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ORIGINAL ARTICLE

Response of soil physical and chemical properties to Rocky desertification succession in South China Karst

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Abstract Three typical karst rocky desertification regions in South China Karst were selected as experiment sites. The succession of karst rocky desertification was divided into five typical degrees: nil, potential, slight, moderate, and severe. Based on the five typical degrees of rocky desertification, sample plots were set up and soil samples were collected to examine the physical and chemical properties. The pattern, dynamics, and change law of soil physical and chemical properties in the succession of karst rocky desertification were studied. The properties of bulk density, capillary porosity, total porosity, field moisture capacity, capillary moisture capacity, pH, organic matter content, hydrolyzed nitrogen content, available phosphorus content, total potassium content, and soil respiration were studied. Results showed that significant differences in soil physical and chemical properties were observed among different degrees of rocky desertification. These properties initially degenerated and then recovered with increased degree of rocky desertification. The soil quality of nil and severe degree of rocky desertification was better than all others. In the succession of soil physical and chemical properties, the key factors were organic matter content, nitrogen content, bulk density, and moisture capacity. Finally, the response mechanism of soil succession was concluded. The results of this study are useful for management of desertified karst ecosystems.

Keywords Karst · Rocky desertification · Soil physical and chemical property · Succession · Control

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Introduction

Karst is a distinctive topography in which the landscape is largely shaped by the dissolving action of water on carbonate bedrock (usually limestone, dolomite, or marble). This geological process, occurring over many thousands of years, results in unusual surface and subsurface features ranging from sinkholes, vertical shafts, disappearing streams, and springs, to complex underground drainage systems and caves (Legrand 1973). South China Karst is the karst distributing region of South China, covering Guizhou, Guangxi, Yunnan, Sichuan, Hunan, Guangdong, Jiangxi, Hubei, and Chongqing provinces of China, with the total area of approximate 540,000 km^2. It is the largest region of bare carbonate rock among the three karst-concentrated distribution areas in the whole world. Moreover, South China Karst is an extremely fragile eco-environment system with large altitude gradient and complex landscape pattern formed from the Qinghai–Tibet Plateau uplifted in the South Asia Subtropical Climate Zone (Legrand 1973; Xiong et al. 2011). The area features a large number of mountain cover and a significant amount of rainfall. The soil layer is very thin, and the rate of soil formation is extremely slow with a high risk of soil erosion (Xiong et al. 2002). Thus, South China Karst is a very typical fragile ecological zone of non-zonality with serious land degradation (Zheng 2008; Zhang et al. 2010).

As a typical kind of land degradation, rocky desertification is one of the most threatening environmental issues in limestone areas resulting from serious soil erosion, extensive exposure of basement rocks, drastic decrease in soil productivity, and appearance of a desert-like landscape because of irrational and intensive land use on a fragile karst eco-environment, especially in warm tropical and subtropical karst mountain areas with abundant rainfall (Sweeting 1995; Wang et al. 1999; Wang 2005). At present, more than 100 million inhabitants live in the South China Karst area, including about 48 ethnic minorities experiencing poverty. Moreover, the contradiction between population and land resources is very distinct (Wang et al. 2002; Wang 2005). Once slope vegetation is destroyed, soil erosion acutely increases, leading to loss of the thin soil layer and the occurrence of rocky desertification with a rapid decrease in water and nutrient storage capacity of the ecosystem. Karst rocky desertification has become a serious ecological issue in South China Karst, gravely hindering the local sustainable development of economy and society (Wang 2005; Li et al. 2009).

Soil is a very important part of the terrestrial ecosystem with many ecosystem processes occurring in soil. Thus, soil research is important and indispensable in studies on the succession of plant community (Cai 1996). Studies on soil physical and chemical property changes in ecosystem succession under special environmental conditions can clarify the interactions and action mechanisms of different overground and underground parts in ecosystem evolution and can offer scientific basis for the artificial regulation of plant community succession (Wei et al. 2012; Kobza et al. 2004). Although the single ecology process of the karst ecosystem has been extensively studied (He et al. 2008; Zhang et al. 2011), reports on the soil physical and chemical properties of the karst ecosystem especially the pattern and change law in the process of rocky desertification succession are limited (Liu et al. 2009). The control of rocky desertification severely lacks scientific basis in terms of soil physical and chemical properties. Many scientific questions urgently need to be answered to elucidate the artificial rehabilitation of the karst rocky desertification ecosystem, such as the reverse effect of physical and chemical properties for artificial vegetation rehabilitation, among others. Accordingly, three typical rocky desertification regions in the South China Karst were selected as experiment sites in the present work. Based on the five typical degrees of rocky desertification (i.e., nil, potential, slight, moderate, and severe), the patterns, change law, and response mechanisms of soil physical and chemical properties in the process of rock desertification succession were studied to investigate the reverse effect of physical and chemical properties for artificial vegetation rehabilitation. The results can offer scientific basis for the rehabilitation of rocky desertification ecosystem and have important significance in the protection of the karst forest ecosystem.

Materials and methods

Experiment sites

Three typical rocky desertification regions in South China Karst were selected as experiment sites, namely, Salaxi (Site I), Hongfenghu (Site II), and Huajiang (Site III). The selection was based on climate, landform, degree of rocky desertification, vegetation, soil, and so on. The location and basic information of the three experiment sites are presented in Table 1 and Fig. 1.

Experiment site I is located at the rural area of Salaxi town with a distance of 13 km from Bijie city, Guizhou province, China and belongs to the Wujiang River Valley, a tributary of Yangtze River. At this site, a karst plateau mountain is the main landform, the terrain is large and undulating, and the altitude ranges from 1400 to 1742 m. The annual rainfall ranges from 618 to 995 mm, with an average of about 863 mm (rainfall dates originate from Guizhou Meteorological Bureau, China, the same below.). Rainfall is mainly distributed from July to September and accounts for 52 % of the total annual rainfall. Experiment site II is located at the rural area of Hongfeng town with a distance 12 km from Qingzhen city, Guizhou province, China and belongs to Wujiang River Valley. The landform is the typical karst plateau basin with moderate slopes and flat basin. The greatest relative height is about 180 m, with altitude ranging from 1271 to 1451 m. The annual average rainfall is about 1215 mm, mainly distributed in the period of April to August and accounting for 75 % of the total annual rainfall. Experiment site III is located on both sides of the Beipanjiang River with a distance of 10 km from Huajiang Town, Anshun City, China. The karst plateau gorge is the main landform. The greatest relative height is about 1000 m with altitude ranging from 450 to 1450 m. The annual average rainfall is about 1100 mm mainly distributed from May to October and accounts for 83 % of the total annual rainfall.

