Environ Sci Pollut Res (2016) 23:8610–8616
DOI 10.1007/s11356-016-6091-9

RESEARCH ARTICLE

Rock outcrops redistribute water to nearby soil patches in karst landscapes

Dian-jie Wang[1] **· You-xin Shen**[1] **· Jin Huang**[2] **· Yu-hui Li**[3]

Received: 14 August 2015 / Accepted: 11 January 2016 / Published online: 22 January 2016

Abstract The emergence of rock outcrops is very common in terrestrial ecosystems. However, few studies have paid attention to their hydrological role in the redistribution of precipitation, especially in karst ecosystems, in which a large proportion of the surface is occupied by carbonate outcrops. We collected and measured water received by outcrops and its subsequent export to the soil in a rock desertification ecosystem, an anthropogenic forest ecosystem, and a secondary forest ecosystem in Shilin, China. The results indicated that outcrops received a large amount of water and delivered nearly half of it to nearby soil patches by means of runoff. No significant difference was found in the ratio of water received to that exported to the soil by outcrops among the three ecosystems annually. When the outcrop area reaches 70 % of the ground surface, the amount of water received by soil patches from rock runoff will equal that received by precipitation, which means that the soil is exposed to twice as much precipitation. This quantity of water can increase water input to nearby soil patches and create water content heterogeneity among areas with differing rock emergence.

Responsible editor: Philippe Garrigues

✉ You-xin Shen
yxshen@xtbg.ac.cn

[1] Key Laboratory of Tropical Forest Ecology; Restoration Ecology Research Group, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Kunming 650223, People's Republic of China

[2] Stone Forest Scenic Area Administration, Shilin 652211, People's Republic of China

[3] Yunnan Normal University, Kunming 650092, People's Republic of China

Keywords Karst · Outcrops · Precipitation · Runoff soil water · Biodiversity nutrients

Introduction

Soil water is critical to terrestrial plants and ecosystems. As part of hydrological cycles, soil water is subjected to the combined influences of precipitation, evapotranspiration, and percolation, among other things (Osman 2013). The physical and chemical properties of soil determine the water storage capacity and amount of water available to plants in the soil (Kirkham 2014; Lavelle 2001). Other factors, such as topography, vegetation, soil depth, and temperature, may also impact soil water content (Chen et al. 2009; Custovic et al. 2014; Hopmans 2006; Lavelle 2001). The emergence of rock outcrops is very common in terrestrial ecosystems, especially in karst ecosystems, but little quantitative research has been conducted on rock outcrops, making it difficult to evaluate their effect on water redistribution to nearby soil patches.

Carbonate outcrops form as a result of the differential corrosion rate of carbonate rock derived from its minor chemical compositional difference (Ford and Williams 2007; Zhang et al. 2005). Based on carbonate rock chemical composition, climate, and the like, the morphologies and proportion of outcrops differ at different localities. The total area of typical karst in south China amounts to approximately 452,000 km^2, of which 26 % has carbonate rocks cropped out at a proportion of more than 30 %, and with little vegetation forms a so-called rock desertification landscape (RDL) (Gazette of Rock Desertification in China, 2012). Among the 20×10^6 km^2 of karst land in the world, considerable areas are occupied by carbonate outcrops on the surface (Ford and Williams 2007), and outcrops in a high density of more than 30 % appear to be common in these areas if south China's proportions can be taken as a general estimate. These outcrops are thought to redistribute most of the precipitation water to nearby soil patches and to exert certain impacts on soil water content. However, no research studies as of yet have examined this specific role of karst outcrops.

Outcrops may redistribute precipitation water to nearby soil patches and improve soil water content (Wang et al. 2013; Zhang et al. 2008), which may have a certain significance for karst soil and vegetation. Due to the low soil formation rate and emergence of carbonate rock, karst soil is shallow and patchy in many areas (Aley 1990), which indicates a low soil water storage capacity; thus, some karst wood species penetrate deeply into the aquifer in order to gain access to water (Liu et al. 2014). For those tree seedlings, shrubs, herbs, and grass species whose root systems are less developed and thus unable to reach the aquifer water, soil water is critical to their survival and growth. Soil moisture in areas close to rock outcrops was higher than in areas farther away (Conn and Snyder-Conn 1981; Li et al. 2014), which implied that runoff water from outcrops supplemented water to the surrounding soil and then may serve to relieve the desiccation of plants to a certain degree.

