Catena 116 (2014) 157–162

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Influence of bare rocks on surrounding soil moisture in the karst rocky desertification regions under drought conditions

S. Li *, H.D. Ren, L. Xue, J. Chang, X.H. Yao

Research Institute of Subtropical Forestry, Chinese Academy of Forestry, Fuyang, Zhejiang 311400, China

ARTICLE INFO

Article history:
Received 6 September 2012
Received in revised form 11 December 2013
Accepted 24 December 2013

Keywords:
Karst rocky desertification (KRD)
Bare rocks
Soil moisture
Shade
Drought

ABSTRACT

A large number of bare rocks exposed in the field represent one of the most spectacular scenes of the Karst Rocky Desertification (KRD) process. The presence of bare rocks modifies the microenvironment. An understanding of soil moisture variability is necessary to characterize the linkages between a region's hydrology, ecology, and physiography. The objective of the study was to determine the influence of those exposed bare rocks on soil moisture in the surrounding area in a typical KRD region—the Forest Station of Sandoqing, in Fu'yuan County, Yun'nan Province, Southwest China. Dynamic soil moisture was quantified in Feb, 2010 during an extreme drought period. Results showed that during the drought period, soil moisture on the north side of the rocks was significantly higher than those on the east, west and south sides ($p < 0.01$). Soil surface moisture increased with the aboveground height of the rocks. The size of the bare rocks was significantly correlated with soil moisture on the west and north sides of the rocks ($p < 0.01$) and the east side of the rocks ($p < 0.05$). Sharper rocks were associated with declining soil moisture on the east, west and north sides of the rocks. Soil moisture began to increase and then declined on the north, east and west sides, but showed a continued increase on the south side with the distance from the rocks. The soil moisture around the rocks increased gradually with depths of soil layers. During the drought period bare rocks created some shade, resulting in higher soil moisture on the north side of the rocks compared to the other three directions. The location at 15 cm north of the rocks had the highest soil water content, thus becoming the most ideal site for establishing vegetation restoration in the KRD area under stressful environmental conditions. Results from this study can be used to assist in restoration of ecological system damaged by the KRD process.

1. Introduction

Spatial heterogeneity is one of the important properties of soil (Burgess and Webster, 1980), and it occurs on various scales in all types of soil environments (Cain et al., 1999; Farley and Fitter, 1999; Gross et al., 1995; Jackson and Caldwell, 1993; Schlesinger et al., 1996). The moisture of surface soil layer has a significant role in this microenvironment and is a key parameter in soil surface modeling. Soil moisture is also an essential condition for normal plant growth, affecting both quality and survival; therefore, the variability and pattern of soil surface moisture are receiving increased attention from local to continental scales (Koster et al., 2004; Parent et al., 2006; Qi et al., 2004; Qiu et al., 2001). So far, little attention has been paid to surface soil moisture variability, specifically in fragile ecosystems or in the context of vegetation restoration efforts in the karst region of subtropical China (Chen et al., 2010; Zhang et al., 2011).

Karst rocky desertification (KRD) is one major type of desertification caused by human impacts on the vulnerable eco-geo-environment (Huang et al., 2009; Li et al., 2009b; Sweeting, 1993; Wang et al., 2004). KRD is a process in which soil is eroded seriously or even thoroughly, so that bedrock is exposed widespread, carrying capacity of land declines seriously, and at last, landscape appears similar to desert under violent human impacts on the vulnerable eco-geo-environment (Huang and Cai, 2007). The main features are: serious soil erosion; extensive exposure of bedrocks; drastic decrease of soil productivity; and the appearance of a desert-like landscape, caused by human activities degrading the fragile subtropical karst environment. It can have far-reaching effects on the middle-lower reaches of rivers like the Yangtze and Pearl (Wang et al., 2004). In the karst region of southwest China, development and cultivation on steep slopes, and intensive land use in this extremely fragile geological environment often result in serious soil loss by water erosion, which finally lead to a drastic decrease in soil productivity, progressive poverty of the local residents, and extensive exposure of basement rocks in the form of rocky desertification (Wang et al., 2004). The sloping farmlands occur in small patches, distributed irregularly among exposed rocks and in fissures. Compared with other regions, the mosaic of rock and soil increases the complexity of topography and diversity of microhabitats in the karst region of southwest China. This kind of mosaic may play an important role in the spatial

---

* Corresponding author. Tel.: +86 571 63326156.
E-mail address: lnlyls@163.com (S. Li).

