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Original Research

Environmental Factors Controls on Soil Water-Heat in the Qilian Mountains, China: A Quantitative Analysis

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Abstract

Soil water-heat plays a significant role in land surface processes and has an impact on almost all ecosystem processes and functions practically. However, the controls of soil water-heat by environmental factors remain to be elucidated. In this study, relationships of soil water-heat with environmental factors in the Qilian Mountains, China were quantified using data obtained from a regional soil survey during the summer of 2019. Our results showed that soil water content (SWC) depicted a trend of being high in the east and low in the west, and soil temperature (ST) showed an opposite trend. The PLSPM suggested that topography, climate, vegetation, and soil properties had a similar control on SWC, with total effect values of 0.41, -0.34, 0.33, and -0.47, respectively. Soil properties and vegetation directly influenced SWC, topography indirectly influenced SWC by altering climate, and climate directly influenced SWC and indirectly through vegetation. Conversely, the factor controlling ST was topography (total effects = 0.39), which influenced ST directly and positively. The VPA indicated that the combination of environmental variables explained 64.26% of the variation in SWC and 27.69% of the variation in ST.

Keywords: soil water-heat, quantitative analysis, PLS-PM, VPA, Qilian Mountains

Introduction

Global warming poses a challenge to the stability of global ecosystems [1], as manifested by changes in the operation of coupled surface-atmosphere systems [2]. As a key component of land surface processes, soil water-heat is the combined product of material and energy exchange between the land surface and the atmosphere [3]. Soil water content (SWC) and temperature (ST) as the two crucial physical variables that measured material transfer and energy flow and influenced almost all ecosystem processes and functions [4]. Therefore, we need to gain insight into the distribution of SWC, ST, and their interaction

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processes with the environmental factors, which will be important for assessing and responding to global warming.

Soil water-heat is the key variable in the hydrologic function of ecosystems ranging in scale from local to regional [5]. At the local scale, Soil water-heat is spatially highly variable and influences organic matter decomposition, nutrient availability [6], and plant growth and distribution patterns [7]. At the regional scale, Soil water-heat buffers interactions between the land surface and the atmosphere, by moderating the exchange and partitioning of water and energy fluxes [8]. The exploration of soil water-heat can contribute to a deeper understanding of many ecological processes. In the past, researchers have focused on stability [9], spatial and temporal characteristics [10], and relationship with environmental factors [11] of SWC. Currently, the development of remote sensing technology has led to more research on spatial and temporal variation [12], influencing factors [13], predictive mapping [14-15] and the interaction with environmental factors [16-17] of SWC. Some studies have already pointed out that SWC is influenced by environmental factors such as vegetation, climate, topography, and soil properties. For example, in the semi-arid zone, SWC is mainly influenced by rainfall and vegetation type [18]. Similarly, in the subtropical regions, SWC is influenced by a combination of topography, runoff, vegetation, and precipitation [19]. But there was more influence on SWC by soil properties in the permafrost area [20]. These studies did not describe the pathways of influence and the extent of contribution of each factor, which hinders further understanding of the ecological effects of SWC. Compared to SWC, relatively little attention has been paid to ST. However, ST has an important influence on vegetation phenology [21], microbial community composition and activity [22], soil respiration [23], and decomposition of the above and below ground biomass [24]. As same as SWC, the research of ST also focused on predictive mapping [25], spatial and temporal variability [26], and coupling with environmental factors [27]. In contrast, there was little research on the controlling factors, mechanisms of influence, and the extent to which they contribute to ST. In general, the content characteristics of SWC and ST determine the stability of regional ecosystems. Therefore, there is an urgent need for systematic analyses of the controlling factors, pathways, and the extent of the contribution of soil water-heat.

The Qilian Mountains have attracted the attention of researchers as an important ecological barrier area in China [28]. However, there was a paucity of research on SWC and ST. And in the available studies, researchers have found that the amount of precipitation did not lead to a change in the coefficient of variation in surface SWC [29]. However, SWC was increased with altitude and influenced by the type of vegetation [30]. In addition, soil texture had an important influence on the unfrozen SWC in permafrost [31]. Concerning ST, researchers found that ST varied less than SWC in grasslands and showed a linear positive correlation with altitude [32]. Yet, ST in spruce forests tended to decrease with increasing altitude [33]. In summary, we can conclude that characteristics of soil water-heat exhibited complex and variable trends, caused by a combination of factors in the Qilian Mountains. However, there were lilted known about how environmental factors shape the soil water-heat processes. Therefore, a quantitative analysis of the effects of environmental factors on soil water-heat is needed, which will be important for further sorting out the ecological barrier function of the Qilian Mountains.

Based on the above research questions, we collected and analyzed 46 soil samples covering the main vegetation cover types and different elevation gradients in the Qilian Mountains. By extracting data on environmental factors, we aim to explore the following four specific questions.

1) How does the distribution of SWC and ST vary in horizontal space and vertical depth in the Qilian Mountains?

2) Which environmental factors have a significant impact on the SWC and ST in the Qilian Mountains?

3) What are the main factors and pathways that mediate the soil water-heat in the Qilian Mountains?

4) How many variations in SWC and ST could be explained by these factors in the Qilian Mountains?

Materials and Methods

Study Area

The Qilian Mountains (Fig. 1, 35~40°N, 92~105°E), as an important ecological security barrier area in China [34], has a total area of about 18.2×10^4 km^2 and is located in a sensitive area at the boundary division line of the first and second terraces in China. It is the boundary line between the arid and semi-arid region of the northwest and the alpine region of the Qinghai-Tibet Plateau, as well as the intersection of the monsoon and westerly wind belts. The regional altitude range is 1743-5799 m. The study area has a temperate continental climate and typical continental characteristics, with annual precipitation of about 400-700 mm, mostly concentrated in May-August, and gradually decreasing from southeast to northwest. The average annual temperature is 5.25-10.75ºC. The natural conditions are complex, and the combination of natural factors leads to the development of a variety of vegetation types and soil types with vertical gradients and horizontal differences. The vegetation types contain meadows, grasslands, forests, scrub, deserts, and bare land. The main soil types are grey calcium soil, chestnut calcium soil, grey, brown soil, meadow soil, and cold desert soil.