Emergent rocks have been shown to receive water and to benefit nearby soil patches in other ecosystems, such as the cobbles in the coastal Negev desert, which support a lush vegetation cover and richness in the surrounding soil by condensing dew (Kidron and Starinsky 2012). In some drylands, mineral outcrops enhance the surrounding soil moisture (Chan et al. 2012). Goransson et al. (2014) referred to the process of rock runoff water toward soil as "the funneling effect" of rocks. But, scant attention has been paid to karst ecosystems, in which outcrops frequently dominate, and their water contribution to nearby soil patches, at least not in a quantitative manner.

In this research, we collected precipitation water and runoff water on the surface of carbonate outcrops in Shilin in southwestern China for 1 year. The objectives of this study were to determine the amount of water received by rock outcrops and subsequently the amount exported to nearby soil patches in different seasons and in different karst ecosystems and then to assess the ecological significance of this water output. We hypothesized that (i) a large proportion of water received by rock outcrops is redistributed to nearby soil patches and that (ii) the ratio of water received to that exported to soil by outcrops varies across different ecosystems and different seasons.

Material and methods

Site description

This study was conducted in Shilin County, Yunnan Province, southwestern China. Devonian, Carboniferous, and Permian carbonate rocks make up many karst landforms in Shilin (Sebela et al. 2004). Listed as one of the Global Geoparks in 2014 by UNESCO, Shilin is famous for its various karst landforms, such as peak forest, cone karst, hum, and karst basin, among others. Zonal vegetation consists of semi-humid evergreen broad-leaved forest and *Pinus yunnanensis* forest (Zhang et al. 1997). A subtropical plateau monsoon climate prevails with a mean annual rainfall of 967.9 mm. May to October make up the rainy season, during which 80–88 % of rainfall occurs. The dry season takes place from November to April, and annual transpiration amounts to 2097.7 mm, with the highest amount in April and the lowest amount in November. The mean annual temperature is 15.5 °C. Red earth and calcareous soil are the principal soil types. Three typical local ecosystems were selected:

1. A rock desertification ecosystem (RDE), in which trees were cut by local farmers, and lower intervening *Spiraea salicifolia*, *Heteropogon contortus*, *Themeda triandra*, *Bidens pilosa*, *Sophora viciifolia*, and the like were found. The elevation of the site is 1775 m, and a black film of cyanobacteria covered the rock surface.
2. An anthropogenic forest ecosystem (AFE), in which the outcrops are underneath a canopy of *Pinus yunnensis*, *Photinia × fraseri*, *Pyracantha fortuneana*, and *Koelreuteria paniculata*. The site elevation is 1789 m, 2150 m away from RDE. The cyanobacteria film on the rock surface was darker in color here than in the RDE. Both of these ecosystems are within the vicinity of the Geoparks. Tian et al. (2002, 2003) conducted research on the species and communities of epilithic cyanobacteria film in the Geopark.
3. A secondary forest ecosystem (SFE), with *Cyclobalanopsis glaucoides*, *Pistacia weinmannifolia*, *Neolitsea homilantha*, and *Olea yunnanensis*, mixed with such deciduous components as *Pistacia chinensis*, *Albizia mollis*, and *Carpinus mobeigiana*, are the major tree species (Shen et al. 2005). Cyanobacteria, lichen, bryophyte, and a few vascular plants were found on the rock surface (Xu et al. 2006). The elevation of the site is 1918 m, 21.5 km away from AFE, located in the natural reserve of the Geopark.

Water collection and epilithic organic matter sampling

While outcrops in Shilin can reach as high as 10 m, we focused exclusively on low pinnacles no higher than 3 m, which are termed stone teeth in China. Within each ecosystem, 10 outcrops were randomly selected; their general features are listed in Table 1. From the rock ridge to the bottom, a portable cutting machine was used to create three grooves on the left, right, and bottom margins of the rock surface, enclosing a surface area of approximately 1 m^2. Polyvinyl chloride (PVC) strips of 6 cm in width were fixed in grooves by means