The rock and soil of these three sites are similar. The rock is mainly composed of limestone with partially distributed purple sand/(and) shale of Jurassic. The soil is mainly composed of terra fusca and purple soil. The

Table 1 Basic information of the three experiment sites and sample plots in the study

Experiment site	Location	Latitude and longitude of centre	Altitude (m)	Landform	Rock	Soil type	Vegetation	Sample plots	
								Sum and serial number of plots	Degree of rocky desertification
I	Salaxi, Bijie, China	27°15.08′N 105°21.263′E	1400–1742	Karst plateau mountain	Limestone with partially distributed purple sand/(and) shale of Jurassic	Terra fusca and purple soil	Subtropical evergreen and deciduous broad-leaved mixed forest, mainly secondary forest	6, I_1–I_6	Nil
								6, I_7–I_{12}	Potential
								6, I_{13}–I_{18}	Slight
								6, I_{19}–I_{24}	Moderate
								6, I_{25}–I_{30}	Sever
II	Hongfenghu, Guiyang, China	26°30.961′N 106°20.328′E	1271–1451	Karst plateau basin				6, II_1–II_6	Nil
								6, II_7–II_{12}	Potential
								6, II_{13}–II_{18}	Slight
								6, II_{19}–II_{24}	Moderate
								6, II_{25}–II_{30}	Sever
III	Huajiang, Anshun, China	25°39.40′N 105°39.042′E	450–1450	Karst plateau gorge				6, III_1–III_6	Nil
								6, III_7–III_{12}	Potential
								6, III_{13}–III_{18}	Slight
								6, III_{19}–III_{24}	Moderate
								6, III_{25}–III_{30}	Sever

vegetation of these three sites is investigated on the spot by authors. The vegetation is subtropical evergreen and deciduous broad-leafed mixed forest, and the forest is mainly a secondary forest because the original vegetation has basically been destroyed. In the natural vegetation community, the tree layer is mainly composed of species of genera *Cyclobalanopsis*, *Pinus*, *Betula*, and *Cupressus*. The shrub layer that has typical limestone characteristics is composed of species *Viburnum chinshanense*, *Pyracantha fortuneana*, *Pyracantha angustifolia*, *Ficus tikoua*, *Rosa multiflora*, *Rosa roxbunghii*, *Rubus corchorifolius*, *Rhamnus hemsleyana*, and so on. The common species of herbaceous layer are *Imperata cylindrical*, *Miscanthus floridulu*, *Miscanthus sinensis*, *Arthraxon hispidus*, and *Clematis florida*.

Rocky desertification classification

Xiong et al. (2002) proposed that the karst rocky desertification (KRD) should be classified from four factors: percentage of vegetation, slope, percentage of bare rock and average depth of top soil. According to the factor, this paper classified the KRD into five degrees, i.e., (1) nil rocky desertification (Nil RD); (2) potential rocky desertification (Pot RD); (3) slight rocky desertification (Sli RD); (4) moderate rocky desertification (Mod RD); (5) severe rocky desertification (Sev RD), and the threshold of each degree are listed in Table 2.

Soil sample collection

Aiming on these five typical degrees of rocky desertification (Fig. 2), 90 sample plots, each with an area of 20 × 20 m, were set up in the three experiment sites. In per experiment site, 6 sample plots for per degree of rocky desertification were set up, respectively. From 2008 to 2012, the plant diversity and the soil physical and chemical properties were studied in these ninety sample plots. Based on the classification standard of rocky desertification (Table 2), the rocky desertification degree of the ninety sample plots all did not change in the duration. Three sample points were selected using the S-shaped method at the center of each plot, and the distance between points is <5 m. Soil at each point was collected at about 0–15 cm depth in three replicates using ring knives and then mixed into the tested sample. The soil layer was very thin and about 15 cm depth in the rocky desertification ecosystem; thus, samples were collected only at a depth of 0–15 cm in this study.

Determination of soil physical properties

Bulk density was determined using the method of ring knives. Total porosity was calculated by the formula of