Sample Collected and Examined

In June 2019, 138 samples from 46 sample plots, covering regions with meadow, shrub, forest, grassland, and bare land, were collected from the region of the Qilian Mountains (Fig. 1). All the sampling sites were in well-protected national nature reserves to minimize the effects of anthropogenic disturbance. These sites were located in areas of homogeneous vegetation, which were well represented for each vegetation type. Before collecting the soil samples, the top layer was removed from the herb litter, and then samples were collected in layers of 0-20 cm, 20-40 cm, and 40-60 cm from top to bottom. Three replicates were taken from each sample plot following the diagonal sampling method. A portable soil thermometer (Moisture meter, China) is used to determine the ST in each layer. The samples were collected using sterile sampling bags and cutting rings, respectively. Soil samples were taken back to the laboratory, air dried for 1-2 months until completely dry and then sieved through 0.5 mm and 2 mm sieves respectively. After the samples of BD were brought back to the laboratory, they were dried at 105ºC for 10 hours to a constant weight, and the fresh weight and the dry weight after drying were used to calculate the BD and SWC. For the determination of soil texture, 0.5 g of 0.5 mm sieve sample was placed in a beaker and 10 ml of 10% H_2O_2 was added and heated until the bubbles disappeared to remove the organic matter from the sample. 10 ml of 10% HCl was added to remove the carbonates from the sample and the sample was filled with distilled water and left to stand for 10 h. After the reaction was complete, the supernatant was removed and 10 ml of $(NaPO_3)_6$ dispersant were added. Finally, we used a laser diffractometer (FBS-6100B, China) to determine the soil particle size distribution. Each sample was repeated three times and the final mean value was taken.

Environmental Variables

To analyze the factors influencing the soil water-heat characteristics, we extracted four categories of environmental data, including climate, vegetation, topography, and soil properties, which correspond to June 2019. The climate data in June 2019 were obtained from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn/) and included mean monthly temperature (MMT), mean monthly precipitation (MMP), and potential evapotranspiration (PET) with a spatial resolution of 1 km. The normalized difference vegetation index (NDVI), net primary productivity (NPP), and leaf area index (LAI) for June 2019, which have a spatial resolution of 1 km, were used to represent vegetation characteristics. NDVI data were acquired from Resource and Environment Science and Data Center (https://www.resdc.cn/). NPP data were gained from National Centers for Environmental Information (NOAA, https://www.ngdc.noaa.gov/). LAI were obtained from National Tibetan Plateau Data Center (http://data.tpdc.ac.cn/). A digital elevation model (DEM) of 1 km spatial resolution was obtained from

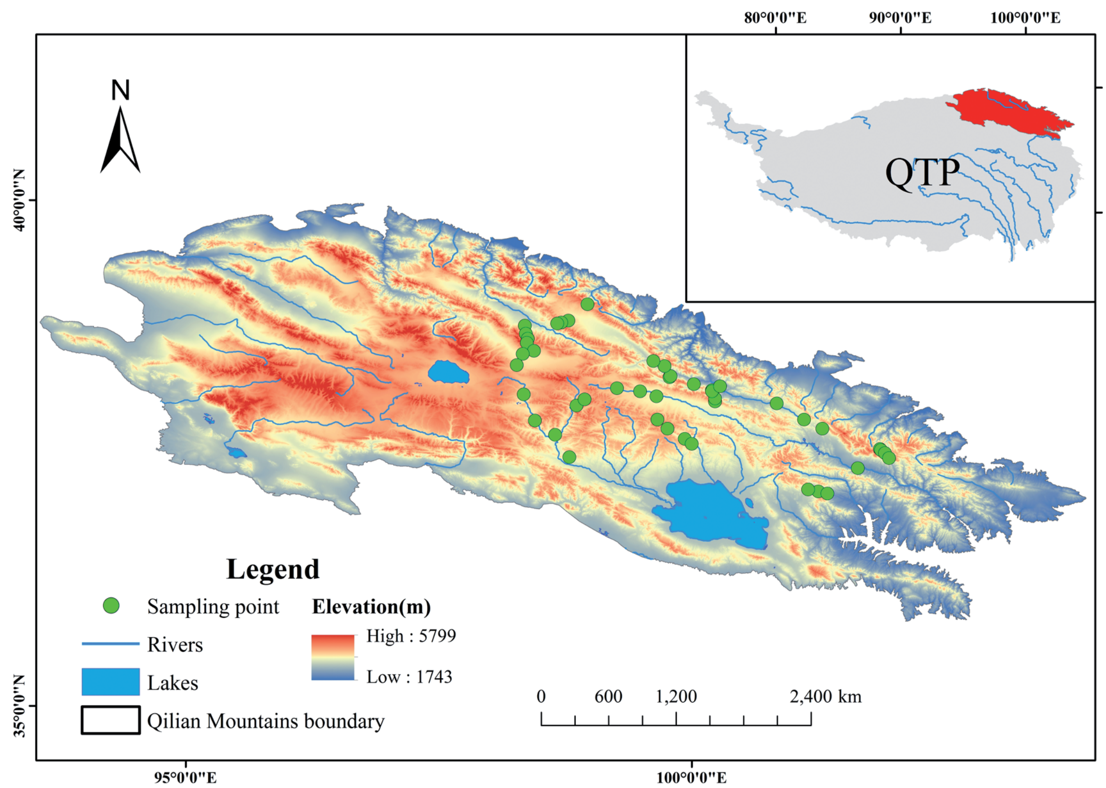

Fig. 1. The location of study area and study sites.

National Tibetan Plateau Data Center (http://data.tpdc.ac.cn), which were used to derive terrain attributes (including altitude, slope gradient (SG), slope aspect (SA), slope length (SL, Eq. 1), land surface roughness (SR, Eq. 2) and relief degree of land surface (RDLS, Eq. 3).

$$SL_i = \frac{DEM_i}{sin\left(\frac{slope_i \times \pi}{180}\right)} \quad (1)$$

$$SR_i = \frac{1}{cos\left(\frac{slope_i \times \pi}{180}\right)} \quad (2)$$

$$RDLS_i = DEM_{max} - DEM_{min} \quad (3)$$

Where SL_i (m) is the slope length at sample point *i*. DEM_i (m) is the altitude at sample point *i*. $Slope_i$ (°) is the slope at sample point *i*. SR_i is the land surface roughness at sample point *i*, which were calculated from the difference between the maximum and minimum values of the regional DEM.

