Rainfall Determines Shallow Soil Seepage in a Piedmont Summer Pasture of Alpine Meadow on the Northeastern Qinghai-Tibetan Plateau

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Research Article

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Abstract

The soil seepage is an important component for quantifying hydrological processes while remains unclear in high-altitude alpine meadows. The shallow soil seepage was continuously measured by an auto-logged micro-lysimeter (diameter = 30 cm, depth = 30 cm) from July 2018 to June 2019 in a piedmont summer pasture of alpine meadow on the Northeastern Qinghai-Tibetan Plateau. The results showed that all the shallow soil seepage events occurred during the non-frozen period from April to September and the accumulative amount was 106.8 mm, which consumed about 1/5 annual precipitation. The maximum and minimum monthly soil seepage was 30.7 mm in September and 1.0 mm in April, respectively. The binary Logistic model revealed that daily half-hour rainfall frequency (R^2 = 0.37, individual explanatory power) and amount played significant roles in the daily soil seepage odds (R^2 = 0.50). The best subsets regression analysis showed that the same-day rainfall amount (R^2 = 0.59), the first 3-day rainfall frequency, and the first 4-day solar radiation accounted for 73% of variations in the daily soil seepage amount. Monthly soil seepage correlated with monthly rainfall frequency significantly (R^2 = 0.74, p = 0.005). Our results highlighted that precipitation, including its amount and frequency, was the key determinant of the probability and amount of the shallow soil seepage in the piedmont summer pasture of alpine meadow. These findings would be helpful for improving predictions of the water budgets of piedmont alpine meadows.

1 Introduction

Soil seepage is the key element of terrestrial water budgets and plays an essential role in aquifer charge and river flows (Chapin et al. 2011; D'Odorico et al. 2010). It is especially true for the high-altitude alpine regions, which are generally referred to as “water towers” to the lowlands (Gao et al. 2019; Zheng et al. 2000). Because of the seasonal freeze-thaw cycle and distinct stratification of organic matter content along with soil profile in alpine meadows (Bayard et al. 2005; Zhang et al. 2019), soil seepage is important yet poorly understood in hydrological processes (Wilcox et al. 2017). However, previous researches are usually based on model simulations (Ge et al. 2011; 2008); few observational studies have been conducted in cold areas (Dai et al. 2019; Yang et al. 2016). Therefore, quantifying the soil seepage and its underlying environmental controls would further improve our knowledge of the ecohydrological processes and the estimations of water resources over alpine regions (Ireson et al. 2013; Levia et al. 2020).

Soil seepage of a certain site is regulated by precipitation input, evapotranspiration loss, soil water storage change, and surface runoff, where the last two items are mostly ignored during long-term studies (Chapin et al. 2011; Wilcox et al. 2017). In alpine humid meadows, evapotranspiration was much determined by radiation energy availability and generally recycles almost all precipitation inputs back to the atmosphere (Zhang et al. 2018). Consequently, shallow soil seepage should be closely related to rainfall (frequency and amount) and soil hydraulic conductivity (extremely low in a frozen soil layer) at a short-term (daily or monthly) scale (Hinzman et al. 1991; Zhang et al. 2019). Meanwhile, shallow soil seepage events mainly occurred during the non-frozen periods with a peak in June (Dai et al. 2019) or July (Yang et al. 2016). However, the degree to which soil seepage odds and amount are dependent amongst environmental controls is highly constrained. The field soil seepage observations are critical to addressing these issues and can deepen the mechanistic understanding of the water cycles in alpine meadows.

The piedmont summer pastures are generally the common rangelands and are located at the foot of mountains and the soil depth is less than 40 cm (Zheng et al. 2000). More importantly, it has been severely degraded because of the tragedy of the commons, which could affect ecohydrological processes and water budgets substantially (Wang et al. 2008). In this study, we employed a micro-lysimeter to quantify the seasonal pattern of shallow soil seepage (probability and amount) and the potential environmental controls in a piedmont summer pasture of alpine meadow on the northeastern Qinghai-Tibetan Plateau. Since the higher precipitation and shallower soil layer in summer pastures with comparisons to winter pastures (Dai et al. 2019; Yang et al. 2016), we hypothesized the soil seepage in the higher-altitude summer pasture would be precipitation-dependant.