0341-8162/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.catena.2013.12.013

distribution of nutrients due to differences of soil and water loss at different sites (Crowther, 1982; Descroix et al., 2001). Southwest China is in the fragile karst ecological zone (Sweeting, 1993), with 129,600 km^2 of land undergoing the process of KRD. Exposure of large amounts of rocks above ground level is the most spectacular scene in KRD regions. Karst lands can be very dry where the shallow soil layers and bare rocks are interwoven (Chen et al., 2012; Zhang et al., 2011), forming a highly heterogeneous ecological system with dramatic variation in soil ecological functions (Wang et al., 2004). In general the microenvironment in the KRD regions is changing toward more drought and heat conditions (Li et al., 2009a), which have led to low plant survival rates and reduction in the efficiency of current vegetation restoration practices.

Karst ecosystems with vegetation covers on thin soils overlying limestone are sensitive to global change. They are extremely vulnerable to soil degradation, water loss, and erosion due to intensive land use and other human activities (Tuyet, 2001; Zhang et al., 2011). Although it is known that the surface soil moisture plays an extremely important role in the ecological process of surface soil (Chen et al., 2010), there are very few studies characterizing the relevant factors quantitatively (Zhang et al., 2011); furthermore, no progress has been made toward understanding the effect of exposed rocks on the surface soil water content. Therefore, more attention should be paid to the spatial variability of soil moisture in the karst area of southwest China.

This study began with a data collection survey in a typical KRD region of Fuyuan County in Yunnan Province, China. The influence of bare rocks on surface soil moisture was then analyzed. Results from this study can be used to guide vegetation restoration under stressful environmental conditions, and to direct ecological management of areas affected by KRD.

2. Methods

2.1. Site description

The study was carried out in San-do-qing Forestry Station (25°02′30″–25°58′22″N, E103°58′37″–104°49′48″), which is in Fuyuan County, Yunnan Province (Fig. 1). Fuyuan County has a total area of 3251 km^2. It is on the eastern Yunnan karst plateau. The topography is mainly mid-mountain at the early developmental stage of karst landform. The whole county has 2049.311 km^2 of karst. The KRD area is up to 601.018 km^2, which is 18.49% of the total arable land, or 29.33% of the karst region.

The area has a northern subtropical monsoon climate. The annual average temperature is 13.8 °C. July is the hottest month with an average temperature of 19.8 °C; January is coldest with an average air temperature of 5.7 °C. The annual hottest temperature is 39.4 °C, and the lowest is −10.7 °C. The annual sunshine duration is 1819.9 h. The frost free season is 240 days, and annual average precipitation is 1332 mm. The rainy season is from May to October (Fig. 2). The main soil type is Haplic Alfisols (Chinese for ‘red limestone soil’), according to FAO soil classification systems (FAO, 1998). Rivers within the county are in the Pearl River basin. County population is 716,400, with a population density of 220 per km^2. From Sept., 2009 to April, 2010, this region experienced an extreme drought period. The precipitation during this period was 107.8 mm, and was 57.2% compared with that of the dry reason of normal years (188.6 mm).

2.2. Data collection

In Feb., 2010, on the south slope of the experimental site, a plot with typical mid-level KRD features, 50% vegetation cover, 60% outcrops cover, soil depth between 10 cm and 30 cm and minor human disturbance was selected (Fig. 3). 102 rock outcrops were chosen along a 1000 meter sampling line. These rocks were selected with length from 0.20 m to 3.70 m, width from 0.19 m to 3.50 m and height from 0.13 m to 2.5 m. The cover area and height of the rocks were measured. Soil moisture in the upper 5 cm of the soil at 5 cm north, west, south and east of the rocks was measured as volumetric soil water content in m^3 m^{-3}, with a soil moisture sensor (5TE, Decagon Devices, Pullman, Washington, USA) coupled to a readout device (ProCheck, Decagon Devices, Pullman, Washington, USA) (Moody and Ebel, 2012; Sperdouli and Moustakas, 2012). Each rock's location was recorded using a GPS device (Fig. 1).

Rocks were selected that were well-separated from each other and had regular external shapes. There was any soil but no large shrubs around the rocks (Fig. 4b).

On the south slope of the experimental site in Feb., 2010, an agricultural field, a mixed (needle leaf and broad leaf) scrub, a *Pinus armandii* scrub, and a KRD field were selected for study. At a depth of 5 cm soil moisture was measured using a 5TE probe coupled to a ProCheck readout device.