Statistical Analysis

Environmental variables were extracted and calculated by using ArcGIS 10.8 software. The inverse distance weighting method (IDW) was used to interpolate point data of SWC and ST across the region to explore the spatially variable characteristics of SWC and ST in the Qilian Mountains. A one-way ANOVA was conducted using SPSS 22.0 to explore the effects of different vegetation zones and soil depth on soil water-heat characteristics. The correlation between environmental factors and soil water-heat characteristics was investigated using Pearson correlation analysis based on topographic, vegetation, and climatic data extracted from the web dataset, combined with soil properties measured in the laboratory. Based on the main influencing factors, a partial least squares path model (PLS-PM) was used to identify the direct and indirect associations with the soil water-heat. Finally, variation partitioning analysis (VPA) was used to quantify the contribution of each group of factors. PLS-PM and VPA were conducted using R statistical software v.4.0.2.

Results

Spatial Distribution Characteristics of the Soil Water-Heat

Fig. 2 showed the spatial distribution map constructed using the IDW for the SWC of each vertical soil layer. ST ranged from 4.63 to 12.89°C, with a trend of being high in the west and low in the east at 0-60 cm

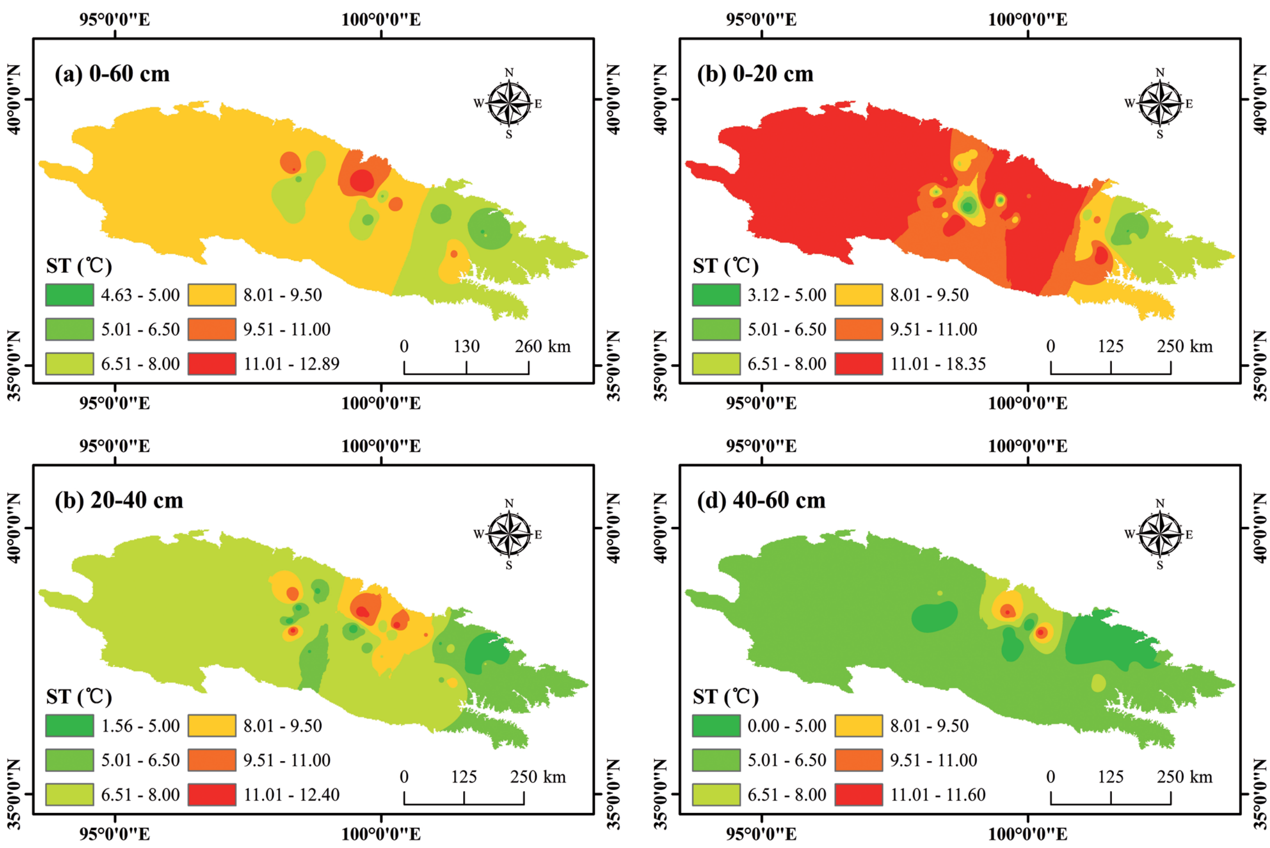

Fig. 2. Spatial distribution characteristics of ST at 0-60 cm a), 0-20 cm b), 20-40 cm c), and 40-60 cm d) in the Qilian Mountains.

(Fig. 2a). ST showed a similar variation characteristic in the different layers and decreased with the soil depth increased. As shown in Fig. 2b), the highest ST (more than 11.01ºC) is found in the west and center of the region while the eastern areas show the least ST value (less than 5.00ºC) in the region at a soil depth of 0-20 cm. At 20-40 cm (Fig. 2c), the value of ST dropped below 8ºC in most areas, only some areas were higher in the central part, and all of them were from 8ºC to 12ºC, which was a greater decrease compared to the surface layer. As the soil depth deepens to 40-60 cm (Fig. 2d), ST fell below 6.5ºC over most areas, with the high-value areas being small and mainly located in the northern foothills of the central part. We found the above results to be contrary to the distribution of vegetation in the field survey and therefore speculate that vegetation cover affects soil water-heat.