2 Material And Methods

2.1 Site description

The observation has been conducted at a piedmont summer pasture of alpine meadow (37°41' N, 101°21' E, 3550 m a.s.l.). The studying site is 10 km northeast away from Haibei National Field Research Station for Alpine Grasslands (hereafter Haibei Station, 37°37' N, 101°19' E, 3200 m), which lies on the northeastern Qinghai-Tibetan Plateau. The climate is typical plateau continental, where summer is warmer and wetter and winter is colder and drier. The soil of summer pasture is a silt loam of about 20–40 cm thickness. The 0–10 cm, 10–20 cm, and 20–40 cm soil bulk density and organic carbon content are 0.59 and 7.53%, 0.75 and 5.96%, 1.26 $g \cdot cm^{-3}$ and 4.17 %, respectively (Wu et al. 2014).

The vegetation in the piedmont summer pasture is classified as alpine forb meadow. The dominated plants consist of *Carex moorcrofti*, *Leontopodium nanum*, *Poa pratensis*, *Saussurea Katochaete*, *Kobresis humilis*, *Elymus nutans*, and *Stipa aliena*. The aboveground and topsoil belowground biomass in August was about 190 $g \cdot m^{-2}$ and 1040 $g \cdot m^{-2}$, respectively (Wu et al. 2014). The summer pastures have been experiencing a heavy grazing intensity (10 $sheep \cdot hm^{-2}$) and degraded seriously (Fig. 1).

2.2 Micro-lysimeter and environmental variables

The size of a cylindrical micro-lysimeter is 30 cm in height and 30 cm in diameter, with a PVC material (Fig. 1). The depth of the lysimeter could cover 95% of belowground biomass. The out tanker was installed vertically into the soil and the top was horizontal to the soil surface. A weighting sensor (5 g precision, corresponding to 0.071 mm) and a tipping bucket rain gauge (0.003 mm precision) were installed at the bottom of the out tanker, and were used to monitor the weight of the inner tanker and soil seepage, respectively. The inner tanker was filled with a block of natural turf and soil of the same size and shape as the drum. The inner tanker with soil totally weighed about 30.0 kg. The infiltrated seepage was automatically pumped out by a micro-pump. The data of tanker weight and soil seepage was stored by a CR800 datalogger (Campbell, USA) at a 30-minute interval.

Radiation (including incoming/outgoing long-wave, incoming/outgoing short-wave radiation) was measured with four radiometers (CNR4, Kipp & Zonen, Netherlands) at 1.5 m height. Air temperature and relative humidity were monitored by a temperature and humidity probe (HMP155A-L, Vaisala, Finland) at 1.5 m height. Wind speed, wind direction, and precipitation were sampled at a height of 2.2 m by a cup anemometer, a dogvane (05103, RM Young, USA), and a rain gauge (52203, RM Young, USA), respectively. Daily rainfall frequency (Rain-fre) and maximum rainfall amount (Rain-max) were simply estimated as accumulative counts and the maximal value of half-hour precipitation during the whole day, respectively. 5 cm soil temperature and volumetric soil water content were measured synthetically with coaxial impedance dielectric reflectometry (Hydra probe II, Stevens, USA). Half-hour means of meteorological data were recorded with the other CR800 data logger. The observation system of the micro-lysimeter and the auxiliary meteorological factors has been conducted since late May 2018.

2.3 Statistic analysis

The one-year round daily data from July 2018 to June 2019 were analyzed for quantifying the season pattern of the shallow soil seepage. During the periods from April to September when the soil seepage happened, we first defined the daily seepage amount above 0 mm and equaling 0 mm as “1” event (soil-seepage) and “0” event (non-soil-seepage), respectively. The sample volume was 198 and the probability of daily shallow soil seepage was thus analyzed by a binary Logistic model. The main environmental controls were included air temperature, solar radiation, rainfall, rainfall frequency, rainfall maximum, and volumetric soil water content. And forward method (Likelihood Ratio) was adopted for the Logistic regression variable selection. Secondly, we took the hysteresis effect into consideration and selected the daily soil seepage above 0 mm and created a 26-column matrix with daily soil seepage amount, soil water content, rainfall, rainfall frequency, rainfall maximum, and solar radiation from 4-day, 3-day, 2-day, 1-day, and 0-day before seepage events. Then the best subsets regression was performed to exploring the environmental controls on daily shallow soil seepage amount. The statistical analyses were conducted in SYSTAT 13.0 (Systat Software Inc., USA), and all figures were plotted in OriginPro 2016 (OriginLab Cor., USA).