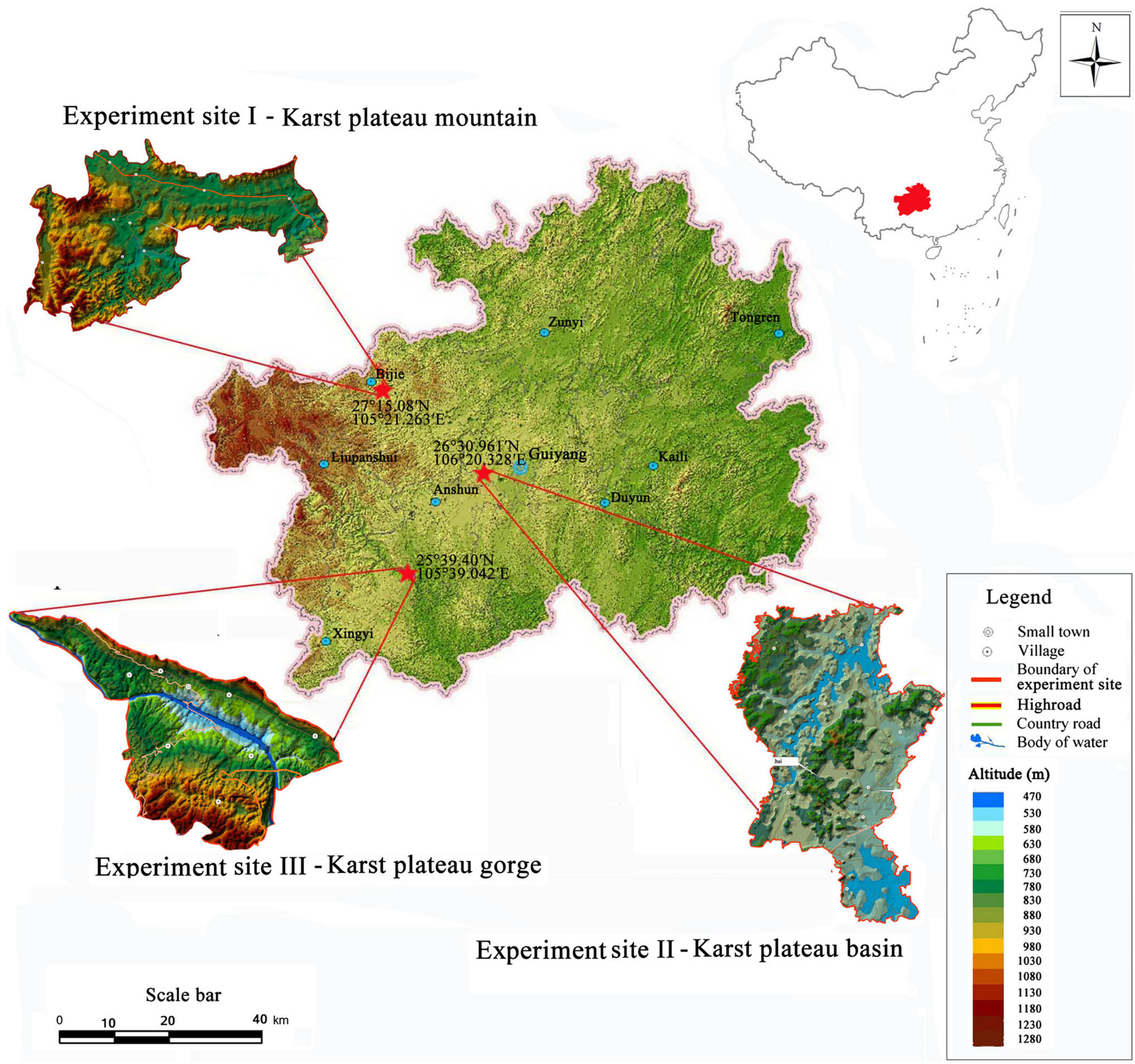

Fig. 1 Location and basic information of the three experiment sites studied

Table 2 Classification standard of Karst rocky desertification (Xiong et al. 2002)

	The standard of the Karst rocky desertification				
	Nil	Potential	Slight	Moderate	Severe
Percentage of vegetation (%)	>80	<80	<70	<50	<30
Slope (°)	<15	>15	>15	>20	>25
Percentage of bare rock (%)	<20	>20	>40	>60	>80
Average depth of top soil (cm)	>20	<20	<15	<10	<5

$p_t = 93.947 - 32.995 \times b$, where b is bulk density and p_t is total porosity. Capillary porosity was also determined using the method of ring knives, and non-capillary porosity was calculated by the formula of $p_o = p_t - p_c$, where p_o is non-capillary porosity and p_c is capillary porosity; Factors of soil moisture capacity and infiltration features were determined by the method of double-ring infiltration. All methods were as previously described by Ma (1994).

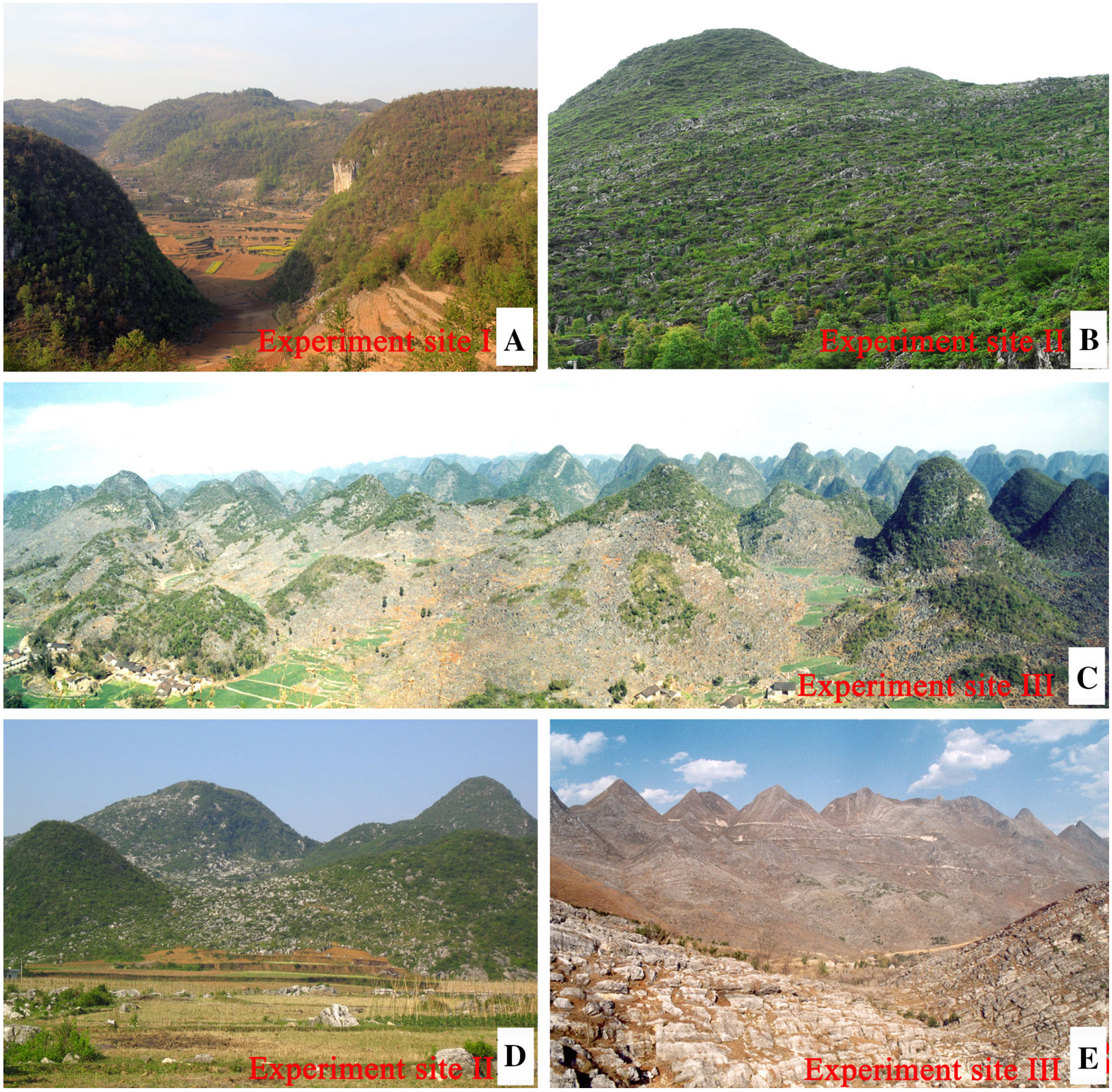

Fig. 2 Landscapes of karst rocky desertification (**a** nil rocky desertification; **b** potential rocky desertification; **c** moderate rocky desertification; **d** slight rocky desertification; **e** severe rocky desertification)

