mainly refers to the phenomenon whereby crops cannot grow and develop normally due to atmospheric drought or soil drought; thus, resulting in the reduction of production (Wilhite, 1993; Sadras and Milroy, 1996; Laio et al., 2001; Heim, 2002). Atmospheric drought is caused by excessive water consumption through plant evapotranspiration due to high atmospheric temperature, low relative humidity, strong solar radiation, and certain wind actions (Correia et al.,1994; Hayes.et al.,1999; Gonzalez and Valdes, 2006). Soil drought prevents the root system of crops from absorbing enough water to compensate for water evapotranspiration due to the low soil water content and low water potential, with the result that there is inadequate water in plants to maintain normal physiological activities, leading to wilting or even death(Jensen et al., 1998; Narasimhan and Srinivasan, 2005; Soltani et al., 2000). Grassland has important ecological and production functions. Animal husbandry is the main economic activity in Qinghai Province and throughout the whole of North China. The natural grassland in Qinghai Province depends on a completely natural soil water system that is reliant on natural precipitation and groundwater supply. Qi (2009) reported that the underground water level of natural grassland in Qinghai Province is deeper than 2 m and the compensation of soil water by groundwater can be neglected. This demonstrates that inadequate soil water is the primary cause of agricultural drought in non-irrigated regions (Yuan and Zhou, 2004; Sterck et al., 2006; Gholipoor et al., 2012). Studies have shown that crop growth has a response threshold to soil drought (Sadras and Milroy, 1996; Chen et al., 2007). Crop growth is changed significantly only when the soil drought degree is lower than the critical value. This soil drought degree is called the threshold of soil drought. Therefore, the occurrence and development of drought can be reflected by an appropriate soil drought threshold. This enables the objective identification and quantitative monitoring of agricultural drought. Thus, drought is a dynamic process that develops gradually, with long-term accumulation of drought conditions that is influenced by a series of factors, such as duration and soil water transmission. The use of soil water content to quantify plant responses to water deficits has the advantages of being simple and reflecting some apparent physiological mechanisms (Sadras and Milroy, 1996), but it cannot reflect the duration of drought.

In this study, we evaluated the concepts of drought intensity and drought degree for determining the effects of drought on soils and crops. Accordingly, we used a drought index to evaluate the water stress on a soil. The aim was to (1) quantify soil drought intensity and soil drought degree based on the soil water status, (2) determine the soil drought threshold in the growth period of pastureland and combine it with soil moisture data, and (3) investigate the influences of precipitation and soil moisture on the development of drought.

2 Study area and research methodology

2.1 Study area and experimental design

This experiment was implemented in a large controllable water test site in the Haibei Animal Husbandry Meteorological Test Station (36°57′N, 100°51′E) in Qinghai Province (China) from April to September, 2017. The altitude at this station is 3010 m, and the annual average temperature is 0.9℃.The annual average precipitation is 403.6 mm, with about 60% of the total occurring in summer, especially August (about 90.6 mm). In the 0–30 cm layer, the range of soil bulk density, field capacity, and wilting humidity are 1.24–1.32 g/cm^3, 29.3–31.0 g/g, and 7.5–8.8 g/g, respectively. The physical properties of the soils in different layers are listed in Table 1.

In the sampling site, the unit area of a sampling plot is 7.2 m^2 (2.4 × 3 m) and a piece of rust-proof iron sheet was inserted into the ground to a depth of 20 cm, while the surface was exposed to a height of 20 cm. There was no water connection between the surface and root systems in the different sampling plots. Natural precipitation was shielded by a large electronic rain shelter during the growth period of the pasture. This whole experiment was composed of three growth stages of pasture: green period (F); vegetative growth period (S); and leaf-expansion period (H). Sampling plots were marked as F11–F54 and D61–D64 in the F period (April–May), S11–S54 and D61–D64 in the S period (June–June), and H11–H54 and D61–D64 in the H period (August–September). The specific distributions are shown in Table 2.