3 Results

3.1 Seasonal pattern of environmental variables

The annual air temperature and precipitation were − 0.53^{o}C and 550.6 mm during the studying periods, respectively (Fig. 2). The warmest and coldest monthly air temperature was 9.1 ^{o}C in August and − 12.2 ^{o}C in January, respectively. The rainfall during the vegetation growing season from June to September was 420.0 mm. The annual solar radiation averaged 197.7 W m^{-2} and the maximum monthly value was 258.4 W m^{-2} in May (Fig. 2b). The monthly 5 cm volumetric soil water content was about 0.36 ± 0.03 cm^3 cm^{-3} (Mean ± S.D.) in the growing season. Although soil water content increased when high-intensity rainfall occurred (Fig. 2c), there was little positive correlation between monthly soil water content and monthly rainfall ($R^2 = 0.04, p = 0.30$). Daily half-hour rainfall frequency averaged 5.3 ± 1.0 in the growing season and the maximum half-hour rainfall was 10.4 mm on August 3, 2018. Daily rainfall amounts were jointly controlled by rainfall frequency and rainfall maximum with a similar standardized coefficient (0.53 Vs 0.49).

3.2 The probability of shallow soil seepage

The whole shallow soil seepage events happed from late April to late September (Fig. 1d). The forward selection binary Logistic regression analysis showed that rainfall frequency ($p < 0.001$) and soil water content ($P < 0.001$) were the significant controls on the probability of shallow soil seepage events (Table 1); however, the correct percentage of soil seepage events was 46.5%. Rainfall frequency played a much more important role in the odds of shallow soil seepage with an individual explanatory power of 37% (Table 1). The model with rainfall frequency variable alone suggested that the odds of the soil seepage were above 90% when the daily half-hour rainfall frequency was more than 16.

Table 1
The binary Logistic models of soil seepage events in the summer pasture of alpine meadow.

Model*	Variable	Coefficients	Sig.	Nagelkerke R^2	Percentage correct	
					No Seepage	Seepage
I	Rain-fre	0.22	0.00	0.37	94.2%	37.2%
II	Rain-fre	0.22	0.00	0.50	94.2%	46.5%
	SWC	24.24	0.00			

Note: the model could be described as Log(P/(1-P) = ax + b, where P is the probability of soil seepage, a is regression coefficient, b is the regression intercept, log(P/(1-P)) is the logarithm of the odds (P/(1-P)).

3.3 Seasonal variations of soil seepage and environmental controls

The accumulative shallow soil seepage was 106.8 mm. The maximum monthly soil seepage was 30.7 mm in September, following by 26.3 mm in June, 20.4 mm in August, and 20.0 mm in July. The minimal monthly soil seepage was 1.0 mm in April and 8.4 mm in May (Fig. 3). The soil seepage in the vegetation growing season accounted for 91% of the total amount. It should be noted that there was little difference ($p = 0.91$, N = 5) in monthly soil seepage between daytime (52.8 mm) and nighttime (54.0 mm), which might be induced by non-significant different precipitation ($p = 0.41$) between the two periods. Ignoring surface runoff, the mean monthly rain yield efficiency (seepage/rainfall) was 23.8%, where the peak was 41.1% in September and the others were 19.4 ± 3.0%. The annual precipitation yield efficiency was 19.4%.

The best subsets regression showed that the daily soil seepage amount was determined by daily rainfall, 3-day rainfall frequency, and 4-day solar radiation, which could explain 73% of variations of the daily soil seepage (Table 2). Daily rainfall amount, more than frequency was the most important environmental control on the daily soil seepage, with a slope of 0.33 ($R^2 = 0.58$, $p < 0.001$, Fig. 3a, b). The further general linear model revealed that the main effect of rainfall amount ($p < 0.001$), rather than rainfall frequency ($p = 0.58$), exerted significant influence on daily rainfall amount. On a monthly scale, monthly rainfall frequency alone accounted for 68% of variations in the monthly soil seepage ($p = 0.03$, N = 6, Fig. 3d). There was a significantly asymptotical relationship between monthly soil seepage and monthly rainfall amount (Fig. 3c). Therefore, shallow soil seepage was much determined by rainfall frequency and amount.