Table 1 General features of the sampled outcrops

Features	Rock desertification ecosystem	Anthropogenic forest ecosystem	Secondary forest ecosystem
Organic matter per unit rock surface area (g m^{-2})	7.65 ± 0.74a	48.38 ± 9.19b	92.21 ± 19.72c
Height (cm)	123.05 ± 7.03a	123.3 ± 10.04a	164.7 ± 15.50a
Slope (°)	66.44 ± 3.1a	73.9 ± 3.63a	73.65 ± 2.53a
Canopy coverage above rock in rainy season (%)	0.00 ± 0.00c	15.75 ± 9.95b	54.11 ± 13.45a
Canopy coverage above rock in dry season (%)	0.00 ± 0.00c	23.75 ± 11.68b	75.00 ± 12.03a
Orientation	NE(4) SE(3) SW(2) NW(1)	E(2) NW(2) SE(1) SW(1) NE(1) S(1) W(1) N(1)	NW(2) SE(2) NE(2) SW(1) N(1) E(2)

The *different lowercase letters* indicate the significant differences between the different systems ($P < 0.05$). The *numbers in brackets* represent the number of sampling rock surfaces in a specific orientation

of silicon sealant, and L-shaped aluminum foil strips cm in width were attached on the bottom PVC strip surfaces to form a trough along the bottom of the rock; the troughs were set at a gradient of 20–45° so as to drain the water. Drained water was led via polyethylene tubing to a 15-L barrel set in a hole on the ground; all intersections were sealed. This system was used to collect rock runoff water (see Fig. 1). One to one and a half meter adjacent to a sampled rock, a separate hole on the ground held a 10-L barrel with an upright funnel 22 cm in diameter on the top. The barrel and funnel were connected by means of tubing as well. The water collected by this system was used to represent the water input to the rock surface. Canopy conditions, such as coverage above the funnel, were quite the same as for the sampled rock within each set. Barrels and holes were covered, and both had an opening through which the tubing passed. Funnels and troughs were covered

Fig 1 Runoff water collection systems, polyvinyl chloride (PVC) strips were inserted into grooves and sealed by silicon sealant to enclosed rock surface with an area of approximately 1 m^2. An L-shaped aluminum foil strip was attached to the bottom PVC strip surfaces to form a trough with a gradient of 20–45°, leading by means of polyethylene tubing to a 15-L barrel set in a hole in the ground

by polypropylene mesh to prevent canopy litter from getting stuck in them. The water in the barrels was measured manually at least once a month in the dry season and after each heavy rainfall in the rainy season, according to a real-time meteorological report available on www.weather.com.cn. As the water volume was not measured based on each event, we summed it up based on seasonal interval, i.e., May to July, August to October, and November to April in accordance with the local rain pattern. To measure the sampled surface area of the rock runoff, a 2 × 2-m white paper was covered on the rock surface, and the boundary was marked on the paper. The sampled catchment area was determined using a plumb and an overhanging horizontal projection board, and the trough opening area was included and was also calculated separately based on the trough opening width and length. The seasonal water volume of the precipitation input to the rock surface divided by the funnel opening area resulted in the input water quantity per unit of the rock-projected area. The seasonal water volume of rock runoff divided by the sampled catchment area resulted in an export water quantity per unit of rock-projected area.

Epilithic organic matter here denoted both live and dead sources, with a patch 20 × 20 cm in area scraped off from the rock surface adjacent to the runoff sampling boundary. Due to the mixture with carbonate rock powder, the organic matter content was determined by means of the oil-bath $K_2Cr_2O_7$ titration method.

Statistical analysis

A paired *t* test, ANOVA, and multiple comparisons were applied to analyze water quantity (per unit of projected rock area) differences between input and export, between different seasons, and between different ecosystems on R 3.1.2 (R Foundation for Statistical Computing). We used data transformation, the Kruskal–Wallis rank sum, and Wilcoxon signedrank tests if prerequisites of normality and homogeneity of variances were not met.

We used a rock emergence ratio of 30 and 70 % ground surface to evaluate the significance of runoff water, since 30 % is the lowest criterion for rock desertification set by the National Forest Bureau of China and 70 % is the criterion for severe rock desertification (Technology Regulations of Vegetation Restoration in Karst Desertification Zone, LY/T 1840–2009).