Determination of soil chemical properties

Soil pH (1:2.5 w/v in distilled water) was determined using a potentiometer. Organic matter content was determined by the potassium dichromate oxidation–ferrous sulfate titrimetry method (Nelson and Sommers 1982). Total nitrogen content was tested by the alkaline potassium persulfate digestion—UV spectrophotometric method, and hydrolyzed nitrogen was determined by the method of decomposed distillation by alkali (Bremmer and Mulvaney 1982). Total phosphorus and available phosphorus were determined using the Burriel–Hernando method (Díez 1982). Total potassium and available potassium were determined by the hydrofluoric acid perchlorate–flame photometer method and ammonium acetate–flame photometer method, respectively (Lu 1999). Soil respiration was monitored using a multiple-sensor respirometer (Micro-Oxymax, Columbus, OH, USA).

Data statistics

The variances in soil physical and chemical properties between different degrees of rocky desertification or different seasons were compared by one-way ANOVA, Duncan test, and *t* test. The correlation between soil physical and chemical properties was analyzed by the correlation analysis method. Principal component analysis (varimax rotation) of rocky desertification ecosystem was also conducted. All statistical analyses were conducted using SPSS16.0 software (Du 2009).

Results

Comparisons of soil physical and chemical properties between different degrees of rocky desertification.

Bulk density

Bulk density is an important parameter of soil compaction reflecting the permeability of air and water and the limit of plant root extension (Zheng et al. 1998). Comparisons of soil physical properties between different degrees of rocky desertification (Table 3) show significant differences in soil bulk density between different degrees of rocky desertification. Specifically, the soil bulk density of Pot RD (mean of 1.28 g/cm^3) is significantly greater than Mod and Sev RD (mean of 1.15 and 1.13 g/cm^3, respectively). No significant differences among Nil, Pot, and Sli RD (mean of 1.16, 1.28 and 1.18 g/cm^3, respectively) are observed.

Porosity

Soil porosity directly reflects the permeability of air and water, as well as the limit of plant root growth, which affects other soil factors (Liu and Huang 2005). Results of the present study (Table 3) show significant differences in soil porosity between different degrees of rocky desertification. Specifically, soil total porosity of Pot RD (mean of 52.56 %) is significantly less than that of Mod RD (mean of 57.48 %), and the soil capillary porosity of Pot RD (mean of 33.71 %) is significantly less than that of Sev RD (mean of 40.36 %). However, no significant difference exists in soil non-capillary porosity between different degrees of rocky desertification.

Moisture capacity

Results of the present study show no significant difference in soil natural moisture capacity between different degrees of rocky desertification, but significant differences exist in soil field moisture capacity and capillary moisture capacity between different degrees of rocky desertification (Table 3). The soil field moisture capacity of Pot RD (mean of 28.12 %) is significantly less than that of Sev RD (mean of 34.42 %), and soil capillary moisture capacity of Pot and Sli RD (mean of 35.09 and 36.96 %, respectively) are significantly less than that of Sev RD (mean of 45.06 %).

Infiltration features

Infiltration features reflect the ability of soil to transform surface runoff into interflow or groundwater runoff and obviously affect the soil function of water conservation and

Table 3 Soil physical properties of different degrees of rocky desertification

Degrees of rocky desertification	Bulk density[1] (g/cm^3)	Capillary porosity (%)	Non-capillary porosity (%)	Total porosity (%)	Natural moisture capacity (%)	Field moisture capacity (%)	Capillary moisture capacity (%)	Upper strata saturated permeability (mm/mim)	Lower strata saturated permeability (mm/mim)	*F* test
Nil	1.16 ± 0.11ab	38.13 ± 0.78ab	18.67 ± 0.31a	56.81 ± 2.11ab	28.57 ± 1.11a	33.17 ± 1.13ab	38.94 ± 1.31ab	11.00 ± 1.81a	3.74 ± 0.41a	**
Potential	1.28 ± 0.12a	33.71 ± 0.91a	18.92 ± 0.24a	52.56 ± 1.71a	23.90 ± 0.61a	28.12 ± 0.91a	35.09 ± 1.52a	8.91 ± 0.79a	6.96 ± 0.78a	
Slight	1.18 ± 0.12ab	36.35 ± 1.11ab	18.84 ± 0.67a	55.18 ± 2.01ab	24.55 ± 0.87a	29.10 ± 0.78ab	36.96 ± 1.41a	8.36 ± 1.23a	10.33 ± 1.23a	
Moderate	1.15 ± 0.13b	38.96 ± 0.88ab	17.69 ± 0.54a	57.48 ± 1.31b	27.25 ± 1.08a	30.65 ± 1.32ab	39.09 ± 1.76ab	15.67 ± 1.31a	8.80 ± 0.71a	
Severe	1.13 ± 0.10b	40.63 ± 1.12b	16.40 ± 0.51a	56.78 ± 1.21ab	26.04 ± 0.71a	34.42 ± 1.25b	45.06 ± 2.01b	12.34 ± 0.91a	5.33 ± 0.86a	

[1] There is no significant difference ($p > 0.05$) between degrees with same letter, and there are significant differences ($p < 0.05$) between degrees without same letter, ** indicates the extremely significant difference ($p < 0.01$)

soil fertility maintenance (Wu et al. 2004). Results of the study show no significant difference in the saturated permeability of soil upper and lower strata between the five different degrees of rocky desertification (Table 3).