Two pieces of rock (A and B in Fig. 1) with uniform size and shape were selected from the 102 rocks. Locations at 5, 15, and 25 cm to the east, west, north, and south of these two rocks were chosen to detect soil moisture, respectively. Soil moisture was measured at depths of 5, 10, and 15 cm for each location as described above (Fig. 4a). Mean value of soil bulk density around the rock is 1.17 g·cm^{-3}. Three measurements were taken for each spot, and the mean was

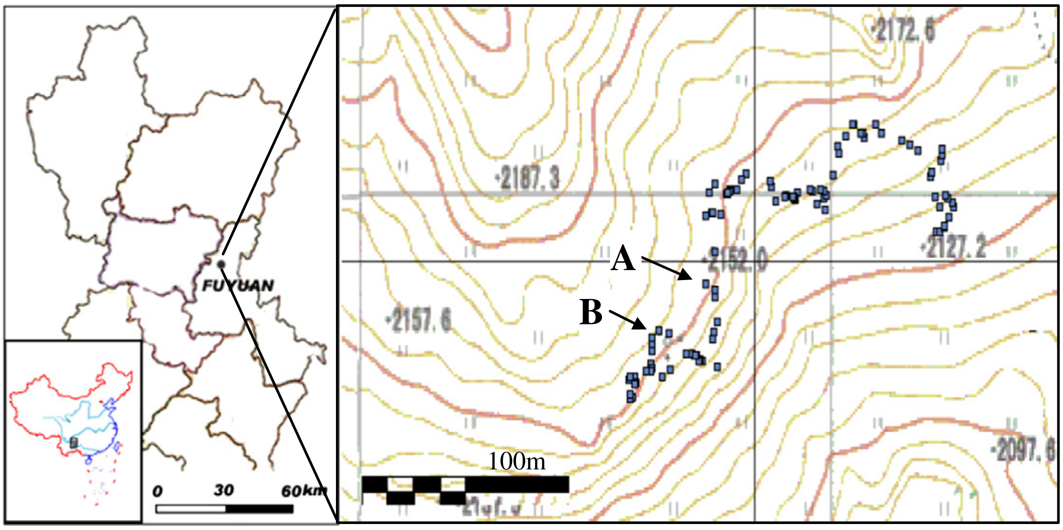

Fig. 1. Research area and the GPS map of investigation sites of bare rocks for surface soil moisture determination.

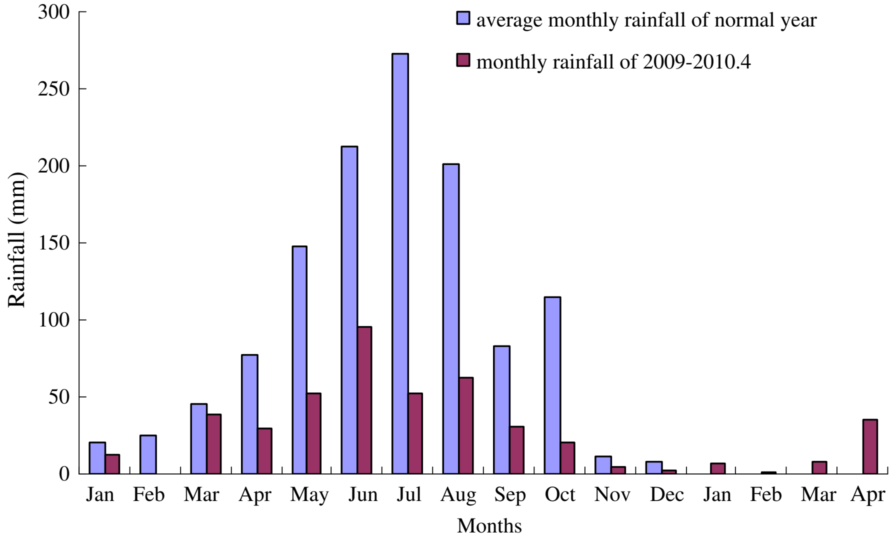

Fig. 2. Monthly rainfall of 2009.9–2010.4 compared with average monthly rainfall of normal years.

used as the water content. The control plot was a 20 m^2 waste grassland (CK, Fig. 4c) on the same slope as other samples where there were no bare rocks. Soil moisture was measured following the same procedure as treatment samples.