According to the grading standards of pasture risk assessment in Qinghai Province, rain sheltering was provided to ensure different precipitation levels (0, 20, 30, 60, and 100%). For example, 0% represents natural precipitation without shielding and 20% represents a 20% reduction of natural precipitation. Different groups were recorded as groups 1–5. Each group was replicated four times, resulting in a total of 52 sampling plots. In the study, periods S and H were combined as one study period.

Soil temperature and humidity were measured automatically every day from 00:00, with a measurement made every about 10 min by a three-parameter sensor (SDI-12, Acclima Co., USA) in three layers (0–10, 10–20, and 20–30 cm) in each sampling plot. A statistical analysis was conducted using SPSS software. Variances such as the soil water content among the plots in each group were comparable to those between groups and were therefore treated as independent values.

2.2 Research methodology

2.2.1 Soil drought intensity and degree

Soil drying is a progressive process, with the rate of development referred to as drought intensity. As the process continues, drought will accumulate to the level at which irreversible water stress and crop damage occurs. The accumulative drought level is termed the drought degree. In a given crop growth period, the drought hazard is determined by the duration and intensity of the drought. Thus, soil and crop drought should be expressed rationally by drought intensity and drought degree, as described below (Zargar et al., 2010; Chen et al., 2010). For drought intensity, in a specific soil layer with plant roots, soil drought occurs because the rate of water depletion, including evapotranspiration and redistribution, is faster than the rate of water restoration (from the depth below the root zone and precipitation). Differences in the rate of water depletion and restoration can be equated with the soil drought intensity. For a given crop, drought occurs because the rate of water loss from the leaves is larger than the rate of water taken up by the roots or transported through the crop. Thus, the difference between water lost and water taken up provides a measurement of plant drought intensity. Water use is driven by the meteorological conditions, but can be limited by soil water availability. Therefore, soil and crop drought intensity can be expressed by the relationship between soil water depletion and supply (Chen et al., 2010).

We established drought intensity (I) in a given soil layer as follows:

$$I = 1 - \frac{\text{water depletion in a layer}}{\text{water supply in a layer}} = 1 - f(\text{soil water changes}) = 1 - f(w) \quad (1)$$

where f(w) is a function of water depletion and supply, which is determined by how fast the soil water changes. Chen et al. (2010) found that the function f(w) could be expressed using a simple empirical parameter (a). The drought intensity (I)is expressed by the following formula:

$$I = 1 - e^{1+a} \quad (2)$$

where the value of I always falls within [0,1] because in the course of soil drying the empirical regression parameter $a \leq -1$. This result is derived in Section 3.

On the other hand, for the drought degree (D), soil and plant drought develops gradually, and is influenced not only by drought intensity but also by drought duration, so the damage done to plants under drought stress is gradually cumulative. Therefore, it is reasonable to assume that the soil drought degree can be expressed as a function of the sum of drought intensity. As follows:

$$D = \sum I \quad (3)$$

In practice, to account for the initial soil water, Chen et al. (2010) rewrote the equation as:

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

where x_0 is the maximal value of transpirable water in a soil layer, calculated from the field capacity minus the air-dried soil water content; and x_1 is the transpirable water at the beginning of soil water monitoring. The value of D falls within [0,1]. A high D value implies a strong soil water stress and more serious damage to crops.

2.2.2 Soil relative humidity

Soil relative humidity was calculated as follows:

$$R = \frac{W_g}{f_c} \times 100\% \quad (5)$$

$$W_v = W_g \times \rho \quad (6)$$

where R is the soil relative humidity (%); W_v and W_g are the 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).

3. Results and analyses

3.1 Soil moisture changes in different continuous drought processes

3.1.1 Soil moisture changes in different layers

The volumetric soil water content profiles for each group are shown in Fig. 1, from which we can observe some interesting water changes in the soil profile. With a reduction in the volumetric soil water content and deepening of the soil layers, the amplitude of the 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. In the early period of drought, the 0–10 cm soil layer presented the most significant inter-group differences in volumetric soil water content, followed successively by the 10–20 and 20–30 cm layers. These differences were present but diminished in the 10–20 and 20–30 cm layers. The volumetric soil water content in the 0–10 cm layer decreased most quickly over time. The inter-group difference in the 10–20 cm layer narrowed the most rapidly, and this 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 differences began to decrease early in the drought period.