Organic matter, pH, and soil respiration

Organic matter is an important component of soil and directly affects the soil physical, chemical, and biological properties. Furthermore, organic matter is the nutrition source of plant together with mineral substances (Liu and Huang 2005). The present results (Table 4) show that the soil organic matter content of Pot RD (mean 35.24 mg/kg) is significantly less than that of Nil RD (mean of 52.74 mk/kg). Moreover, no significant difference among Nil, Sli, Mod, and Sev RD (mean of 52.74, 47.48, 46.48, and 45.44 mk/kg, respectively) is observed. Comparisons of pH between different degrees of rocky desertification reveal that soil pH of Nil RD (mean of 6.18) is significantly less than that of Pot, Sli, Mod, and Sev RD (mean of 7.19, 7.49, 7.46, and 6.96, respectively); however, soil pH of Sev RD is <7, the same as the pH of nil RD. No significant difference in soil respiration is observed among different degrees of rocky desertification.

Nitrogen content

The total nitrogen content is the indicator of soil nitrogen nutrient, which generally reflects the availability of soil nitrogen supply (Lin et al. 2004). Additionally, the hydrolyzed nitrogen content can well reveal the short-term supply of soil nitrogen and the rate of soil nitrogen release. The present results (Table 4) reveal no significant difference in soil total nitrogen content between different degrees of rocky desertification. However, significant differences are observed in soil hydrolyzed nitrogen content among different degrees of rocky desertification. Specifically, the soil hydrolyzed nitrogen content of Nil and Mod RD (mean of 201.15 and 222.95 mg/g, respectively) is significantly greater than that of Pot RD (mean of 122.91 mg/g), and the soil hydrolyzed nitrogen content of Sev RD (mean of 138.46 mg/g) is significantly less than that of Mod RD (mean of 222.95 mg/g).

Phosphorus content

The total phosphorus content is an indicator of soil phosphorus types and is evidently affected by parent rocks and soil-forming processes. The total phosphorus content is also related to soil texture and organic matter (Ding et al. 2010). The present results (Table 4) reveal no significant difference in soil total phosphorus content between different degrees of rocky desertification; however, significant

Table 4 Soil chemical properties of different degrees of rocky desertification

Degrees of rocky desertification	pH	Organic matter content (mg/kg)	Total nitrogen content (g/kg)	Hydrolyzed nitrogen content (mg/g)	Total phosphorus content (g/kg)	Available phosphorus content (mg/kg)	Total potassium content (g/kg)	Available potassium content (mg/kg)	Soil respiration (co_2 mg g^{-1} h^{-1})	*F* test
Nil	6.18 ± 0.15a	52.74 ± 1.24a	2.90 ± 0.35a	201.15 ± 10.09ac	0.64 ± 0.02a	3.35 ± 0.23a	3.07 ± 0.45a	110.13 ± 9.01a	0.31 ± 0.03a	**
Potential	7.19 ± 0.23b	35.24 ± 1.54b	2.10 ± 0.24a	122.91 ± 8.90b	0.76 ± 0.04a	6.76 ± 0.21b	2.11 ± 0.46ab	106.12 ± 7.98a	0.12 ± 0.02b	
Slight	7.49 ± 0.27b	47.48 ± 1.32ab	2.88 ± 0.21a	191.33 ± 8.29ab	0.82 ± 0.02a	5.69 ± 0.34ab	1.65 ± 0.57b	92.03 ± 10.01a	0.13 ± 0.01b	
Moderate	7.46 ± 0.18b	46.48 ± 1.89ab	2.65 ± 0.56a	222.95 ± 9.46c	0.74 ± 0.03a	3.94 ± 0.55ab	1.47 ± 0.49b	96.03 ± 6.98a	0.06 ± 0.01b	
Severe	6.96 ± 0.16b	45.44 ± 1.67ab	2.60 ± 0.34a	138.46 ± 11.12ab	0.71 ± 0.03a	3.43 ± 0.34a	1.48 ± 0.23b	90.81 ± 9.07a	0.05 ± 0.01b	

** Indicates the extremely significant difference ($p < 0.01$)

differences in soil available phosphorus content are observed between different degrees of rocky desertification. Specifically, the soil available phosphorus content of Pot RD (mean of 6.76 mg/kg) is significantly greater than that of Nil and Sev RD (mean of 3.35 and 3.43 mg/kg).

Potassium content

Potassium is an important indicator of soil fertility that is the essential element of plant growth, especially the processes of photosynthesis, starch synthesis, and carbohydrate metabolism (Ding et al. 2010). Available potassium, a fraction of soil potassium, can be utilized in plant metabolism and accurately reflect the soil potassium supply. The present results (Table 4) reveal significant differences in soil total potassium content between degrees of rocky desertification. In particular, the soil total potassium content of Nil RD (mean of 3.07 g/kg) is significantly greater than that of Sli, Mod, and Sev RD (mean of 1.65, 1.47, and 1.48 g/kg, respectively). However, no significant difference is observed in the soil available potassium content between different degrees of rocky desertification.

Additionally, the comparisons also show that the variation of majority of soil physical and chemical properties, such as soil bulk density, capillary porosity, total porosity, field moisture capacity, capillary moisture capacity, pH, organic matter content, and available phosphorus content, appear the phenomenon of initial decrease and later increase with increased degree of rocky desertification.

Correlations of soil physical and chemical properties in the karst rocky desertification ecosystem

Correlation analysis of soil physical and chemical properties in the rocky desertification ecosystem reveals significant correlations between soil physical and chemical properties (Table 5). Organic matter content has extremely significant positive correlation with total nitrogen content, hydrolyzed nitrogen content, available potassium content, total porosity, natural moisture capacity, capillary moisture capacity, minimum moisture capacity, and upper strata saturated permeability; significant positive correlation with total phosphorus content and lower strata saturated permeability; and extremely significant negative correlation with bulk density. Meanwhile, total nitrogen content has extremely significant positive correlation with pH, organic matter content, total phosphorus content, hydrolyzed nitrogen content, available potassium content, total porosity, capillary moisture capacity, minimum moisture capacity, and upper strata saturated permeability; extremely significant negative correlation with bulk density; and significant positive correlation with available phosphorus content. Hydrolyzed nitrogen content has extremely significant positive correlation with organic matter content, total nitrogen content, total phosphorus content, total porosity, capillary moisture capacity, minimum moisture capacity, and upper strata saturated permeability; significant positive correlation with pH, available potassium content, and lower strata saturated permeability; and extremely significant negative correlation with bulk density. Correlation analysis results also reveal significant correlations of soil capillary moisture capacity, bulk density, and porosity with other soil physical and chemical properties. Thus, soil organic matter content, nitrogen content, capillary moisture capacity, bulk density, and porosity can be concluded as the key factors affecting soil physical and chemical properties that have important functions in improving soil physical and chemical properties and advancing the cycle of soil nutrient in the karst rocky desertification ecosystem.