3. Results

3.1. Variation of surface soil moisture around the bare rocks

The surface soil moisture (0–5 cm soil depth) around the 102 rock outcrops is contained in Table 1. The average soil moisture near the rocks was as low as 9.57%, and the water content differed highly significantly ($p < 0.01$) among the four sides of the rocks. The soil north of the rocks had the highest water content; it was significantly different from those on the south and west sides, but the difference from the east side soil did not reach the significant difference level. Soil moisture on the east and west sides of the rocks had no significant difference, but both were highly different from the south side. The difference in soil moisture between the west and south sides of the rocks was also highly significant. During the drought period, soil moisture varied greatly depending on the relative direction from the rocks and could be attributed to the shade of the rocks.

Soil moisture in the bare rock field was the lowest among the four land cover types (Table 2). The coniferous and broad-leaved mixed forest ensured a much higher soil moisture level, which was 1.96 fold higher than that of bare rocks. In spots having exposed bare rocks, intensive evaporation of soil water occurred due to the absence of vegetation as ground cover. Together with the diffuse reflection of solar radiation from the bare rocks, it created an environment with elevated temperature. The consequential intensified soil evaporation led to a decline of the surface soil moisture around the bare rocks. This phenomenon also occurs in the rainy season with plentiful precipitation (Li et al., 2009a). On the other hand, appropriate vegetation and litter coverage together could have improved soil moisture.

3.2. Effect of the shapes of the bare rocks on the surface soil moisture

The 102 bare rock outcrops were divided in four groups according their altitude above ground (0–0.5 m, 0.5–1.0 m, 1.0–1.5 m, and >1.5 m). The surface soil moisture (0–5 cm depth) increased around taller rocks (Fig. 5), and water content decreased in the order of north > east > west > south relative to the rocks.

The relationship between soil moisture and rock height, the cover area, and the ratio of height to cover area were determined (Table 3).

Fig. 3. Landscape of karst rocky desertification at investigation sites.

Fig. 4. Schematic map of individual rock samples for soil moisture measurement and the photo of 'A' rock and CK (a: Schematic map of individual rock samples for soil moisture measurement at different distances and depth; b: Rock sample of A; c: Sample of CK far from A 6 m).

The soil moisture had a positive correlation with the rock height, which is stronger than that with the cover area. The correlation between the height and the cover area of the rocks and soil moisture on the west and north sides was higher than those on the east and south sides.

The height of the rocks had a highly significant correlation with soil moisture on the west side of the rocks, but not in the other three directions. For the cover area of the rocks, correlation with soil moisture was highly significant ($p < 0.01$) on the west and north sides but only significant ($p < 0.05$) on the east side of the rock soil. The ratio of height to cover area is a measurement of the taperingness of the rocks: the higher ratio indicates more tapered rocks. The ratio of height to cover area is negatively correlated with soil moisture on the east, west, and north sides of the rocks. These results indicate that more tapered rocks encourage lower soil moisture on the east, west, and north sides of the rocks, relative to more rounded rocks.

3.3. Changes of moisture for various depths of soil around the bare rocks

Soil moisture for different depths was determined at different distances from the two selected bare rocks and the control plot (Table 4). Soil moisture declined in the order of north > east > west > south sides of the rocks, and this was similar to the results of the 102 rock outcrops. It is very likely that soil on the south side of the rocks had received the strongest solar radiation. When reflected by the rocks, the strong solar radiation induced faster evaporation of surface soil water on the south and west sides of the rocks. Due to the shade effect from the bare rocks, light intensity was lower on the north and east sides where the soil water content was higher. On the waste grassland of the control samples, the surface soil moisture was higher than soils of 5 and 15 cm south of the rocks, but lower than those on the other three sides. At a distance of 25 cm from the rocks, soil moisture was higher than the control.

For locations 5, 15, and 25 cm east of the rocks, soil moisture had a significant difference ($p = 0.049$) for the surface layer (0–5 cm), but not the deeper soil layers (5–10 cm and 10–15 cm). On the south side at the same distances from the rocks, water content had no significant difference for the surface soil layer (0–5 cm), but the difference was significant for the 5–10 cm and 10–15 cm soil layers ($p = 0.046$; 0.035). No significant variation was found for soil moisture on the west and north sides at any depth or distance.

On the north, east and west sides of the rocks, the soil moisture increased at shorter distances and then declined as it moved away from the rocks. On the south side of the rocks, soil moisture showed a continuous increase as it got farther away from the rocks. It is very likely that those rocks would generate a very strong heating effect, causing serious soil water loss in the surrounding nearby area. Such effect dwindled with the distance from the rocks, and meanwhile soil water appeared to increase continuously.