Fig. 3 shows the spatial distribution map constructed using the IDW for the SWC of each vertical soil layer. Compared to ST, SWC showed an opposite spatial trend (Fig. 3, high in the west and low in the east). The range of SWC at 0-60cm was from 11.65% to 85.83% and the majority of the area was from 20.1% to 50.00% (Fig. 3a). Same as 0-60 cm, the range of SWC at 0-20 cm depth (Fig. 3b) generally exceeded 30% and in some areas was higher than 50%. And the areas of high value were mainly located on the eastern edge and in parts of the central southern foothills. As the soil depth increased to 20-40 cm (Fig. 3c), the area of the high-value zone was expanded, and the location of the high and low-value zones was the same as the 0-20 cm depth. When the soil depth increased to 40-60 cm (Fig. 3d), the area of low values of SWC increased significantly, with the majority of the Qilian Mountains having an SWC of less than 30% and some areas less than 20%. And the areas of high value were only located in the west of Qinghai Lake and the range was from 50.01% to 82.47%. This deepened our speculation that the cover of vegetation has a significant impact on soil water-heat.

Vertical Distribution Characteristics of the Soil Water-Heat

In spatial distribution, we found that ST (Fig. 2) and SWC (Fig. 3) decreased with increasing soil depth and had a consistent or opposite relationship with the cover of vegetation. Therefore, we further classified the samples into meadow, shrub, forest, grassland, and bare land, to investigate whether there are differences in soil water-heat characteristics within different vegetation zones. We found that there were no significant differences in SWC (Fig. 4a) and ST (Fig. 4b) between the different vegetation zones (P<0.05). This was unexpected, so we further analyzed the different depths separately.

And further studies found that the SWC (Fig. 5a) of meadow soils was significantly higher at 0-20 cm depth than at 20-40 cm (P<0.05) and 40-60 cm

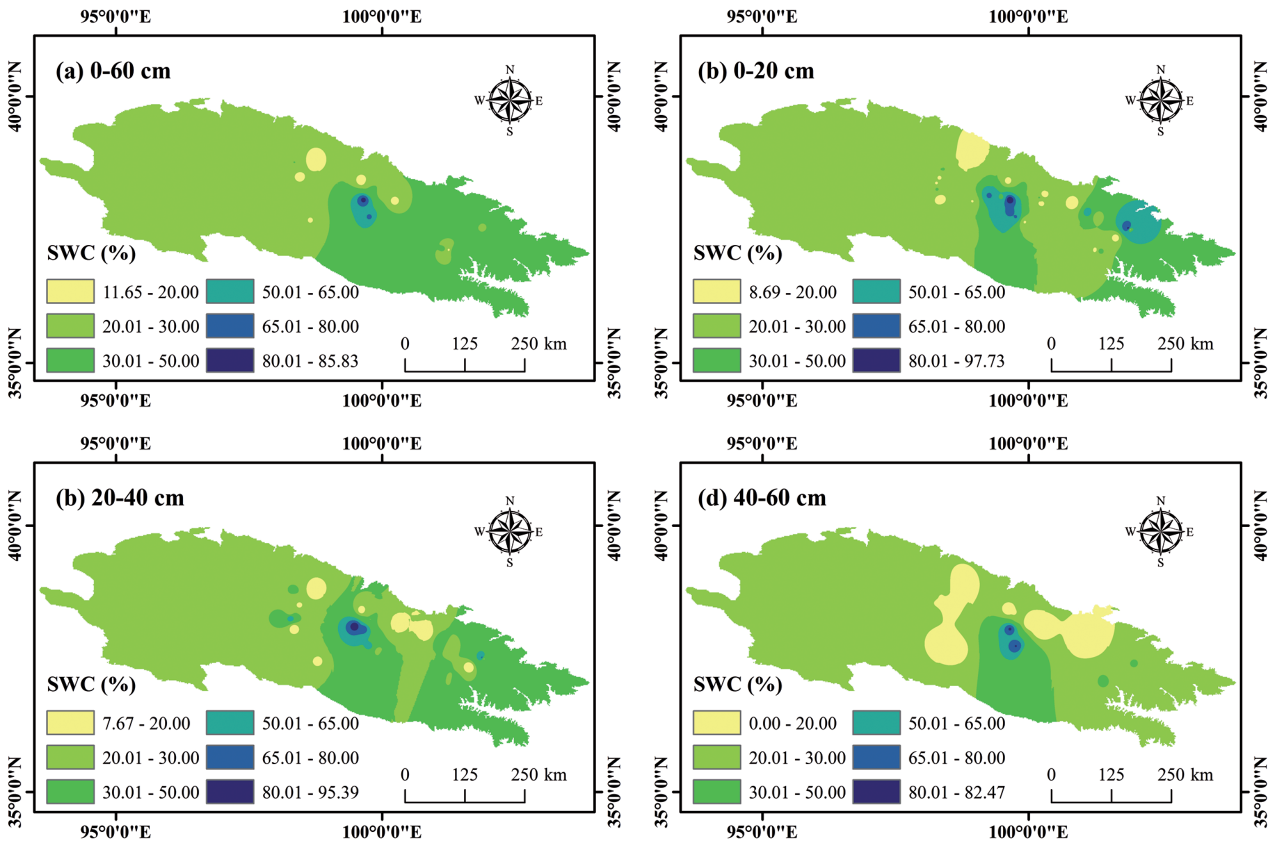

Fig. 3. Spatial distribution characteristics of SWC at 0-60 cm a), 0-20 cm b), 20-40 cm c), and 40-60 cm d) in the Qilian Mountains.

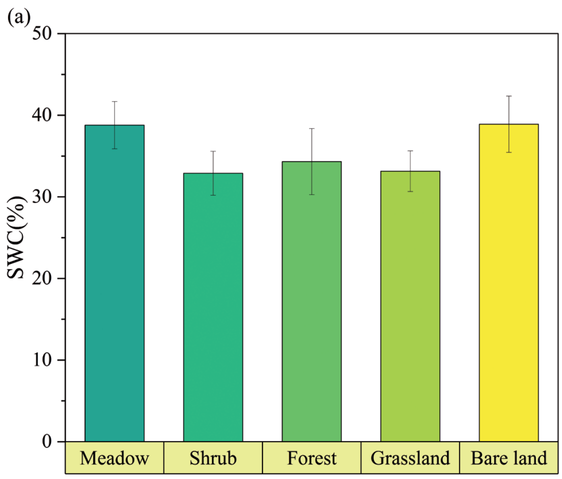

Fig. 4. SWC a) and ST b) in different vegetation zones in the Qilian Mountains.