3.1.2 Soil moisture balance

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

Because the water supply of group 5 was 0 mm, its soil moisture changes could generally represent the variation law of soil moisture(itself). The daily water losses in the major soil layers of group 5 are shown in Fig. 2. Soil water storage in all layers was higher than 0 mm and water loss occurred for the majority of the study period. Daily soil water loss generally fluctuated within 0–0.4%. The daily soil water loss rate was highest in the first seven days, while from the seventh to the 32nd day, in the remaining soil layers soil water depletion occurred at a slightly slower rate. From the 33rd to the 49th days, the soil water balance was positive in individual periods, indicating that the soil gained water. These three periods represent the soil water depletion patterns during soil drying. In the early stage of soil drying, water was extracted mainly from the 0–20 cm layer. As soil drying persisted, the 20–30 cm soil water layer was restored through supplies from the lower layers, and the water balance changed slightly. The final water loss of the 0–10, 0–20, 0–30, 10–20, and 20–30 cm layers was 2.7, 3.18, 3.12, 3.66, and 2.98%. The results shown in Fig. 2 strongly confirm the view in the region that water is not easily transported to the upper roots because soil hydraulic conductivity decreases dramatically with a decrease in soil water content. Based on the above analysis, it was apparent that the soil water balance changes and water dynamic changes in the 0–20 cm layer were representative of the water changes in the whole pasture root system.

During soil drying, soil water in different layers is depleted at different rates. There is considerable in the depletion rate, which determines the soil drought intensity of the 0–10, 10–20, and 20–30 cm layers over the course of drying, and it is difficult to determine using a single equation. However, for a given soil layer, we found that the relationship between the accumulated relative depletion (y) and the remaining transpirable soil water (x) fitted a log-linear model:

$$y=a\ln x+b \qquad (7)$$

where a and b are the fitted parameters. In a given soil layer, the daily water depletion is w_i (mm), the remaining transpirable soil water on the same day is x_i (mm), and accordingly, the relative depletion, r_i, is w_i / x_i (%). On a given day, the accumulated relative depletion is $y_i = \sum r_i$. Over the course of soil drying, we obtained two water data sets: (1) the accumulated relative depletion set Y = (y_1, y_2, . . ., y_i, . . ., y_n), and (2) the remaining transpirable water set X = (x_1, x_2, . . ., x_i, . . ., x_n). The measured data from different soil layers in the plots fitted Eq. (7) very well, as shown in Table 3.

We found that the fitted parameter a (slope) in Eq. (7) was less than 0 due to the inverse correlation between the remaining soil water and the depletion. Furthermore, parameter a was less than 1 when soil water was depleted (by soil drying) and larger than 1 when soil water was restored (by precipitation or irrigation). The slower the water depletes, the closer the parameter a approaches 1. Thus, the slope a reflects the rate of water change in a soil layer over the course of a drought. Hence, the value of a accounts for the relationship between water depletion and water supply in a soil layer. The soil drought intensity, I in Eq. (2), is actually the indexation of parameter a.

3.2 Soil drought intensity and soil drought degree

Using Eq. (2) and (7), we calculated the soil drought intensity, as shown in Fig. 3. The figure demonstrates the daily course of drought intensity in different soil layers during soil drying. The 0–10 cm layer values of drought intensity were larger than those of the 0–20 cm layer, revealing that soil water depletion in the topsoil occurred faster than in the subsoil. It should be noted that drought intensity is not a reflection of absolute water depletion, but is a relative rate based on the remaining water storage. Hence, as shown in Fig. 3, the drought intensity did not decrease with the consequent decrease in the quantity of water depleted during soil drying.