Seasonal dynamic of soil physical and chemical properties in the rocky desertification ecosystem

Comparisons of soil physical and chemical properties determined in January and August of 3 years from 2012 to 2014 were analyzed by the *t* test (Table 6). Results reveal obvious differences in seven soil physical and chemical factors determined during different seasons, i.e., winter (January) and summer (August). Specifically, among soil physical properties, significant differences are observed in total porosity, and capillary moisture capacity, and extremely significant differences are observed in natural moisture capacity and capillary porosity between winter and summer. Soil total porosity and capillary moisture capacity in summer (mean of 57.235 and 40.127 %, respectively) are significantly greater than that in winter (mean of 53.303 and 35.951 %, respectively). Moreover, soil capillary porosity in summer (mean of 39.704 %) is extremely greater than that in winter (mean of 33.880 %), and natural moisture capacity in summer (mean of 23.478 %) is extremely less than that in winter (mean of 28.479 %). Among soil chemical properties, the differences in total potassium and available phosphorus content between summer and winter is significant, and the total potassium and available phosphorus content in summer (mean of 1.6982 g/kg and 3.942 mg/kg, respectively) is significantly less than the values in winter (mean of 2.5084 g/kg and 5.7723 mg/kg, respectively).

Principal component analysis of rocky desertification based on soil physical and chemical properties

Principal component analysis of karst rocky desertification was conducted based on 18 soil physical and chemical

Table 5 Correlation of soil physical and chemical properties in rocky desertification ecosystem

	X_1^I	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}
X_2	0.096	1.0000																
X_3	0.356**	0.834**	1.0000															
X_4	0.496**	0.270*	0.533**	1.0000														
X_5	−0.393**	0.051	−0.105	−0.149	1.0000													
X_6	0.224*	0.749**	0.757**	0.331**	−0.177	1.0000												
X_7	0.525**	0.056	0.243*	0.581**	−0.073	−0.020	1.0000											
X_8	−0.037	0.427**	0.377**	0.149	0.225*	0.249*	0.409**	1.0000										
X_9	−0.295	0.105	0.224	0.100	0.537**	0.166	−0.095	0.227	1.0000									
X_{10}	−0.64	−0.504**	−0.509**	−0.143	0.005	−0.550**	0.120	−0.199	−0.217	1.0000								
X_{11}	−0.004	0.355**	0.396**	0.091	−0.054	0.464**	−0.197	0.184	0.249	−0.781**	1.0000							
X_{12}	0.114	0.098	0.142	0.135	−0.036	0.214	−0.145	−0.070	0.208	−0.348**	0.351**	1.0000						
X_{13}	−0.101	0.215	0.206	−0.029	0.006	0.178	−0.013	0.215	0.010	−0.322**	0.447**	−0.667**	1.0000					
X_{14}	−0.231	0.335**	0.169	−0.098	0.215	0.203	−0.015	0.200	0.170	−0.306**	0.213	−0.243*	0.393**	1.0000				
X_{15}	0.183	0.497**	0.561**	0.234*	−0.158	0.545**	0.016	0.280*	0.153	−0.742**	0.702**	0.288*	0.297**	0.184	1.0000			
X_{16}	0.112	0.544**	0.533**	0.215	0.007	0.485**	0.063	0.379**	0.262	−0.642**	0.523**	0.259*	0.195	0.204	0.844**	1.0000		
X_{17}	−0.008	0.376**	0.334**	0.095	−0.078	0.420**	−0.052	0.296*	0.064	−0.405**	0.446**	−0.139	0.483**	0.166	0.466**	0.349**	1.0000	
X_{18}	0.100	0.292*	0.225	0.025	−0.165	0.293*	0.007	−0.006	−0.103	−0.226	0.265*	−0.216	0.406**	0.197	0.267*	0.064	0.591**	1.0000

X_1 pH, X_2 organic matter content, X_3 total nitrogen content, X_4 total phosphorus content, X_5 total potassium content, X_6 hydrolyzed nitrogen content, X_7 available phosphorus content, X_8 available potassium content, X_9 soil respiration, X_{10} bulk density, X_{11} total porosity, X_{12} capillary porosity, X_{13} non-capillary porosity, X_{14} natural moisture capacity, X_{15} capillary moisture capacity, X_{16} field moisture capacity, X_{17} upper strata saturated permeability, X_{18} lower strata saturated permeability

^{I} : *, ** Indicate the significant difference at $\alpha = 0.05$, and 0.01, respectively

Table 6 Comparison of soil physical and chemical properties determined in different seasons of summer (August) and winter (January) from 2012 to 2014 year

Soil physical and chemical properties	Summer (August)			Winter (January)			*t* value
	N	Mean	Std. error Mean	*N*	Mean	Std. error Mean	
Bulk density (g/cm^3)	111	1.1561	0.0282	111	1.1395	0.0235	−0.051
Capillary porosity (%)	111	39.680	1.2280	111	33.812	0.7218	4.091**
Non-capillary porosity (%)	111	17.301	1.3778	111	19.568	0.8813	−1.370
Total porosity (%)	111	57.213	0.9750	111	53.276	0.8199	3.079*
Natural moisture capacity (%)	111	23.471	1.4066	111	28.483	1.2234	−2.665**
Field moisture capacity (%)	111	31.850	1.1282	111	29.312	1.0566	1.589
Capillary moisture capacity (%)	111	40.135	1.1890	111	35.972	1.3998	2.265*
Upper strata saturated permeability (mm/mim)	114	10.819	1.5735	114	10.698	1.3388	0.037
Lower strata saturated permeability (mm/mim)	114	6.8180	1.3921	114	6.7205	1.2986	0.050
pH	117	7.0035	0.1498	117	7.0001	0.1535	0.005
Organic matter content (mg/kg)	117	43.078	3.2489	117	46.210	3.1188	−0.598
Total nitrogen content (g/kg)	117	2.5212	0.1995	117	2.6301	0.1982	−0.380
Total phosphorus content (g/kg)	117	0.7350	0.0533	117	0.7185	0.0502	0.249
Total potassium content (g/kg)	117	1.6971	0.1608	117	2.5080	0.2702	−2.551*
Hydrolyzed nitrogen content (mg/g)	117	172.98	15.1590	117	169.25	13.6230	0.336
Available phosphorus content (mg/kg)	117	3.9412	0.4989	117	5.7651	0.6952	−0.076*
Available potassium content (mg/kg)	117	95.504	3.7386	117	106.98	5.3439	−1.785