Table 1
Surface soil moisture at different orientations around the bare rock outcrops.

Orientation	*E*	*S*	*W*	*N*
0–5 cm soil moisture (%)	8.99 ± 2.73AB*	7.37 ± 1.93C	8.62 ± 2.72B	9.79 ± 2.98A

* Different letters indicate highly significant differences at $p < 0.01$ level.

Soil moisture increased with soil depth. Under drought conditions, there was a significant difference in the soil moisture between 0–5 cm and 5–10 cm ($p < 0.05$), and the water content was highly different between the 10 and 15 cm soil depths ($p < 0.01$).

15 cm north of the rocks the surface soil water content was lower than the 5 and 25 cm depths. The 5–10 cm and 10–15 cm depths contained higher water content at 15 cm distance than at 5 and 25 cm distances. 5–10 cm and 10–15 cm depths also contained higher water content than all locations in the control waste grassland.

The KRD region has a very shallow layer of soil. In the experimental field, the average soil depth was 20 cm. Plant roots are mainly distributed from 5 to 15 cm depth. Higher soil water at this depth would promote plant root absorption and utilization of water. As this depth has the highest moisture 15 cm north and east of bare rocks, the location 15 cm north of the rocks should be ranked as the suitable site for vegetation restoration, followed by the site at 15 cm east of the rocks.

4. Discussion

An understanding of soil moisture variability is necessary to characterize the linkages between a region's hydrology, ecology, and physiography. In China's subtropical karst region, the spatial variability of surface soil moisture is still unclear for the rocky ecological environment and areas with intensive land use (Zhang et al., 2011).

Our results were in accordance with the studies of Huang et al. (2009) in the same depression area of China that only seasonal drought may have a high impact on the karst ecosystem. Drought for extended period not only causes declining of soil moisture as a whole but also results in redistribution of soil water into a more homogenous state both horizontally and vertically (Huang et al., 2009). The extent of such changes depends on the level and duration of the dryness (Huang et al., 2009; Zhang et al., 2011). This study found that surface soil moisture presented a moderate variability in the depression area at the sampling times, and this result was in accordance with the studies of Zhang et al. (2011) in a karst depression area of southwest China.

By analyzing the soil moisture around the rocks during a drought period, our study identified the rock's important function of providing shade to the land, which partially ameliorated drought-related stresses. The drought period in this study lasted for over 150 consecutive days (from Sept., 2009 to Feb., 2010). Soil was extremely dry, and the average surface soil moisture was reduced to 9.57%. This provided the most ideal environment for measuring the shade effect provided by the rock outcrops.

Table 2
The surface soil moisture from lands with different types of land cover.

Types of land cover	Coniferous and broad-leaved mixed forest	*P. armandii* forest	Farmland	Bare rock field
0–5 cm soil moisture (%)	18.73 ± 1.37A*	10.53 ± 0.64B	10.30 ± 0.96B	9.57 ± 0.64B

* Different letters indicate highly significant differences at $p < 0.01$ level.

Soil moisture in the bare rock field was the lowest among the four land cover types. The coniferous and broad-leafed mixed forest ensured a much higher soil moisture level, which was 1.96 fold higher than the bare rocks. These results were in accordance with the studies of Zhang et al. (2011) that the dominant influencing factors on the variability of surface soil moisture were rainfall and land use types.

One of the most spectacular characteristics of the KRD process in Southwest China is the large amount of rocks exposed at the surface. Those bare rocks not only affect redistribution of light and water resources on the ground but also influence soil water distribution, as well as the local microclimate and vegetation growth. In the typical KRD regions, the specific environmental conditions have hindered the progress of restoration of ecological systems through vegetation reinstallation. Therefore understanding the impact of bare rocks on soil moisture is very important.