The drought intensity in the upper layer fluctuated, with larger amplitudes compared to those in the lower layer. The results suggested that the soil water status in the upper layer was more easily affected by the weather and plant root water uptake. Therefore, the drought intensity fluctuated due to daily weather changes. The 10–20 cm soil layer was influenced only slightly by the daily weather changes. However, after 25 days of drying in this study, as shown in Fig. 3, the drought intensity in the 10–20 cm layer eventually started to increase, suggesting that the water depletion rate in the deeper layer was controlled by the upper layer moisture and by the weather. According to Eq. 3 and 4, a change in the value of I will lead to a change in the value of D.

The soil drought severity level increases for as long as the soil is drying. This trend is clearly demonstrated by the soil drought degree, which accounts for soil drought intensity and duration according to Eq. (3). As shown in Fig. 3, the soil drought degree increased as the drought progresses. In group 1, at the end of soil drying, the relative rates of change in the soil drought degree in the 10 and 20 cm layers were 4.31 and 1.38%, respectively. The soil drought degree ranged from 0.76 in the 10 cm layer to 0.75 in the 20 cm layer, indicating that the soil layer was experiencing drought. Although D only represents the drought degree in a given layer, the D value in the upper layers (e.g., 10 cm), which is more sensitive to weather changes than the deeper layer, is capable of indicating the root zone (usually 0–20 cm) drought status due to the relationship of water transport between soil layers. Therefore, in practice, there is a need to measure more than just the top soil moisture (using automatic instruments) to monitor and predict soil drought status.

The soil drought intensity reflects the speed at which soil drought conditions develop, while the soil drought degree reflects the existing drought situation in specific soil layers. Given a continuous drought without precipitation, a high soil drought intensity would rapidly generate a high soil drought degree. Such changes are indicative of the actual situation of soil drought. According to our preliminary judgment, these two indices were considered reasonable choices to express the drought situation.

3.3 Soil drought threshold

Considering the pasture growth conditions in alpine regions, the soil relative humidity in the 0–20 cm soil layer is used to monitor crop drought under the DB63/T372-2018 standard, with the specific classifications given in Table 4. Hence, the relationship between crop drought and soil drought could be represented by the soil drought degree and soil relative humidity in the 0–20 cm soil layer.

The soil drought degree and soil relative humidity in the different groups are shown in Fig. 4. As the soil dried, the soil drought degree decreased with an increase in soil relative humidity. For example, the negative correlation between soil drought degree and soil relative humidity in group 1 was fitted as:

$$D = -0.0098R + 0.8775 \qquad (8)$$

with $R^2 = 0.7058$ ($p < 0.05$). Similar regression equations could be obtained from other soil layers.

Using Eq. 8 and Table 4, the thresholds of the soil drought degree were determined to be 0.39, 0.49, and 0.68 in the three different soil layers, respectively. The thresholds of the soil drought degree for the different grades of drought are shown in Table 5.

3.4 Effects of precipitation on the duration of drought

The volumetric soil water content can directly influence the duration of drought, as shown in Fig. 5. The duration of heavy drought was longest in group 4, but there was a middling drought in groups 1 to 3. In the different groups, the duration of light and middling drought first increased and then decreased with a continuous reduction in the volumetric soil water content. The duration of heavy drought achieved exponential growth, indicating that the duration of soil drought was not only related to the initial volumetric soil water content but also to previous precipitation. Natural precipitation, the only water resource for pasture growth in alpine regions, may indirectly influence the duration of drought. Hence, the relationship between cumulative precipitation and the duration of different grades of drought during the growth period of pasture could be calculated according to the transitive relationship among precipitation, volumetric soil water content, drought intensity, and duration, as follows:

$$y = 1.7928e^{0.1029x} \qquad (9)$$

where y and x are the cumulative precipitation and duration of different grades of drought, respectively, with $R^2 = 0.7058$ ($p < 0.05$). The measured data from the different soil layers in the plots fitted Eq. (9) very well, as shown in Fig. 6. On this basis, the transition time among the different drought grades could be estimated by combining the current soil drought degree with precipitation forecasts (hourly, daily, and monthly) for a certain period in the future. This provides a strong basis for reasonable pasture management in alpine grasslands.