* Indicates the significant difference ($p < 0.05$), ** indicate the extremely significant difference ($p < 0.01$)

factors. The eigenvalue, percentage, and cumulative percentage of the 18 factors are also obtained and presented in Table 7. The obtained cumulative percentage of components 1, 2, and 3 is 96.21 %, indicating that these components hold predominant information on rocky desertification of the 18 factors and can serve as bases for evaluating the characteristics of rocky desertification. In principal component 1, the weight coefficient of organic matter content, total nitrogen content, hydrolyzed nitrogen content, total potassium content, available potassium content, bulk density, minimum moisture capacity, natural moisture capacity, and capillary moisture capacity is greater, indicating that principal component 1 mainly presents information on organic matter content, nitrogen content, potassium content, bulk density, and moisture capacity of rocky desertification. In principal component 2, the weight coefficient of capillary porosity, non-capillary porosity, lower strata saturated permeability, and pH is greater, indicating that principal component 2 mainly presents information on soil pH, porosity, and infiltration features of rocky desertification. In principal component 3, the weight coefficient of soil respiration, total phosphorus content, and available phosphorus content is greater, indicating that principal component 3 mainly presents information on soil respiration and phosphorus content of rocky desertification.

Discussion

Response of soil physical and chemical properties to rocky desertification succession

Pedogenesis is a very complex process affected by many factors such as climate, vegetation, landform, parent rock, and so on. Moreover, soil constantly changes with the succession of plant vegetation (Kang et al. 2010). In the present study, results reveal no significant difference in total nitrogen content (mean range of 2.10–2.90 g/kg), total phosphorus content (mean range of 0.64–0.82 g/kg), and available potassium content (mean range of 90.81–110.13 mg/kg) between different degrees of rocky desertification, suggesting that the soil physical and chemical properties are evidently affected by the parent rock of carbonate.

Generally, the positive succession of plant community is the process of soil nutrient accumulation and soil physical property improvement, and the negative succession is the process of soil degeneration (Kang et al. 2010). Degeneration of the karst fragile ecosystem driven by strong human activities and caused by destruction of vegetation is a very complex process concentrated on soil productivity degeneration and represented by desertification landscapes (Wei et al. 2012). Soil degradation is believed to increase with

Table 7 Principal component analysis of rocky desertification based on soil physical and chemical properties

Soil physical and chemical properties	Principal components		
	1	2	3
Bulk density	−0.876	0.032	−0.481
Capillary porosity	0.003	−0.919	0.386
Non-capillary porosity	0.000	0.988	−0.130
Total porosity	0.008	0.814	0.579
Field moisture capacity	0.834	−0.329	−0.401
Natural moisture capacity	0.785	0.507	−0.229
Capillary moisture capacity	0.747	−0.458	0.417
Upper strata saturated permeability	0.403	0.442	0.776
Lower strata saturated permeability	−0.399	0.896	0.173
pH	−0.083	−0.813	0.555
Organic matter content	0.996	0.036	−0.066
Total nitrogen content	0.974	−0.032	0.152
Hydrolyzed nitrogen content	0.814	0.188	0.450
Available phosphorus content	0.506	0.088	−0.855
Total phosphorus content	−0.028	0.632	0.661
Total potassium content	0.911	−0.160	−0.381
Available potassium content	0.802	0.446	−0.349
Soil respiration	−0.228	0.185	−0.907
Eigenvalue	7.349	5.422	4.546
Percentage (%)	40.829	30.125	25.253
Cumulative percentage (%)	40.829	70.953	96.206

increased degree of rocky desertification, and soil degradation in high rocky desertification is considered as the most serious (Xiong et al. 2011; Luo et al. 2011; Liu et al. 2005). However, these assumptions are false. Results of the present study reveal that both physical and chemical properties do not always degenerate with increased degree of rocky desertification. Instead, majority of properties initially degenerate and then improve. The observed results can be attributed to the action of soil nutrients accumulated by exposed rocks in the rocky desertification ecosystem (Fig. 3). Exposed rocks do not absorb and save nutrients from atmospheric sedimentations, rock corrosions, vegetation litters, and so on. These nutrients of exposed rock surface only can be washed into surrounding soils by rain or wind, which is the significant action resulting in the increase of soil nutrients content by exposed rocks.

With increased degree of rocky desertification, the action process of soil nutrients accumulated by exposed rocks remarkably increases because of the increase of exposed rocks and soil erosion decreases because of the decrease of soils that can be washed away. In severe degree of rocky desertification, on one hand, soil erosion is weak because of the limited amount of soil that can be washed away, which in turn results in limited soil nutrient loss, and on the other hand, the action process of soil nutrients accumulated by exposed rocks become stronger resulting in more increase of nutrient content. Consequently, the soil nutrient and physical and chemical properties of degenerative soil are improved. Principal component analysis of this study show that organic matter content, nitrogen content, bulk density, and moisture capacity are the key factors affecting soil physical and chemical property in the soil succession of rocky desertification. Accordingly, the change law and mechanism of soil physical and chemical properties in the rocky desertification process can be concluded as follows (Fig. 4): once vegetation is destroyed in the karst ecosystem, rocky desertification begins to occur. At the onset, soil erosion is very strong and soil nutrient is critically washed away. Additionally, the organic matter decreases because of the decrease in plant litters. All aforementioned events result in soil degeneration. With the constant increase in rocky desertification degree, the supply of soil nitrogen and organic matter increases because of the remarkable increase in soil nutrients accumulated by exposed rocks. Concurrently, soil erosion weakens because of the limited amount of soil that can be washed away and the very weak loss of soil nutrient. All aforementioned events result in the improvement of soil physical and chemical properties in the severe degree of rocky desertification ecosystem.