Results

Water input and export on outcrops' surface

Rock outcrops received a larger amount of water and then exported part of them to the nearby soil patches through runoff. Annually, 962.6 ± 32.4-mm water was received by rock outcrops and 440.11 ± 25.58 mm was exported to nearby soil patches. However, no significant difference was found among the three ecosystems in terms of water input and export on the rock outcrops (Fig. 2). The input water to the RDE, AFE, and SFE differed significantly among the three seasons. However, the export amount did not show a significant difference between May to July and August to October in the two forest ecosystems. The input water in SFE from May to July, in AFE from August to October and from November to April, and the export water in SFE from November to April differed significantly from the other ecosystems within these specific seasons (Fig. 3).

In the same season, input and export varied slightly among the three ecosystems. Input in SFE was higher than in the other two ecosystems from May to July; input in AFE was lower from August to October but higher from November to April than in the other ecosystems. Export in SFE from November to April was lower than in the other two ecosystems.

Ratios of water export to water input on outcrops' surface

Nearly half of the input was transferred to nearby soils. No significant difference was found in the ratio of water export to water input among the rock desertification ecosystem ([0.49 ± 0.03]:1), anthropogenic forest ecosystem ([0.41 ± 0.04]:1), and secondary forest ecosystem ([0.47 ± 0.07]:1). However, a significant difference was observed between the ecosystems from November to April (Table 2). Rock desertification experienced the largest ratio from November to April, while in the anthropogenic ecosystem, the largest ratio occurred from August to October. Based on the annual ratios, the contribution of the runoff water to the nearby soil patches can be calculated. At a 30 % rock outcrop emergence ratio, soil patches receive rock runoff water equal to 18–21 % of that received from precipitation in the three ecosystems (Table 3). When the ratio approaches 70 %, the water received from the rock outcrop runoff will be equal to or exceed the amount of water received from precipitation.

Discussion

Water input and export on outcrop's surface

Runoff water from rock outcrops and their ecological significance have seldom been explored in karst studies. Areas immediately adjacent to the outcrops had greater soil moisture

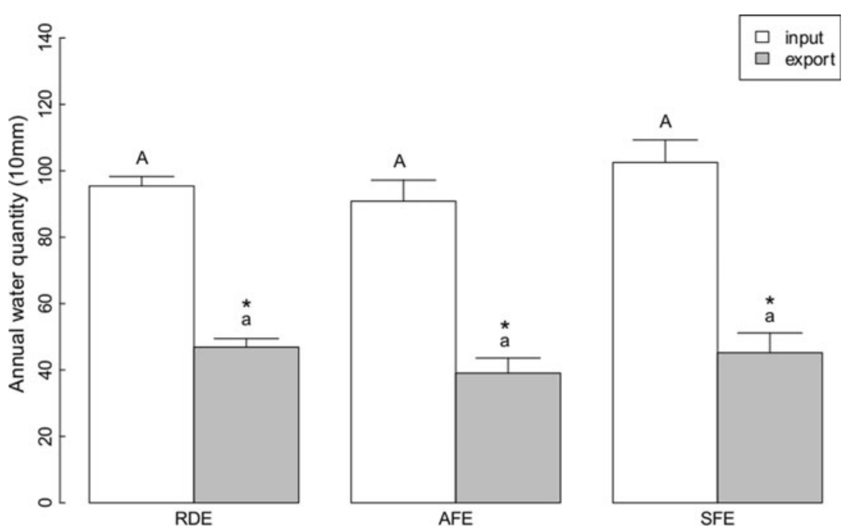

Fig 2 Annual precipitation inputs and runoff exports of water per unit rock-projected area (means ± standard errors) in three ecosystems (rock desertification ecosystem [RDE], anthropogenic forest ecosystem [AFE], and secondary forest ecosystem [SFE]). The *different uppercase letters* indicate the significant differences ($P < 0.05$) in input water between the different ecosystems, the *different lowercase letters* indicate the significant differences ($P < 0.05$) in the amount of export water between the different ecosystems, and the *asterisk* represents a significant difference ($P < 0.05$) between the inputs and exports