4 Discussion

4.1 The response time of crops to a reduction in water stress

The soil moisture began to decrease sharply after the seventh day, as shown in Figs. 2 and 3. Chen et al. (2010) showed that the response time was similar for other crops (summer maize). Therefore, water resources could be effectively regulated and controlled in light of this obvious time threshold.

4.2 Expression of the relationship between water depletion and water supply

According to the mechanism of water depletion and water supply, we found that the relationship between the accumulated relative depletion (y) and the remaining transpirable soil water (x) could be well fitted by a log-linear model (Fig.7) and Chen et al., (2010, their Fig. 2) draw a similar conclusion, which demonstrated that parameter *a* is essentially the function f(w), with the value of a describing the relationship between water depletion and water supply in a soil layer. The conclusions suggest that the soil drought degree, which is based on the theory of soil dynamics, can be a reliable index for evaluating the soil–crop drought development process.

4.3 Rationality of the soil drought degree

The soil drought degree, calculated from the decreasing rate of transpirable soil water, can be used for irrigation scheduling in irrigated areas (Chen et al., 2010). Because it was determined by the soil drying rate and duration, the threshold value was actually independent of the occasional fluctuations in weather. Our experiments with different occlusions of natural precipitation suggested a similar threshold value of D. The results suggest that the threshold value was stable between years. However, studies (Homma et al., 2004; Wang et al.,2013; Ma and Zhou, 2017; An et al.,2017;Shi et al., 2017) have shown that crop physiological variables respond in an unstable manner to water stress and fluctuate with weather, location, crop species, and variety. Crop morphological variables often lag behind soil drought. At the point when changes can be detected, it is already too late because the crop has already suffered due to the drought. In this study, due to the lack of observational data of daily forage growth indicators, soil relative humidity was the only criterion that could be used to initially define soil drought, and then the threshold of soil drought could be further optimized by adjusting the observational factors. On the others hands, strengthening comparative analysis with other drought indices (PDSI, SPEI, VHI) is necessary in future (Dai, 2013; Kogan, 1997; V Vicente-Serrano et al., 2010)

5 Conclusions

First, the daily soil water balance can effectively reflect the soil drought process. Over the time scale of drought development, the soil drought rate and daily water loss on pastureland were higher during the early than late stages. Spatially, the soil water balance in the upper layers changed more quickly than in the lower layers. The upper layers mainly suffered a water loss, while the lower layers were relatively stable. These results confirmed that monitoring or simulating soil moisture dynamics in appropriate layers can reflect pasture drought conditions.

Second, as the soil dried, the threshold of the soil drought degree reached 0.39, indicating the beginning of soil drought. There was a significant logarithmic relationship between soil water storage and cumulative relative water loss. The slope could express both the soil and crop drought degrees. The duration of the different grades of drought was related to the initial volumetric soil water content and previous precipitation levels. The relationship between the duration of drought and cumulative precipitation could 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. Sample plot distribution map of precipitation control experiment

				Isolation belt (2m)					
	F11	F21	F31	F41	F51	F12	D63	D61	
				Isolation belt (1m)					
	F22	F32	F42	F52	F13	F23	D64	D62	
				Isolation belt (1m)					
	F33	F43	F53	F14	F24	F34	F44	F54	
				Isolation belt (1m)					
	S11	S21	S31	S41	S51	S12			
				Isolation belt (1m)					
Isolation belt (2m)	S22	S32	S42	S52	S13	S23	S54		**Isolation belt (2m)**
				Isolation belt (1m)					
	S33	S43	S53	S14	S24	S34	S44		
				Isolation belt (1m)					
	H11	H21	H31	H41	H51	H12			
				Isolation belt (1m)					
	H22	H32	H42	H52	H13	H23	H54		
				Isolation belt (1m)					
	H33	H43	H53	H14	H24	H34	H44		
				Isolation belt (2m)					