Table 2
The best subsets of linear regressions on soil seepage in the summer pasture of alpine meadow.

Model size	**Variable**	**Standard regression coefficients**	**Sig.**	R^2	**MSE**	**Mallow'CP**
One variable	Rain	0.77	< 0.001	0.59	3.06	52.52
Two variables	Rain	0.88	< 0.001	0.69	2.28	29.35
	Rain-fre-3	0.35	< 0.001			
Three variables	Rain	0.89	< 0.001	0.73	2.13	25.58
	Rain-fre-3	0.30	0.002			
	Dr-4	-0.17	0.05			

4 Discussion

4.1 The probability of soil seepage events

Soil seepage event is a function of rainfall density, terrain slope, and soil infiltrability (Wilcox et al. 2017). Rainfall frequency played a substantial role in the odds of daily shallow soil seepage events (Table 1), which agreed well with the similar field experiment results (Dai et al. 2019; Yang et al. 2016). It could be ascribed to the following two aspects. Firstly, the more soil porosity and the higher soil water content would favor soil seepage events. The 0–40 cm soil porosity percentage averaged 63.6%, with 70% more of the 0–20 cm soil layer (Wu et al. 2014). The mean actual topsoil water content was 0.36 $cm^3 \cdot cm^{-3}$

during the growth season (Fig. 2), which was close to the topsoil capillary water capacity (0.51 $cm^3 \cdot cm^{-3}$ (Wu et al. 2014)). Therefore, the relative light-intensity and high-frequency rainfall could be propitious to soil seepage in our piedmont pasture site. Meanwhile, the half-hour rainfall intensity concentrated 0.1 ~ 0.5 mm and their accumulative relative frequency was 54%. Secondly, evapotranspiration losses were energy-limited in our alpine humid site (Zhang et al. 2018). Although annual solar radiation was 198.1 $W \cdot m^{-2}$, the annual net radiation averaged 61.6 $W \cdot m^{-2}$, which was comparable with low-elevation sites (Zhang et al. 2010). Therefore, evapotranspiration loss should be relatively low and soil water could not be consumed too much to limit soil seepage (Fig. 2). It could be partially confirmed by a non-significant difference in soil seepage between the daytime and nighttime, given that evapotranspiration mainly occurred in the daytime (Zhang et al. 2018). In addition, if rainfall frequency were excluded in the Logistic model, rainfall amount became the most important variable in the odds of soil seepage (R^2 = 0.30, correct percentage in soil seepage event was 39.5%). Overall, together with higher soil water content and lower evapotranspiration loss, rainfall exerted a substantial influence on the probability of soil seepage in the piedmont summer pasture of alpine meadow.

4.2 The temporal patterns of soil seepage amount

Due to extremely lower hydraulic conductivity and impeded effect of frozen soil (Hinzman et al. 1991), the soil seepage occurred during the non-frozen period, which agreed well with other similar alpine experiments (Dai et al. 2019; Yang et al. 2016). The seasonal pattern of the first peak of 30.7 mm in September and the second peak of 26.3 mm in June (Fig. 2) coincided with the autumn flood (Wang et al. 2008) and spring river discharge (Cao et al. 2006) of the Plateau.

Rainfall amount and frequency exerted a significant influence on soil seepage at short-term scales (Fig. 3; Tables 1, 2). These findings revealed that consecutive light rainfall preferred to soil seepage amount. It was mainly attributed to the fact the strong rainfall would stimulate surface runoff more than soil seepage (Wang et al. 2009). Furthermore, coarse-textured and high-porosity soils with high hydraulic conductivity would favor rainfall infiltration in our sites (Hinzman et al. 1991; Zhang et al. 2019). Meanwhile, the more rainfall frequency indicated the more cloud days and the consequent less net radiations, which could save water from evapotranspiration loss (Zhang et al. 2018). Together, rainfall, including its amount and frequency, regulated the shallow soil seepage in the piedmont alpine meadow. However, it should be noted that our experiments excluded the effect of lateral soil water flow from meltwater (Jiang et al. 2021), which could reduce the source of water input and then might underestimate soil seepage. Future researches would be needed for quantifying those belowground hydrological, together with the grassland degradations and the resultant surface heterogeneity (Levia et al. 2020).