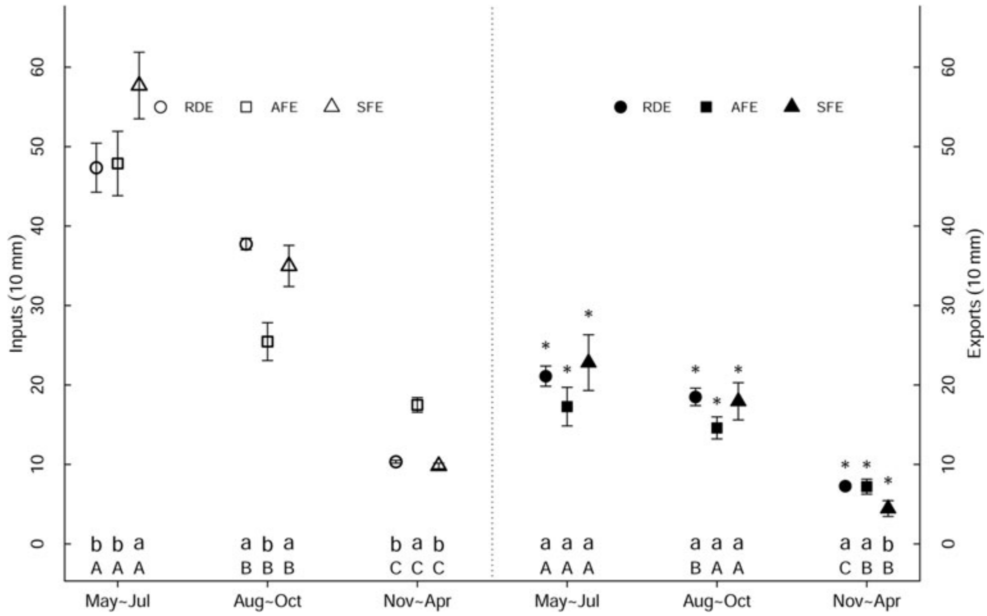

Fig 3 Seasonal precipitation inputs and runoff exports of water per unit rock-projected area (means ± standard errors) in three ecosystems (rock desertification ecosystem [RDE], anthropogenic forest ecosystem [AFE], and secondary forest ecosystem [SFE]). The *different lowercase letters* indicate the significant differences ($P < 0.05$) between the different ecosystems in the same season, the *different uppercase letters* indicate the significant differences ($P < 0.05$) between different seasons, and the *asterisk* in the *right column* represents a significant difference ($P < 0.05$) between the inputs and exports

than areas away from outcrops (Conn and Snyder-Conn 1981; Zhang et al. 2008; Wang et al. 2013). On a karst hillslope with emergent rock outcrops, a moderate to strong spatial dependence of soil moisture was found (Chen et al. 2010). A direct measurement in Fuyuan County (close to our sites) showed that soil surface moisture was influenced by the height of outcrops and the direction and distances from them (Li et al. 2014). Goransson et al. (2014) referred to this as "the funneling effect" of rock in their research in the Central Alps of Switzerland. However, no data was presented showing the annual runoff quantity and the proportion it accounted for of water received by rock outcrops. Our data indicated that a large amount of input water was received by rock outcrops and a big proportion of it was transferred to nearby soil patches (Figs. 2 and 3). Runoff water along with the nutrients it contains is exported to nearby soil patches and consequently influences the soil and plants that grow on it.

Not all water received by rock outcrops was directly redistributed to nearby soil patches; in fact, only 41–49 % of it was transferred, which implies that more than half of the water received by rock outcrops was channeled to other places, where it played various roles. We forgo a discussion of these water routes and their roles here and instead focus on the portion that was redistributed to the nearby soil patches via rock runoff.

Rock outcrops are very common in terrestrial ecosystems. One rock outcrop may not be ecologically significant to nearby soil. But once outcrops account for a large ratio of ground surface, such as 30 % (the lowest criterion for rock desertification given by the National Forest Bureau of China, Technology Regulations of Vegetation Restoration in Karst Desertification Zone, LY/T 1840–2009), they can have a tremendous impact on the whole ecosystem. On the one hand, if 30 % of the land surface is covered by rock outcrops, it cannot support as much biomass as nearby soil patches; in addition, the movement of soil, water, and nutrients in the soil may be blocked by these rock outcrops (negative effect). On the other hand, the amount of water redistributed by the rock outcrops enhances the water supplied to nearby soil patches, an amount equal to 18–21 % of the annual precipitation (Table 2). The average annual precipitation in our study area is 968 mm (Zhang et al. 1997), which means that soil patches will receive 174–203 mm more water than in soil in non-rock outcrop emerged ecosystems at this outcrop ratio, which may benefit karst vegetation on patchy soil. If we also consider that outcrops provide shade for nearby soil, thereby reducing evaporation from the soil and maintaining soil