Table 3. Relationship between relative water depletion and remained transpirable water cumulative relative water in different soil layers for the different groups

Group	Regression equation	Correlation coefficient	n
	0-10cm		
group1	*Y=-1.027ln(x)+3.2650*	1	49
group2	*Y=-1.026ln(x)+2.9869*	1	49
group3	*Y=-1.029ln(x)+2.8824*	1	49
group4	*Y=-1.019ln(x)+2.4819*	1	49
group5	*Y=-1.021ln(x)+1.7399*	1	49
	10-20cm		
group1	*Y=-1.028ln(x)+3.0383*	1	49
group2	*Y=-1.024ln(x)+2.8993*	1	49
group3	*Y=-1.043ln(x)+2.7837*	1	49
group4	*Y=-1.018ln(x)+2.3554*	1	49
group5	*Y=-1.013ln(x)+2.0633*	1	49
	0-20cm		
group1	*Y=-1.026ln(x)+3.1518*	1	49
group2	*Y=-1.019ln(x)+2.9039*	0.9975	49
group3	*Y=-1.030ln(x)+2.8199*	1	49
group4	*Y=-1.015ln(x)+2.4113*	1	49
group5	*Y=-1.012ln(x)+1.9073*	1	49

Table 4. The standard used to indicate agricultural drought

The threshold of relative soil moisture	Crop phenomenon
R <20%	Heavy drought
20≤ R <40%	Crop starts wilting
40%≤ R <50%	Drought
R ≥50%	No drought

Table 5. Drought degree (D) thresholds for different grades of drought.

Drought grade	The threshold of drought degree
No drought	D <0.39
Light drought	0.39≤ D <0.49
Medium drought	0.49≤ D <0.68
Heavy drought	D ≥0.68

Figures

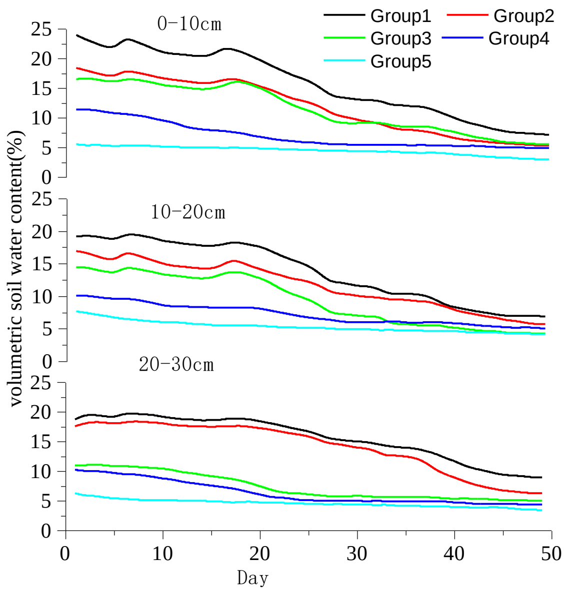

Figure 1. Changes in the volumetric soil water content in different soil layers.