5 Conclusions

The whole shallow soil seepage occurred during the non-frozen period from April to September in a piedmont summer pasture of alpine meadow. Daily half-hour rainfall frequency and soil water content determined the probability of daily soil seepage. Daily soil seepage amount was closely related to daily rainfall amount. Monthly soil seepage peaked in September, following by June, July, August, and May, which were significantly regulated by monthly rainfall amounts. The annual soil seepage amount was equivalent to about 1/5 annual precipitation. Our results revealed that rainfall, including frequency and amount, played a predominant role in the seasonal variations of the shallow soil seepage.

Declarations

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Author contributions: F Zhang, H Li, and Y Yang carried out all analyses. F Zhang conceived the manuscript. All authors collaborated in the interpretation of the results and the writing of the paper.

Conflict of interest: The authors declare no conflict of interest.

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Figures

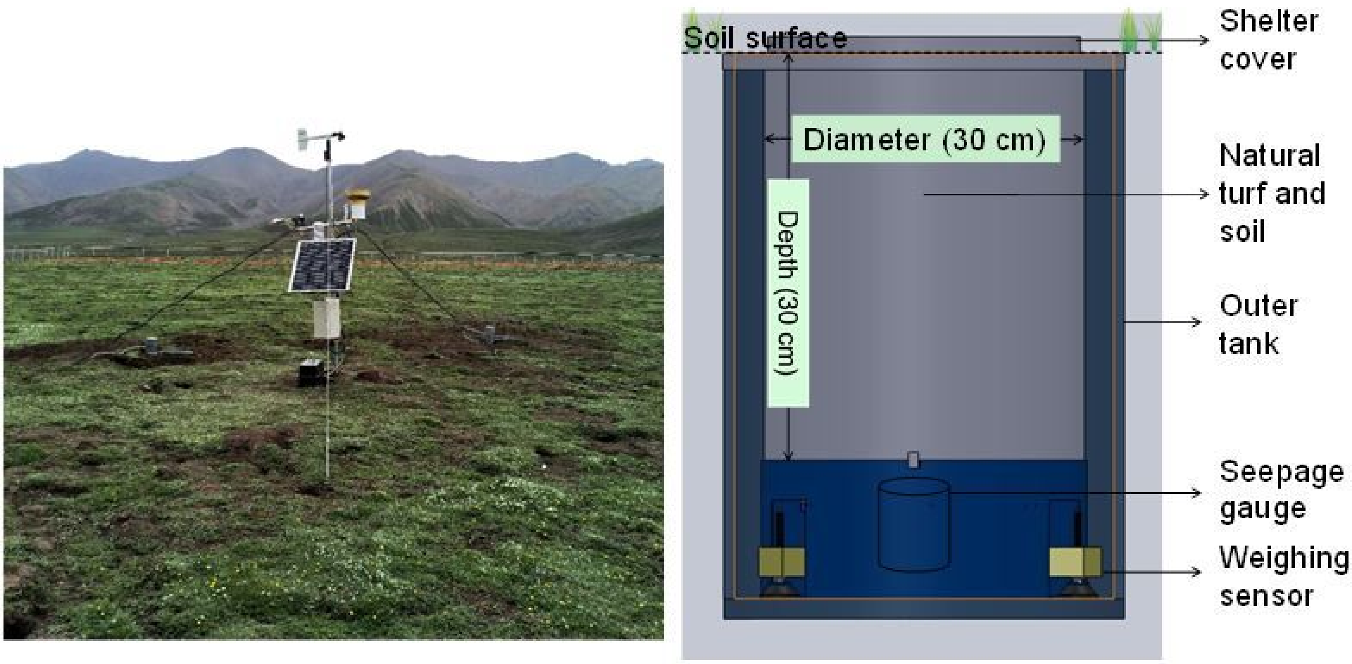

Figure 1

The picture of the experiment in a piedmont summer pasture (left) and the design sketch of a micro-lysimeter (right).