(P<0.01). SWC of shrub soils was significantly higher at 0-20cm depth than at 20-40cm (P<0.05), while there was no significant trend in SWC with soil depth in other vegetated areas. Similarly, ST (Fig.5b) of the meadow was significantly higher at 0-20 cm than at 20-40 cm (P<0.01) and 40-60 cm (P<0.05), and forest soils also showed a consistent trend. ST of shrub was significantly higher at 0-20 cm depth than at 20-40 cm (P<0.05), and that of grassland was significantly higher at 0-20cm depth than at 40-60cm (P<0.01). In a study of the same soil depth between different vegetation zones, we found that the SWC of meadows was significantly higher than that of forests (P<0.05) and grasslands (P<0.01) only at 0-20 cm depth. Apart from this, there was no statistically significant relationship between the SWC of the vegetation zones at the other depths. Similarly, there was no statistically significant relationship between different vegetation zones at the same depth for ST.

Factors Related with Soil Water-Heat Distribution Characteristics

From the above results, it can be seen that SWC and ST showed a certain trend of variation in different vegetation types and soil depths. But this relationship was complex and difficult to explain in terms of a single factor, vegetation. Therefore, we used correlation analysis to further analyzed the relationship between soil water-heat and environmental factors. The results (Fig. 6) showed that altitude was significantly positively correlated with SWC (P<0.01). MMP was positively correlated with SWC (P<0.05). SA, BD, NDVI, MMT, and PET were significantly negatively correlated with SWC (P<0.01). NPP and LAI were negatively correlated with SWC (P<0.01). Conversely, the altitude was negatively correlated with ST (P<0.05), NDVI, MMT, and PET were significantly positively correlated with ST (P<0.01). We have concluded that

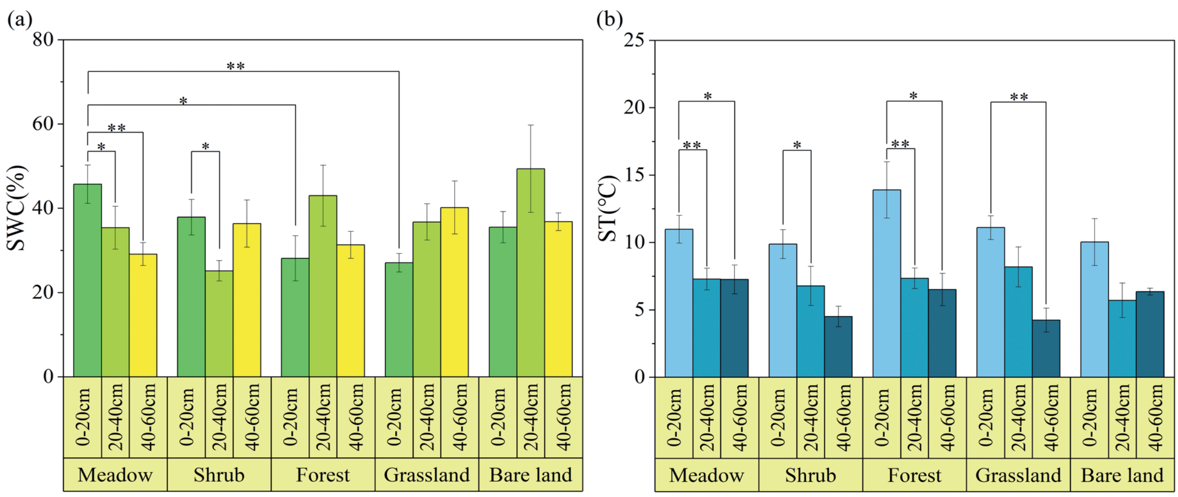

Fig. 5. SWC a) and ST b) in different soil depths and vegetation zones in the Qilian Mountains. The asterisk * denotes significance at P<0.05; ** denotes significance at P<0.01; *** denotes significance at P<0.001.

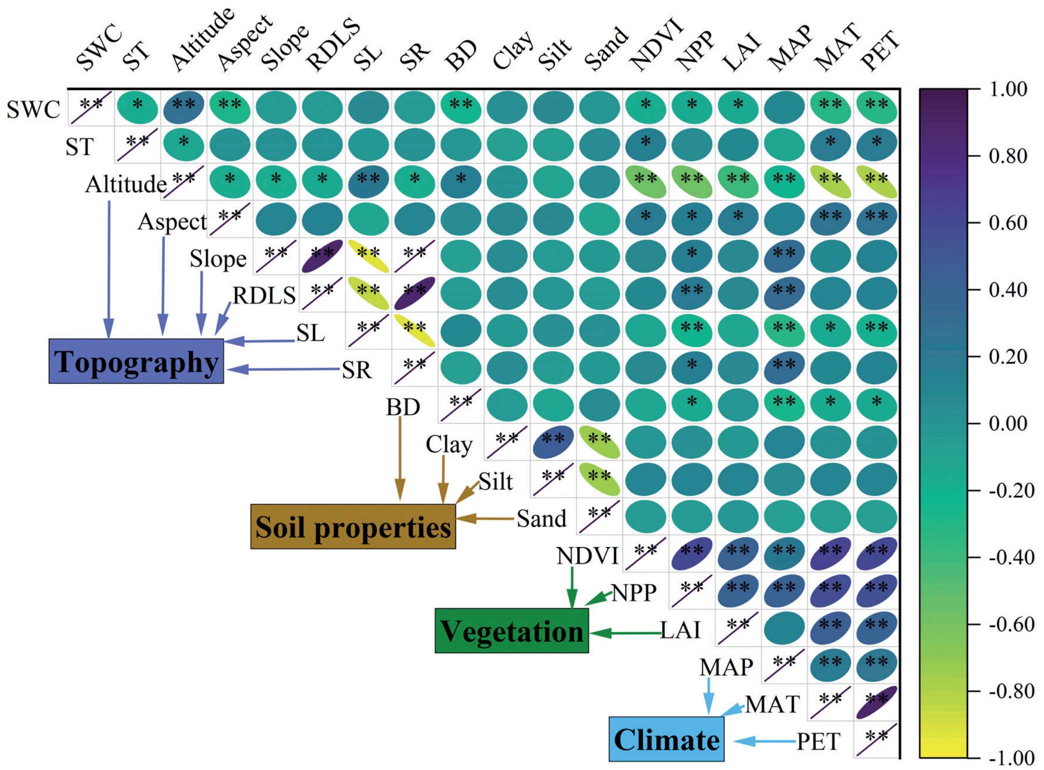

Fig. 6. Correlation between SWC and ST with environmental factors.

topography, soil properties, vegetation, and climate all influenced the SWC, and the environmental factors influenced ST were topography, vegetation, and climate. However, it was not clear exactly how these factors affect the soil water-heat. Consequently, the regulatory role of environmental factors needs to be further explored.