Table 2 Ratios of water exported seasonally to soil patches to that water received from precipitation per unit rock-projected area in three ecosystems

Ecosystems	May to July	August to October	November to April
Rock desertification ecosystem	(0.46 ± 0.04):1aB	(0.49 ± 0.03):1aB	(0.71 ± 0.04):1aA
Anthropogenic forest ecosystem	(0.35 ± 0.05):1aB	(0.58 ± 0.06):1aA	(0.39 ± 0.04):1bB
Secondary forest ecosystem	(0.44 ± 0.08):1aA	(0.52 ± 0.06):1aA	(0.47 ± 0.12):1bA

The *different lowercase letters* indicate the significant differences between the different systems ($P < 0.05$), and the *different lowercase letters* indicate the significant differences between the different seasons ($P < 0.05$)

Table 3 Estimated ratios of water received annually from rock runoff water to water received via precipitation by soil patches with different outcrop area to soil area ratios (R/S) in three ecosystems

R/S	Ecosystems	Rock runoff water/precipitation
3:7	Rock desertification ecosystem	0.21:1
	Anthropogenic forest ecosystem	0.18:1
	Secondary forest ecosystem	0.19:1
7:3	Rock desertification ecosystem	1.14:1
	Anthropogenic forest ecosystem	1.00:1
	Secondary forest ecosystem	1.03:1

moisture, and that soil patches may differ in depth, which greatly affects the soil's water holding capacity, karst soil water heterogeneity should be taken as more than just an assumption but rather as a key reality necessary for understanding the underlying causes of karst biodiversity (Bo et al. 2000; Clements et al. 2006; Li et al. 2013). A larger rock outcrop emergence ratio, such as 70 %, will result in a sharply increased funnel effect toward nearby soil patches (Table 3). Rock runoff water washes down nutrients contained in epilithic organisms and organic matter, in addition to precipitation-borne nutrients, which may supplement soil nutrients and give rise to soil nutrient heterogeneity. Goransson et al. (2014) found rock funneling precipitation water to create a nitrogen hot spot and N:P heterogeneity in nearby soil, on a pristine glacial forefield site in Switzerland. Kidron and Starinsky (Kidron and Starinsky 2012) found cobbles in the Negev desert to serve as a nutrient sink by condensing dew and supplementing nearby soil. Büdel (1999) found the nitrogen content of the topsoil of some savannas to increase as its distance from inselbergs diminished, as a consequence of the weathering supplement from the rock. Karst outcrops differ in their density, size, morphology, and epilithic biomass; thus, nearby soil patches are subjected to different runoff nutrient supplements. This heterogeneity may also have shaped karst biodiversity.

Factors that influenced water input and export on outcrops' surface

Factors related to precipitation, forest canopy, and surface biomass of rock outcrops may have influenced the annual amount of water received and exported by outcrops. Canopies in China have been shown to intercept 11.4~34.3 % of precipitation. Near our study site, an evergreen forest in Tonghai County was shown to intercept 18.2 % of precipitation (Liu et al. 1991). If the precipitation in three ecosystems was parallel in time and equal in quantity, outcrops in a rock desertification ecosystem would receive more water than in the other two ecosystems; however, such did not seem to be the case (Figs. 2 and 3). Precipitation differences in different locations, and canopy modification of precipitation and related bias, may be the reason for this difference (Crockford and Richardson 2000; Gersper and Holowaychuk 1971; Gong et al. 2008; Jordan 1978) or the canopy that extends above the outcrops may not be as dense as those above the soil in other non-karst forest sites; thus, the interception of precipitation may not be very significant. In addition, organic matter accumulation on rock surfaces differed between the three ecosystems (Table 1), and epiliths like cyanobacteria and moss, rock fracture, and weathered condition are supposed to impact water redistribution on the rock surface because they divert runoff water. Several significant variations in the export to input water ratio between ecosystems in the same season (Table 2) might provide evidence of this influence. However, we still found non-significant differences in the ratio between ecosystems in the same season, and more importantly, the annual output water did not show significant difference among the three ecosystems (Fig. 2). Thus, we concluded that features of the rock outcrop surface played a weak role in water runoff. Rock slope may have played an important role since outcrops in the three ecosystems have steep slopes (Table 1), and kinetic energy generated from free fall on those steep slopes may have concealed the effect of runoff water retention by epilithic biomass. The effect of the pattern of rainfall was also weak in our study, as only a few significant differences were found between seasons in the same ecosystem (Fig. 3). The seasonal ratios (Table 2) were higher than the ratios of stem flow to precipitation for vegetation, which range from 0.0012 to 0.25:1 and which even paralleled the 0.49:1 ratio of corn (Chapin et al. 2011; Crockford and Richardson 2000).