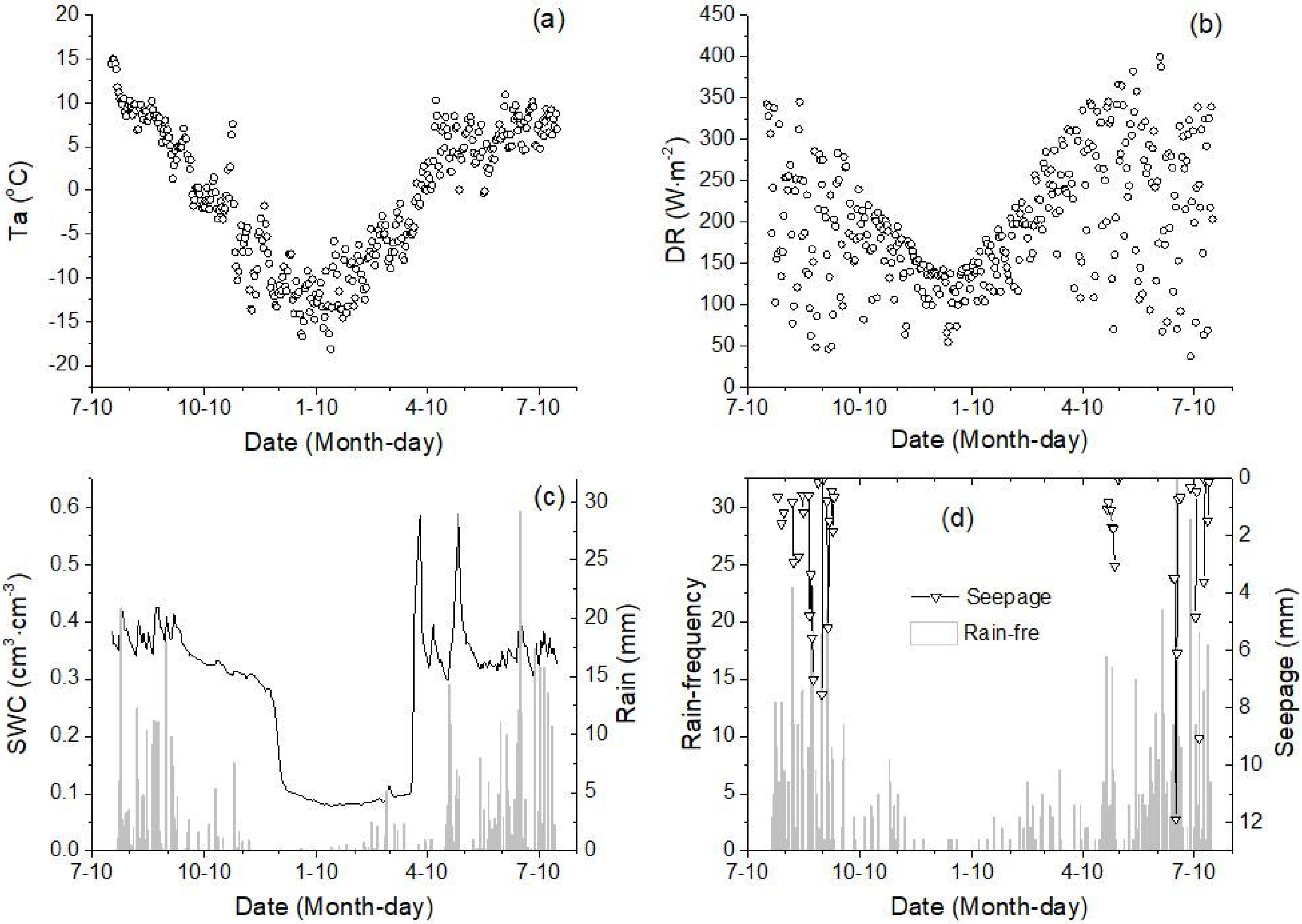

Figure 2

Seasonal variations of daily air temperature (Ta), solar direct radiation (DR), volumetric topsoil water content (SWC) and rainfall (Rain), rainfall-frequency (Rain-fre), and shallow soil seepage (Seepage) in the summer pasture of alpine meadow.