Direct and Indirect Drivers of Change in Soil Water-Heat Characteristics

We analyzed the relationship between soil water-heat characteristics and potential predictors by establishing the PLS-PM model. Before obtaining the final PLS-PM model, we continuously added and removed latent variables and indicators from the meta-model to make

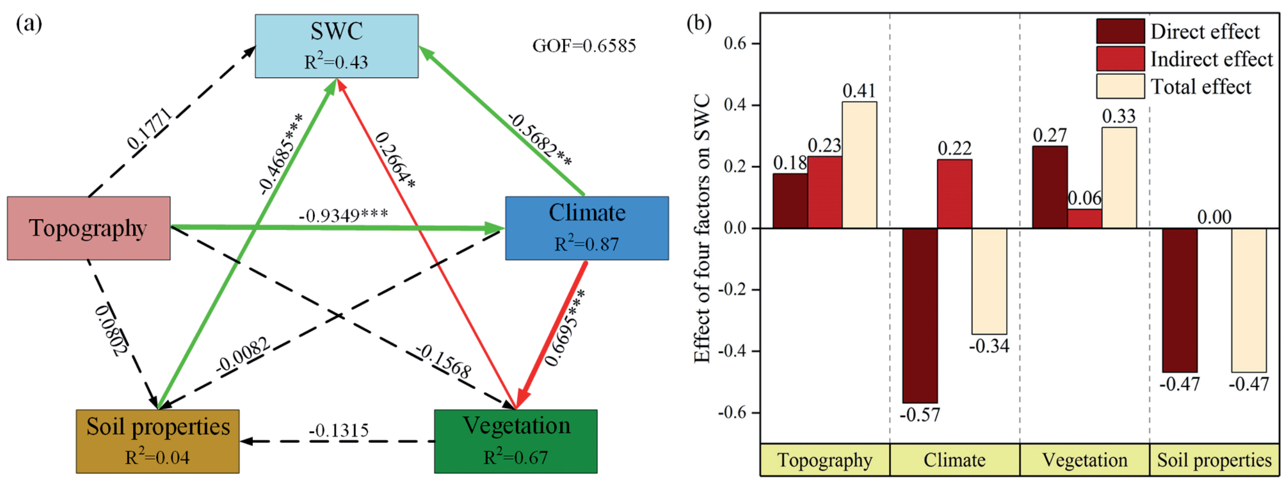

Fig. 7. Results of PLS-PM for SWC a). Effects of the climate, soil properties, topography, and vegetation on the SWC b). Single-headed arrows indicate the hypothesized direction of causation. Indicated values are the path coefficients. Green arrows indicate a negative effect, whereas red arrows indicate a positive effect. Black arrows indicate path is not significant. The arrow width is proportional to the strength of the relationship. Models with different structures were assessed using the Goodness of Fit statistic, a measure of the overall prediction performance.

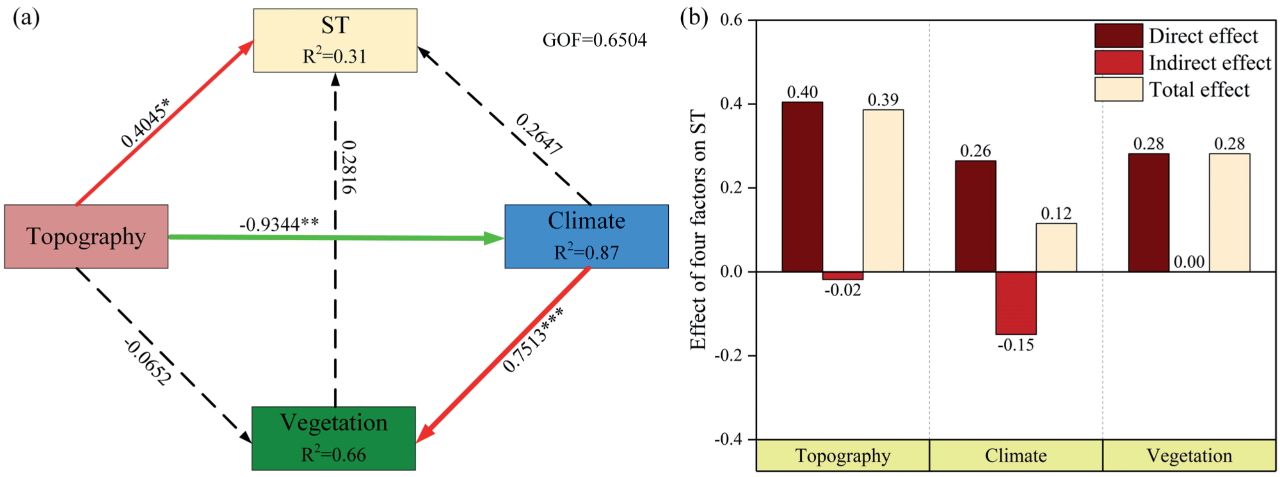

Fig. 8. Results of PLS-PM for ST a). Effects of the climate, topography, and vegetation on the ST b).

the best fit. Finally, the latent variables in the PLS-PM model of SWC (Fig. 7a) include altitude, MMT, PET, NDVI, NPP, LAI, and BD. The latent variables in the PLS-PM model of ST include altitude, MMT, PET, NDVI, SOC, and TN (Fig. 8a).