Impact of outcrops' water redistribution in karst

Karst landscapes constitute approximately 12–15 % of the global terrestrial surface (Ford and Williams 2007). The physical and chemical properties of outcrops, the vegetation cover on and above rocks, and the precipitation may vary greatly in different karst regions. The quantity and proportion of water redistributed by outcrops in various karst ecosystems may not be the same as our case. However, the precipitation funneling effect of rock outcrops forms the basis for their ecological and biodiversity contributions, and should apply to all karst ecosystems, given the water and nutrient heterogeneities in soil patches formed under the impact of various outcrop proportions. In this regard, Clements et al. (2006) pointed out that karst outcrops and the rugged terrain formed "the ark of karst biodiversity."

Rock surface absorption, fissure loss, splash loss, and other hydrological processes may jointly contribute to the redistribution of precipitation received by rock outcrops. Tracing these may grant further insight into the functional role of rock outcrops in karst ecosystems. To evaluate the exact effect of runoff water on soil patches, changes in the soil moisture of soil patches may need to be monitored further, which would be another enormous undertaking.

Conclusion

Rock outcrops received a large amount of water, and approximately half of it was subsequently exported to nearby soil patches by means of rock runoff in Shilin. No significant difference was found among the three ecosystems in terms of annual water input and export. The ratio of water export to water input on the rock surface did not show a significant difference between ecosystems annually. Such factors as precipitation, vegetation canopy, and rock surface biomass are expected to have varying influences on the water input and export on the rock surface; however, the steep slopes of rock outcrops in our study may have concealed some of these effects. With the increase in the rock emergence ratio in the karst ecosystem, water redistribution by means of rock runoff not only supplements the soil with water and water-borne nutrients but also creates water content heterogeneity and nutrient heterogeneity in patchy soil, which may serve to explain the reason for karst biodiversity.

References

Aley TJ (1990) The karst environment and rural poverty. Ozarks Watch 4: 19–21

Bo L, Yang C, Peng L (2000) Ecology. Higher Education Press, Beijing (In Chinese)

Büdel B (1999) Ecology and diversity of rock-inhabiting cyanobacteria in tropical regions. Eur J Phycol 34:361–370. doi:10.1080/09670269910001736422

Chan Y, Lacap DC, Lau MC, Ha KY, Warren-Rhodes KA, Cockell CS, Cowan DA, McKay CP, Pointing SB (2012) Hypolithic microbial communities: between a rock and a hard place. Environ Microbiol 14:2272–2282

Chapin FS III, Chapin MC, Matson PA, Vitousek P (2011) Principles of terrestrial ecosystem ecology. Springer, New York

Chen J, Shi Z, Li L, Luo X (2009) Effects of soil thickness on spatiotemporal pattern of soil moisture in catchment level. Chin J Appl Ecol 20:1565–1570 (In Chinese)

Chen HS, Zhang W, Wang KL, Fu W (2010) Soil moisture dynamics under different land uses on karst hillslope in northwest Guangxi, China. Environ Earth Sci 61:1105–1111

Clements R, Sodhi NS, Schilthuizen M, Ng PKL (2006) Limestone karsts of Southeast Asia: imperiled arks of biodiversity. Bioscience 56: 733–742. doi:10.1641/0006-3568(2006)56[733:lkosai]2.0.co;2

Conn JS, Snyder-Conn EK (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):243–251

Crockford R, Richardson D (2000) Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrol Process 14:2903–2920

Custovic H, Misilo M, Markovic M (2014) Water balance of Mediterranean karst soil in Bosnia and Herzegovina as a water conservation and erosion control factor. Soil Sci Plant Nutr 60:100–107

Ford D, Williams PW (2007) Karst hydrogeology and geomorphology. John Wiley & Sons, Chichester, England