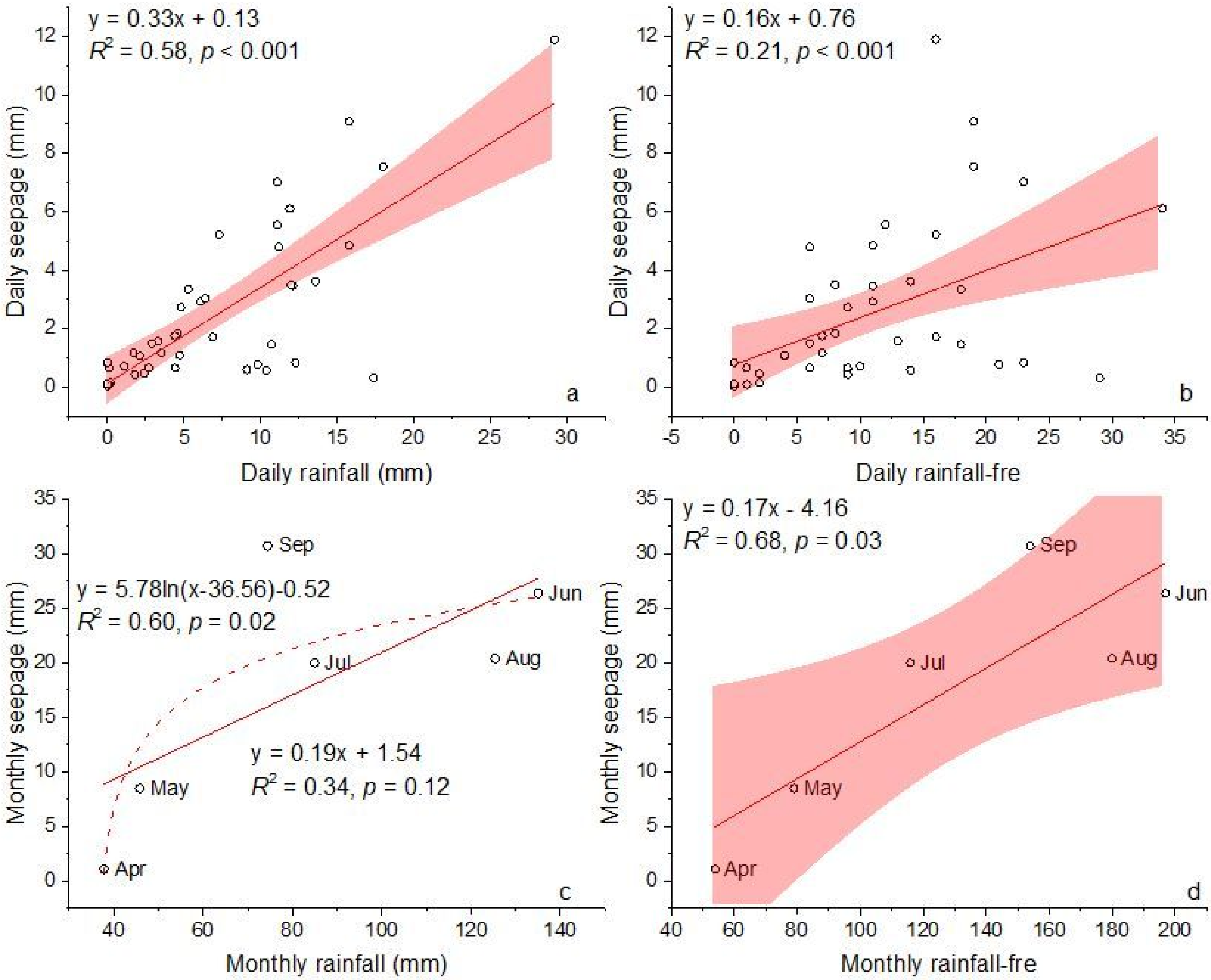

Figure 3

The relationship between soil seepage and rainfall amount (rainfall) and rainfall frequency (rainfall-fre) during seepage events at a daily and monthly scale. The shading areas are the 95% confidence of the regression line.