We found that climate, soil properties, topography, and vegetation had a close effect on SWC by PLS-PM (Fig. 7a), but the pathways mediating the SWC were different. As shown by PLS-PM in Fig. 7a), soil properties (*P*<0.001) and vegetation (*P*<0.05) directly influenced SWC. Similarly, topography indirectly influenced SWC by altering the climate (*P*<0.001). In addition to directly (*P*<0.01) influencing SWC, climate also affected SWC by changing the vegetation (*P*<0.001). As shown in Fig. 7b), the direct, indirect, and total effect of climate, soil properties, topography, and vegetation can be obtained. The paths from topography, climate, vegetation, and soil properties to SWC had direct effect of 0.18, -0.57, 0.27, and -0.47, respectively. The indirect effect of paths from topography, climate, vegetation, and soil properties to SWC were small and the value was 0.23, -0.22, 0.06, and 0.00, respectively. The total effect suggested that topography and vegetation had a positive effect on SWC, with a path coefficient of 0.41 and 0.33, respectively. Conversely, the paths from climate and soil properties to SWC had a total effect of -0.34 and -0.47.

As shown by PLS-PM in Fig. 8a), we found that the level of significance and the pathways of each factor to mediate the ST were different. Topography directly influenced ST (*P*<0.05), and the pathways of vegetation and climate to mediate the ST were no significantly

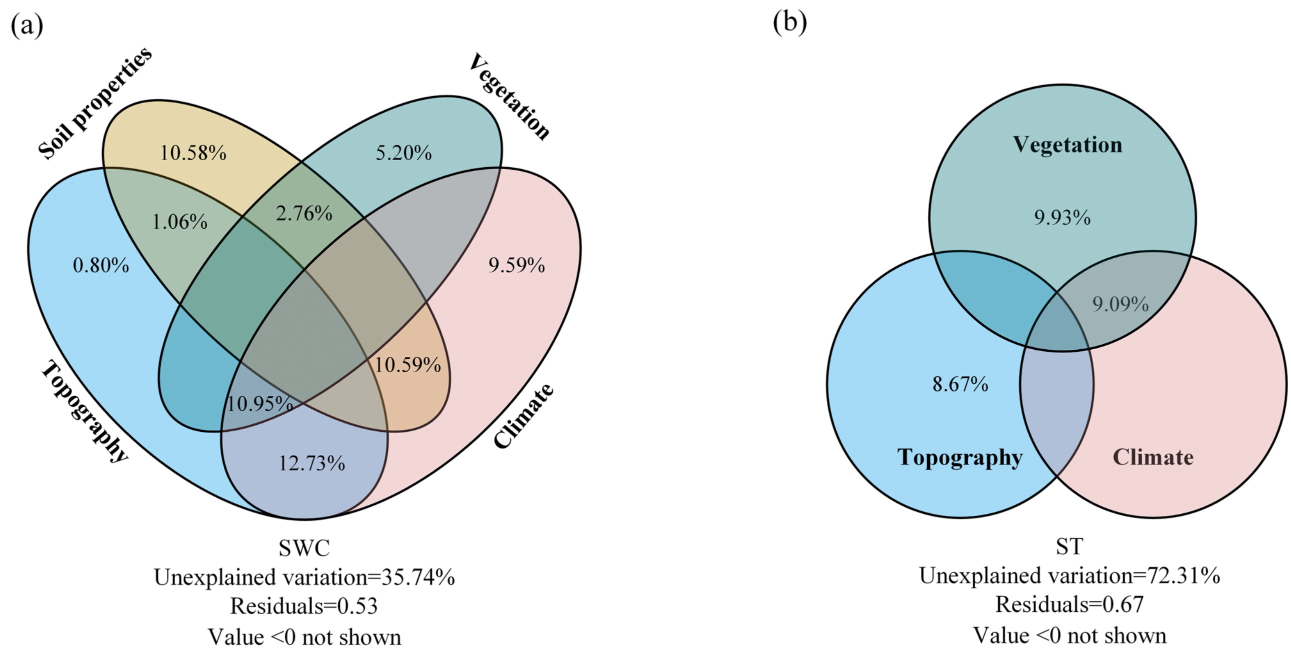

Fig. 9. Relative contributions of topography, climate, vegetation, and soil properties to the SWC a) and ST b).

(P>0.05). This result was unexpected and we speculate that the interactions between environmental factors may have reduced the degree of influence of the mediated pathway. In contrast to SWC, the effect of the three categories of factors on ST was mostly positive (Fig. 8b). The direct effects of topography, climate, and vegetation on ST were positive and followed by 0.40, 0.26, and 0.28, respectively. And the total effects of topography, climate, and vegetation on ST respectively were 0.39, 0.12, and 0.28. The total effect of climate on ST was low due to the negative effect offsets the positive effect. Ultimately, we could gather that the main factor influencing ST was the topography.

The results of VPA revealed that the combination of topography, climate, vegetation, and soil properties variables explained 64.26 % of the variation in SWC (Fig. 9a) and 27.69 % of the variation in ST (Fig. 9b). The decomposition of the variation further demonstrated that the four sets of explanatory variables explained a similar degree of variation in SWC. In addition, the largest pure fraction was explained by soil properties (10.58%), and the largest fractions of the variability in SWC were accounted for by all four groups of explanatory variables (12.73%). Conversely, the largest fraction of the variability in ST was explained by vegetation (9.93%), and the second fraction of the variability in ST accounted for the joint effect of climate and vegetation (9.09%). Similarly, the last part is explained separately by the topography (8.67%).

Discussions

Distribution Characteristics of Soil Water-Heat

We found a decreasing trend in SWC from east to west and the opposite for ST, with both decreasing as soil depth increased (Fig. 2 and Fig. 3). Many previous studies pointed out that SWC and ST have considerable memory compared with the atmosphere [14, 25]. We speculated whether this trend differed between vegetation types. Therefore, we explored the characteristics of soil water-heat in different vegetation types and soil depths (Fig. 4 and Fig. 5). The results indicated that there was little difference in SWC and ST between vegetation zones. This was since the fact that a large amount of SWC is used by vegetation and lost by transpiration in the arid zones, but in wet areas, vegetation could store more water through precipitation to cope with the intense transpiration [35]. Consistent with SWC, there was no significant trend in ST across vegetation zones, suggesting that the combined effects of environmental factors may have reduced or changed the variability in ST between vegetation zones [26, 31, 36]. Therefore, we speculated that the distribution of soil water-heat was largely influenced by the regional environment. Furthermore, we explored the characteristics of SWC and ST at different depths in each vegetation zone. We found that SWC showed a variable trend at different soil depths. This was probably due to differences in the depth of SWC utilized by different vegetation, as well as the combined effects of soil texture and groundwater, which ultimately led to different trends in the vertical distribution of SWC in different vegetation zones [14, 37]. This further validated our speculation. Conversely, ST showed a regular downward trend, which was consistent with previous studies [38-39]. This was caused by the fact that the time it takes for the soil to gain heat from the surface increased and the heat was gradually lost in the transfer process, as the depth of the soil increased.