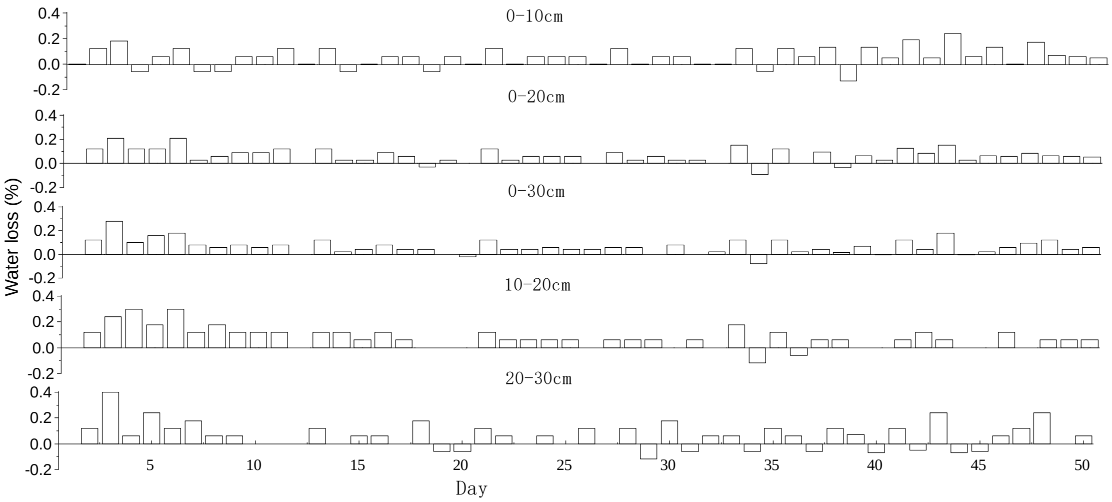

Figure 2. Soil water balance characteristics in the different layers with no precipitation.

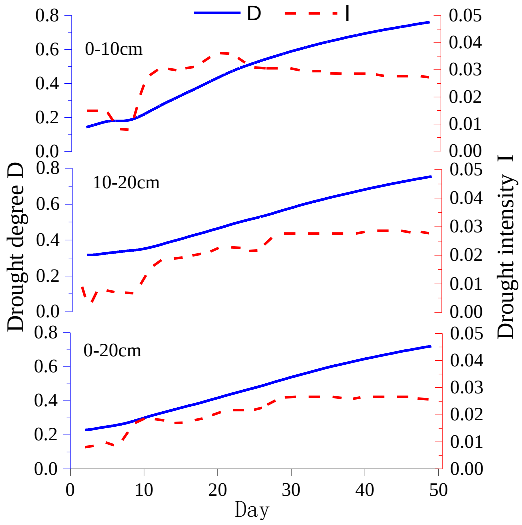

Figure 3. Changes in the drought intensity and drought degree for group 1 in major soil layers.

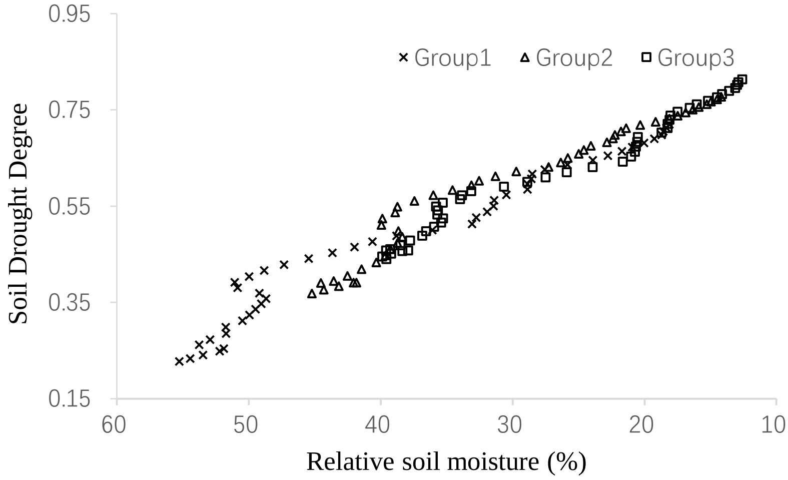

Figure 4. The relationship between soil drought degree and relative soil moisture.