Conn and Snyder-Conn (1981) found that rock outcrops influenced soil moisture in the surrounding area, but the scale of the effect depended on the shape, size, and surface area of the rocks, along with other factors including the smoothness of the rock surface, distribution of cracks, solar radiation angle, wind, precipitation, and vegetation coverage. In their study areas immediately adjacent to outcrops had higher soil moisture content than the areas away from outcrops, which could provide greater runoff, shading, and soil temperature stability. Conn and Snyder-Conn (1981) did not consider the influence of direction from the rock outcrops on soil moisture. Our results showed that during the extreme drought period, soil moisture on the north side of the rock outcrops was significantly higher than the other sides. Our results also found that soil moisture began to increase and then declined on the north, east and west sides with the distance from the rocks, but showed a continued increase on the south side with the distance from the rocks. This result was also different from those reported by Conn and Snyder-Conn (1981) and Noy-Meir et al. (1991). Noy-Meir et al. (1991) discovered that soil moisture content close to or between rocks was significantly higher than elsewhere at the sampling points, particularly the tall smooth rocks. In karst depression areas, soil surfaces are often characterized by the presence of rock outcrops, therefore, the soil moisture content and variability could be deeply affected by rock outcrops.

There are still disagreements in defining factors affecting soil water spatial variation, especially average water content (Zhang et al., 2011). Zhang et al. (2011) suggested that more soil samples might be required and the sampling interval should be shortened in the dry season compared with the rainy season. In one study (Chen et al., 2010), it was suggested that under homogenous vegetation types and even slope conditions, slope position had very minimal effect on water distribution along the slope. This study only determined the physical shading effect from bare rocks during drought period. Other phenomena such as heating effect from bare rocks on soil moisture, and comprehensive changes in soil moisture under the influence of bare rocks will be investigated in future studies.

Cousin et al. (2003) suggested that the color characteristics of rock fragments would lead to heating of the soil and therefore to a decrease of its water content under strong evaporation conditions. Therefore, the effect of rock outcrops on the surface soil moisture and its variability depended on the sampling scale, the sampling point distance from rock outcrops, the rock outcrops' size and their relative position at the soil surface (Zavala et al., 2010). Compared with Zavala's work (Zavala et al., 2010), our research has some differences. First is condition, our work was carried out under natural drought condition but not simulated rainfall. Second is that our research object is outcrop bedrocks but not rock fragments laying on the soil surface. Third is size of the rocks, rock size we researched is length from 0.20 m to 3.70 m, width from 0.19 m to 3.50 m, height from 0.13 m to 2.5 m, and the rock can't be removed. However, Zavala's rock fragments varied from 2 mm to 10 cm, and they carried out the experiment under rock fragments existed and been removed. removed. Our study accounted for these factors by choosing 102 rocks randomly along the 1000 m sampling line to investigate the surface soil moisture at four directions from the rocks and at multiple soil depths.

However, more soil samples are required in extreme dry period in this karst area to take into account differences in soil moisture variability according to rock outcrop distribution patterns. Geostatistical analysis of surface soil moisture would be helpful to the soil moisture management and hydrological modeling of the local karst area. Future research should be focused on the soil moisture balance and its effective management, the mutual relationships of environmental factors and their effects on hydrological processes and vegetation restoration strategies in the karst region of southwest China.

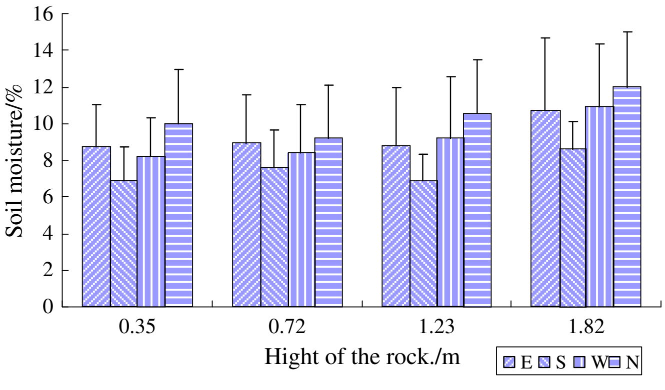

Fig. 5. Surface soil moisture at the east (E), west (W), south (S) and north (N) sides of rock outcrops of various heights.

5. Conclusion

Under severe sustained drought conditions, bare rocks provide some physical shade and affect the soil water content surrounding the rocks. The surface soil water content of the 0–5 cm layer around the rocks was generally lower, but a site with the highest soil moisture (9.79%) was identified on the north side of the rocks, and it reached the highly significantly different level from those on the east, west and south sides of the rocks ($p < 0.01$).

Rock shape also affects soil moisture in the surrounding areas, and soil moisture in the 0–5 cm layer was higher on the four sides of taller rocks. The size of the exposed surface area of bare rocks had highly significant effects on soil moisture on the west and

Table 3
Correlation coefficient between the surface soil moisture and the height, the cover area and ratio of height/cover area of bare rock outcrops at different orientations.