Gersper PL, Holowaychuk N (1971) Some effects of stem flow from forest canopy trees on chemical properties of soils. Ecology 52: 691–702

Gong H, Zhang Y, Liu Y, Yang G, Lu Z, Lu H (2008) Interception capability of in an evergreen broad-leaved forest of Ailaoshan, Yunnan Province. J Zhejiang Forestry Coll 25:469–474 (In Chinese)

Goransson H, Edwards PJ, Perreijn K, Smittenberg RH, Venterink HO (2014) Rocks create nitrogen hotspots and N:P heterogeneity by funnelling rain. Biogeochemistry 121:329–338

Hopmans JW (2006) Principles of soil and plant water relations. Vadose Zone J 5:506–506. doi:10.2136/vzj2005.0100br

Jordan CF (1978) Stem flow and nutrient transfer in a tropical rain forest. Oikos 31:257-263

Kidron GJ, Starinsky A (2012) Chemical composition of dew and rain in an extreme desert (Negev): cobbles serve as sink for nutrients. J Hydrol 420:284–291

Kirkham MB (2014) Chapter 10—field capacity, wilting point, available water, and the nonlimiting water range. In: Kirkham MB (ed) Principles of soil and plant water relations (second edition). Academic Press, Boston

Lavelle P (2001) Soil ecology. Kluwer Academic Publishers, Boston

Li C, Xiong K, Wu G (2013) Process of biodiversity research of karst areas in China. Acta Ecol Sin 33:192–200. doi:10.1016/j.chnaes.2013.05.005

Li S, Ren HD, Xue L, Chang J, Yao XH (2014) Influence of bare rocks on surrounding soil moisture in the karst rocky desertification regions under drought conditions. Catena 116:157–162

Liu WY, Liu LH, Zheng Z, Jin GF (1991) Preliminary study on hydrologic effect of evergreen broad-leaved forest and *Pinus yunnanensis* forest in Central Yunnan. Acta Phytoecologica et Geobotanica Sinica 15:150–167 (In Chinese)

Liu WJ, Li PJ, Duan WP, Liu WY (2014) Dry-season water utilization by trees growing on thin karst soils in a seasonal tropical rainforest of Xishuangbanna, southwest China. Ecohydrology 7:927–935

Osman KT (2013) Soils—principles, properties and management. Springer Netherlands

Sebela S, Slabe T, Liu H, Pruner P (2004) Speleogenesis of selected caves beneath the Lunan Shilin and caves of Fenglin karst in Qiubei, Yunnan. Acta Geol Sin-Engl 78:1289–1298

Shen YX, Liu WY, Li YH, Cui JW (2005) Community ecology study on karst semi-humid evergreen broad-leaved forest at the central part of Yunnan. Guihaia 25:321–326 (In Chinese)

Tian YP, Zhang J, Song LH, Bao HS (2002) A study on aerial cyanophyta (cyanobacteria) on the surface of carbonate rock in Yunnan Stone Forest, Yunnan Province, China. Acta Ecol Sin 22:1793–2020 (In Chinese)

Tian YP, Zhang J, Song LH, Bao HS (2003) A study on aerial algae communities on the surface of carbonate rock of the Yunnan Stone Forest. Carsologica Sinica 22:203–211 (In Chinese)

Wang JW, Zhou Y, Xiao X, Su LJ (2013) Progress of study on karst soil moisture characteristics of southwest China. Soil Water Conservation in China 2:37–41 (In Chinese)

Xu HQ, Liu WY, Shen YX, Liu LH, Li YH (2006) A preliminary study of epiphytes in semi-humid evergreen broad-leaved forest in stone forest karst region, Yunnan Province. Guihaia 26:43–48 (In Chinese)

Zhang FM, Geng H, Li YH, Liang YN, Yang YH, Ren J, Wang FC, Tao HL, Li ZD et al (1997) Study on the Lunan stone forest karst, China. Yunan Science and Technology Press, Kunming (In Chinese)

Zhang Z, Su Z, Wu Q, Li D (2005) Karst drought management. China University of Geosciences Press, Wuhan (In Chinese)

Zhang ZC, Chen X, Shi P, Ma JL (2008) Influences of rock on soil moisture distribution in the karst cluster-peach mountains. Bull Soil Water Conserv 28:42–44 (In Chinese)