Control Factors for SWC

Given that SWC is a complex and widely distributed process in the terrestrial ecosystem [40], the content and distribution of SWC were influenced by multiple environmental factors [14, 37]. Likewise, we found that topography, climate, vegetation, and soil properties were all correlated with SWC (Fig. 6), and further revealed that climate, soil properties, and vegetation directly influenced SWC, whereas topography and climate (there were two significant relationships) indirectly influenced SWC (Fig. 7). This finding probably underlies the widely-held rationale that the varying degrees of action of the various environmental elements leading to a complex and variable distribution of SWC [37]. Specifically, the contribution of soil properties to SWC was negative (P<0.001, total effect = -0.47). This indicated that SWC is reduced by the BD increase, consistent with the findings of previous studies [41-42]. BD affected the relative proportions of the three phases (solids, liquids, and gases) in the soil, which in turn affected the size of the soil porosity and the total porosity, and changed the hydraulic properties of the soil [42]. In contrast, the contribution of vegetation to SWC was positive (P<0.05, total effect = 0.33). Interestingly, the correlation analysis showed that SWC was negatively correlated with NDVI, LAI, and NPP, but the indirect, direct and total effect of vegetation on SWC was positive in the PLS-PM. Interestingly, the correlation analysis showed that SWC was negatively correlated with NDVI, LAI, and NPP, but the indirect, direct and total effect of vegetation on SWC was positive in the PLS-PM. This represented the existence of two opposing relationships between the effects of vegetation on SWC. On the one hand, large amounts of shallow SWC were consumed through vegetation self-growth [43] and transpiration [44]. On the other hand, vegetation and litter contributed to SWC by providing shade and retaining rain-fall to decrease evaporation [37]. Unlike the previous two factors, the climate had two significant pathways that mediate SWC. Firstly, the effect of climate on SWC was negative and directly (P<0.01, direct effect = -0.57), consistent with the findings of previous research [45]. In a coupled air temperature-soil moisture system, MMT influenced SWC by affecting the intensity of transpiration, and the analysis between PET and SWC also demonstrated the consistency of this effects (Fig. 6). Secondly, climate affected SWC by changing the vegetation, and this pathway is positive and active. The positive contribution of MMT could be due to the interception of the promotion of vegetation growth and enrichment of plant litter to reduce evaporation. Finally, we found that topography has an indirect and positive effect on SWC. This was consistent with the findings of [46] and was explained by the decrease in temperature with increasing altitude. Furthermore, our results also suggested that the above processes are more often achieved through the interaction between multiple factors, with the contribution of a single factor being of secondary importance (Fig. 9a).

Control Factors for ST

The distribution of ST is more regular than SWC, and the interaction of multiple factors is relatively less [26, 31]. This study also showed a similar pattern in that topography was the main factor controlling ST (Fig. 8). In general, as altitude increased, soil temperature decreased as air temperature did [47]. However, the direct effect of altitude was positive in this study (Fig. 8), which was contrary to the results of the correlation analysis (Fig. 6). We speculated that this may be because there are mostly permafrost areas and snow cover at higher altitude; where heat loss was lower [48]. Meanwhile, temperatures were colder at higher altitudes, and ambient temperature was the main factor influencing ST [49]. This also demonstrated that correlations do not necessarily reflect the role of environmental factors in controlling soil water-heat. We found that climate was a lesser influence on ST (Fig. 8). This further suggested that the effects of ambient temperature and atmospheric radiation on ST may be limited [49]. We also found that vegetation had a positive effect on regional ST (total effect = 0.28), although this pathway was not significant. This is because good vegetation improved soil texture [50], which in turn accelerates the rate and amount of heat transfer from the atmosphere to the soil [51]. But the presence of seasonal and perennial permafrost may have weakened this effect, as reflected in our observations (Fig. 6). We have assumed that this may be due to the thickness and depth of the permafrost layer changing the original transmission pattern of ST. Finally, we further analyzed the extent to which environmental factors contributed to variation of ST by using VPA (Fig. 9b). However, the above indicators explained only 27.69% of the variation in ST, and we speculated that the influence of these factors was weakened by the frozen ground and snow, as shown in the study by . At the same time, this may indicated a general pattern that environmental factors have a limited effect on ST.

Conclusions

Based on data from 46 samples collected in the field, combined with environmental datasets, we analyzed the distribution patterns, control factors, and mediating pathways of soil water-heat in the Qilian Mountains using the inverse distance weighting method, correlation analysis, partial least squares path model, and variation partitioning analysis.

SWC showed a trend of being high in the east and low in the west, ranging from 11.65-85.83%, 8.69-97.73%, 7.67-95.39%, and 0.00-82.47% at the 0-60 cm, 0-20 cm, 20-40 cm, and 40-60 cm in the Qilian Mountains, respectively. ST showed opposite spatial trends, with the ranges of 4.63-12.89ºC, 3.12-18.35ºC, 1.56-12.40ºC, and 0.00-11.60ºC at 0-60 cm, 0-20 cm, 20-40 cm, and 40-60 cm, respectively. SWC and ST did not differ significantly between the different vegetation zones, but ST tended to decrease significantly at different soil depths in the same vegetation zones.

Topography, climate, vegetation, and soil properties had a similar control on SWC, with total effect values of 0.41, -0.34, 0.33, and -0.47, respectively. Of these, soil properties ($P<0.001$) and vegetation ($P<0.05$) affected SWC directly, topography affected SWC indirectly by altering climate ($P<0.001$), and climate affected SWC directly ($P<0.01$) and indirectly through vegetation ($P<0.001$). Conversely, we found that the main environmental factor control on ST was topography (total effects = 0.39), which had a direct and positive impact on ST.

The results of VPA revealed that the combination of topography, climate, vegetation, and soil properties variables explained 64.26 % of the variation in SWC and 27.69 % of the variation in ST. The results showed that environmental factors had a strong influence on the SWC of the Qilian Mountains soils, but a smaller influence on ST.

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Conflict of Interest

The authors declare no conflict of interest.

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