The correlation coefficient	E	S	W	N
Height of rocks	0.077	0.084	0.270**	0.148
Cover area of rocks	0.203*	0.089	0.265**	0.254**
Ratio (height/cover area)	−0.107	0.029	−0.192	−0.177

*: indicate significant differences at $p < 0.05$ level, **: indicate highly significant differences at $p < 0.01$ level.

Table 4
Changes of water content in various depths of soil at different distances from bare rocks at different orientations.

Distance from rocks (cm)	Soil layers (cm)	E %	S %	W %	N %	CK %
5	0–5	14.36 ± 2.06	10.17 ± 3.10	13.78 ± 4.00	16.24 ± 1.20	10.43 ± 0.54
	5–10	14.64 ± 2.52	13.43 ± 2.83	14.12 ± 2.86	16.45 ± 2.87	12.59 ± 0.49
	10–15	15.55 ± 1.59	14.09 ± 0.94	15.17 ± 2.53	17.94 ± 1.04	15.56 ± 0.80
15	0–5	13.66 ± 0.89	10.05 ± 0.33	13.24 ± 2.69	15.22 ± 3.09	–
	5–10	16.49 ± 2.09	13.87 ± 3.45	15.30 ± 4.16	18.42 ± 4.22	–
	10–15	19.05 ± 5.18	14.86 ± 2.33	16.12 ± 3.61	20.73 ± 2.69	–
25	0–5	13.69 ± 3.71	11.32 ± 2.85	12.26 ± 4.43	15.61 ± 1.27	–
	5–10	17.15 ± 2.43	12.92 ± 3.02	14.27 ± 3.70	15.84 ± 1.18	–
	10–15	17.63 ± 2.40	14.71 ± 4.71	14.91 ± 2.90	17.27 ± 2.65	–

CK: the control plot, a 20 m^2 waste grassland.

north sides, and a significant effect on the east side of the rocks. More tapered rocks (with higher ratio of height and area) caused a decline in the soil moisture on the east, west and north sides. With increasing distance from the rocks, soil moisture increases and then decreases on the north, east, and west sides, but it increased consistently on the south side in 25 cm distances.

Soil moisture around the bare rocks increased with the depth of soil. The bare rocks provided some shade to the surrounding area, leading to a more heterogeneous distribution of soil water, with soil moisture maxima located 15 cm north of the rocks—ideal locations for planting. These findings have instructive value for vegetation restoration in the KRD regions.

Acknowledgments

The research was funded by the National Natural Science Foundation Project (No. 30972351), the Special Research Program for Public-Welfare Forestry (No. 201004033), and the Special Funds for Research Projects of Research Institute of Subtropical Forestry, Chinese Academy Forestry (No. RISF61251). We are very grateful to Qian X.Q., Liu J. and Hou P. for their indispensable assistance with sample plot investigation. We also thank Guizhou-Puding Desertification Ecosystem Research Station (State Forestry Administration, P. R. China) for support of field work.

References

Burgess, T.M., Webster, R., 1980. Optimal interpolation and isarithmic mapping of soil properties. I: the semi-variogram and punctual kriging. J. Soil Sci. 31, 315–331.

Cain, M.L., Subler, S., Evans, J.P., Fortin, M.J., 1999. Sampling spatial and temporal variation in soil nitrogen availability. Oecologia 118, 397–404.

Chen, H.S., Zhang, W., Wang, K.L., Fu, W., 2010. Soil moisture dynamics under different land uses on karst hillslope in northwest Guangxi, China. Environ. Earth Sci. 61 (6), 1105–1111.

Chen, H.S., Zhang, W., Wang, K.L., Hou, Y., 2012. Soil organic carbon and total nitrogen as affected by land use types in karst and non-karst areas of northwest Guangxi, China. J. Sci. Food Agric. 92 (5), 1086–1093.

Conn, J.S., Snyder-Conn, E.K., 1981. The relationship of the rock outcrop microhabitat to germination, water relations, and phenology of *Erythrina flabelliformis* (Fabaceae) in Southern Arizona. Southwest. Nat. 25 (4), 443–451.

Cousin, I., Nicoullaud, B., Coutadeur, C., 2003. Influence of rock fragments on the water retention and water percolation in a calcareous soil. Catena 53, 97–114.

Crowther, J., 1982. Ecological observations in a tropical karst terrain, west Malaysia. I. Variations in topography, soils and vegetation. J. Biogeogr. 9, 65–78.