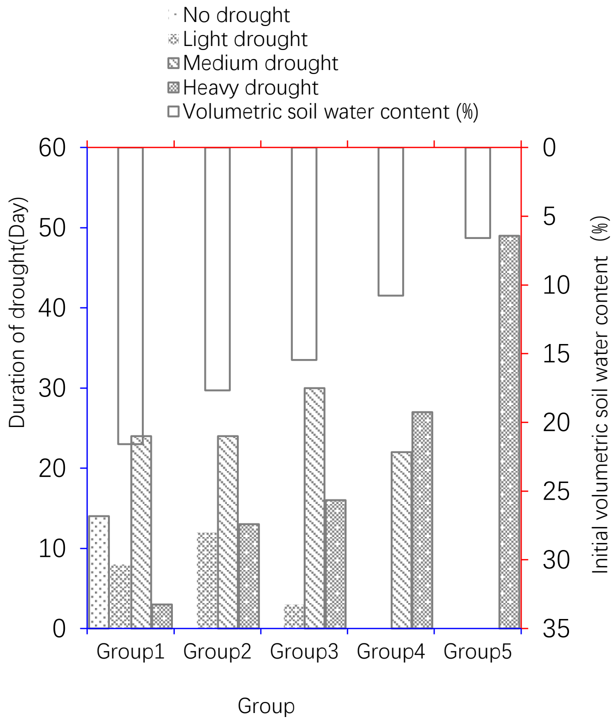

Figure 5. The relationship between the duration of drought and volumetric soil water content in different groups.

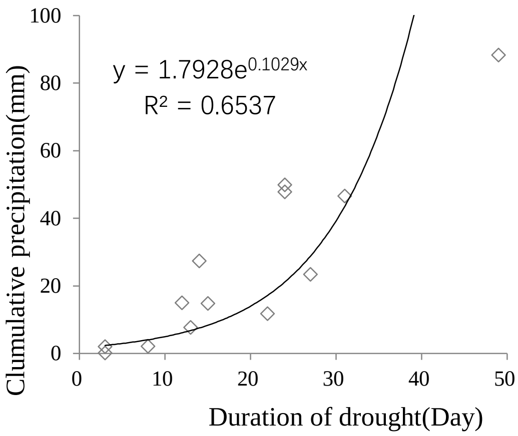

Figure 6. The relationship between the duration of drought and cumulative precipitation.

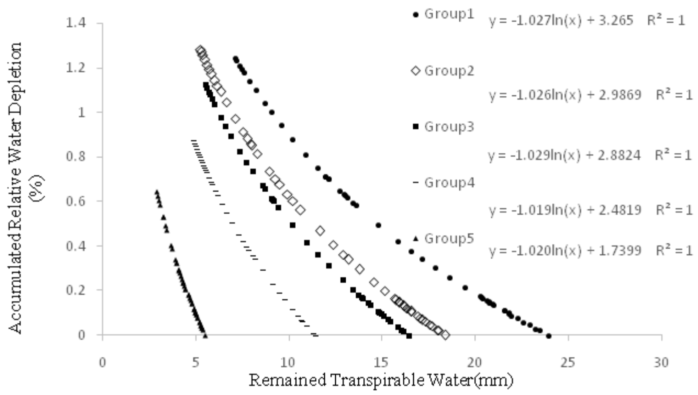

Figure 7. The relationship between accumulated relative water depletion and remaining transpirable water in the different groups.

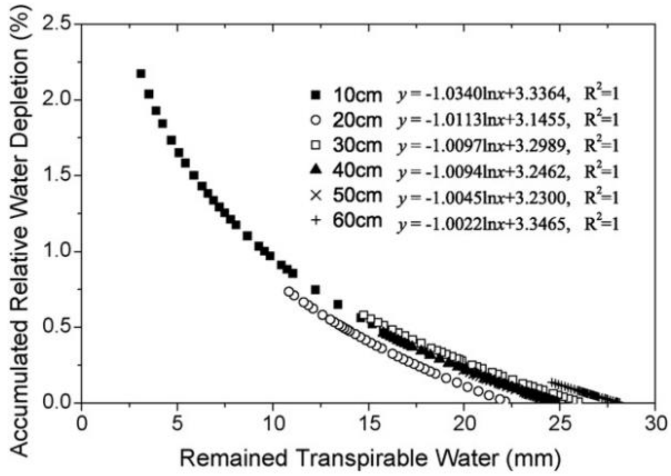

Figure 8. The relationship between remaining transpirable water and accumulated relative water depletion in different soil layers (Chen et al., 2010, Fig. 2).