Descroix, L., Viramontes, D., Vauclin, M., Gonzalez Barrios, J.L., Esteves, M., 2001. Influence of soil surface features and vegetation on runoff and erosion in the Western Sierra Madre (Durango, Northwest Mexico). Catena 43, 115–135.

FAO/ISRIC/ISSS, 1998. World Reference Base for Soil Resources. World Soil Resources Reports. FAO, Rome.

Farley, R.A., Fitter, A.H., 1999. Temporal and spatial variation in soil resources in a deciduous woodland. J. Ecol. 87, 688–696.

Gross, K.L., Pregitzer, K.S., Burton, A.J., 1995. Spatial variation in nitrogen availability in three successional plant communities. J. Ecol. 83, 357–368.

Huang, Q.H., Cai, Y.L., 2007. Spatial pattern of Karst rock desertification in the Middle of Guizhou Province, Southwestern China. Environ. Geol. 52 (7), 1325–1330.

Huang, Y.Q., Zhao, P., Zhang, Z.F., Li, X.K., He, C.X., Zhang, R.Q., 2009. Transpiration of *Cyclobalanopsis glauca* (syn. *Quercus glauca*) stand measured by sap-flow method in a karst rocky terrain during dry season. Ecol. Res. 24, 791–801.

Jackson, R.B., Caldwell, M.M., 1993. The scale of nutrient heterogeneity around individual plants and its quantification with geostatistics. Ecology 74, 612–614.

Koster, R.D., Dirmeyer, P.A., Guo, Z.C., Bonan, G., Chan, E., Cox, P., Gordon, C.T., 2004. Regions of strong coupling between soil moisture and precipitation. Science 305 (5687), 1138–1140.

Li, S., Ren, H.D., Yao, X.H., Zhang, S.G., 2009a. Effect of different land use on environment microclimate diurnal dynamics in Karst zone. Chin. J. Appl. Ecol. 20, 387–395 (in Chinese).

Li, Y.B., Shao, J.A., Yang, H., Bai, X.Y., 2009b. The relations between land use and karst rocky desertification in a typical karst area, China. Environ. Geol. 57 (3), 621–627.

Moody, J.A., Ebel, B.A., 2012. Hyper-dry conditions provide new insights into the cause of extreme floods after wildfire. Catena 93, 58–63.

Noy-Meir, I., Agami, M., Cohen, E., Anikster, Y., 1991. Floristic and ecological differentiation of habitats within a wild wheat population at Ammiad. Israel J. Bot. 40 (5), 363–384.

Parent, A.C., Anctil, F., Parent, L.E., 2006. Characterization of temporal variability in near-surface soil moisture at scales from 1 h to 2 weeks. J. Hydrol. 325 (1–4), 56–66.

Qi, F., Liu, Y.S., Mikami, M., 2004. Geostatistical analysis of soil moisture variability in grassland. J. Arid Environ. 58 (3), 357–372.

Qiu, Y., Fu, B.J., Wang, J., Chen, L.D., 2001. Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the loess plateau, China. J. Arid Environ. 49 (4), 723–750.

Schlesinger, W.H., Raikes, J.A., Hartley, A.E., Cross, A.E., 1996. On the spatial pattern of soil nutrients in desert ecosystems. Ecology 77, 364–374.

Sperdouli, I., Moustakas, M., 2012. Spatio-temporal heterogeneity in *Arabidopsis thaliana* leaves under drought stress. Plant Biol. 14 (1), 118–128.

Sweeting, M.M., 1993. Reflections on the development of Karst geomorphology in Europe and a comparison with its development in China. Z. Geomorphol. 37, 127–136.

Tuyet, D., 2001. Characteristics of Karst ecosystems of Vietnam and their vulnerability to human impact. Acta Geol. Sin. 75 (3), 325–329.

Wang, S.J., Liu, Q.M., Zhang, D.F., 2004. Karst rocky desertification in southwestern China: geomorphology, landuse, impact and rehabilitation. Land Degrad. Dev. 15, 115–121.

Zavala, L.M., Jordán, A., Bellinfante, N., Gil, J., 2010. Relationships between rock fragment cover and soil hydrological response in a Mediterranean environment. Soil Sci. Plant Nutr. 56, 95–104.

Zhang, J.G., Chen, H.S., Su, Y.R., Shi, Y., Zhang, W., Kong, X.L., 2011. Spatial variability of surface soil moisture in a depression area of karst region. Clean – Soil, Air, Water 39 (7), 619–625.