Contribution of this study to the control of rocky desertification

Results of this study reveal that the succession of soil physical and chemical properties initially degenerates and then recovers with increased degree of rocky desertification. Moreover, the soil quality in no and high rocky desertification is significantly better than other

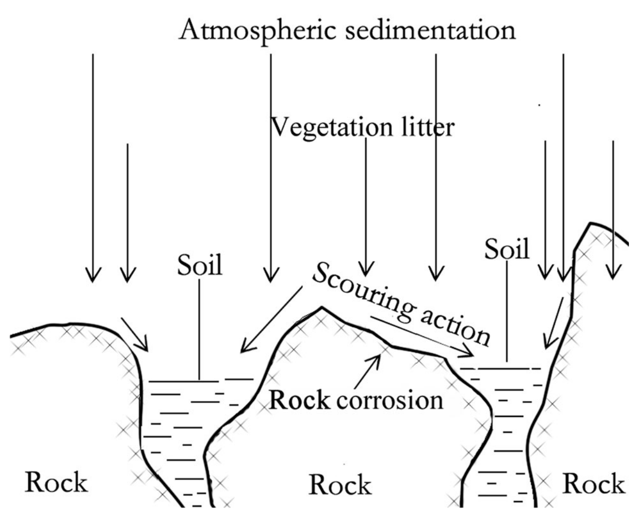

Fig. 3 The mechanism of soil nutrients accumulated by exposed rocks in rocky desertification ecosystem

desertification degrees, which suitably explains the top succession of forest community in the karst bare rocky mountains and completely differs from the traditional opinion that the soil of Karst rocky desertification always degenerates with increased degree of rocky desertification, and the soil of high rocky desertification is the most degenerate (Xiong et al. 2011; Luo et al. 2011; Liu et al. 2005). Soil is known to be a vital part of the terrestrial ecosystem where many ecosystem processes occur. Thus, the results of this study have extremely important value in the rehabilitation of the rocky desertification ecosystem.

Karst rocky desertification is a serious ecological issue that severely restrains regional economic development and societal stabilization in the South China Karst region. Karst rocky desertification also hinders the achievement of the Chinese national strategic objective of well-off society building (Wang 2005; Liu et al. 2009; Peng and Lu 2003). Since 2008, the control of rocky desertification has become a central objective in Chinese national economy construction and society development, with numerous inputs of manpower and material resources (Xiong et al. 2011; Wang 2005). The control results are very unsatisfactory, which can be attributed to the considerable lack of scientific studies on the soil of a rocky desertification ecosystem (Liu et al. 2005; Zhu 2003; Yao et al. 2001) resulting in a number of control technical measures only obtained from past experiences and practices of rocky desertification rehabilitation. For example, the vegetation of high rocky desertification has long been thought to be rehabilitated only by the measure of closed forest, and artificial afforestation is believed to be impossible in high rocky desertification surroundings, which is even stated in some local control regulations of karst rocky desertification (Xiong et al. 2011). By contrast, the present results discredit these false assumptions. The soil quality of high rocky desertified area is better than that of potential or low degree of rocky desertification, and vegetation rehabilitation can be completely carried out through artificial afforestation in some areas with thicker soil layer, which is well supported by many control practices. For example, successful breeding of the plant of *Zenia insignis*, a high tree, has been carried out in the vegetation rehabilitation of high rocky desertification in Huajiang, Guizhou province, China. By contrast, the soil of potential or low degree of rocky desertification is more infertile. Thus, successful rehabilitation of vegetation through artificial afforestation is very difficult, which has also been supported by a number of control practices carried out (Xiong et al. 2011).

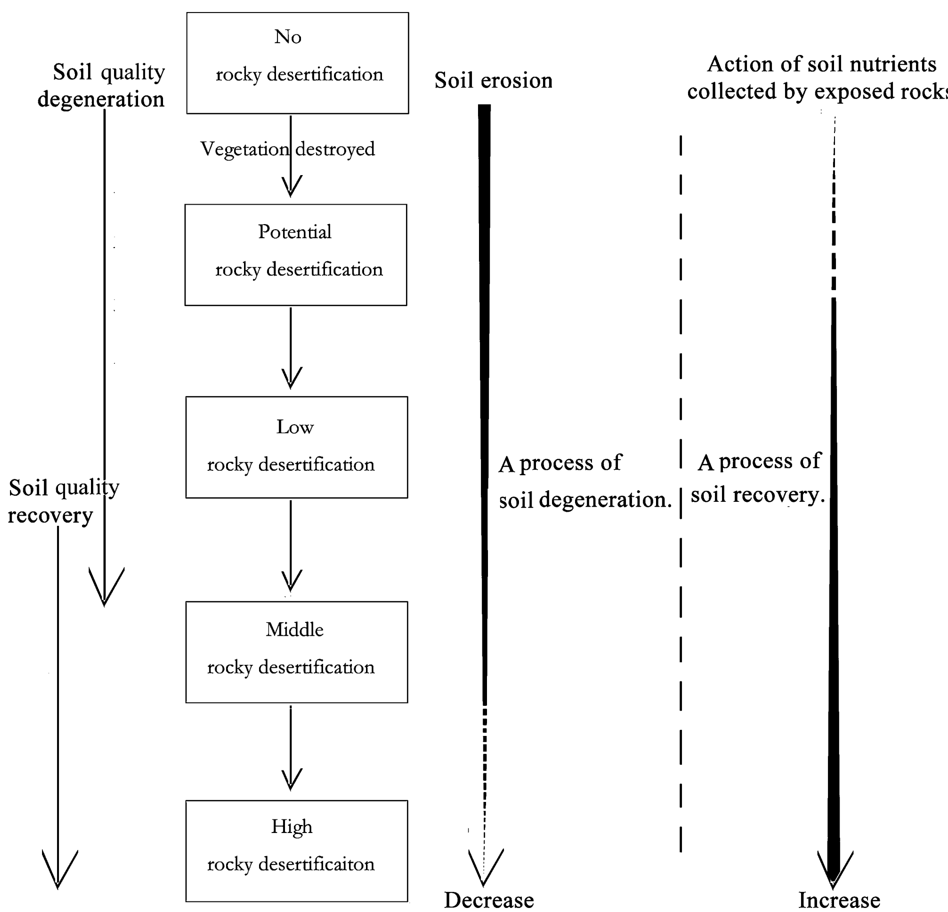

Fig. 4 Change law and mechanism of soil physical and chemical properties in rocky desertification process

The control of rocky desertification is very complex and integrates engineering with multiple departments of forestry, agriculture, water conservation, and so on (Xiong et al. 2011; Peng and Lu 2003; Su 2002). However, the technical measures of rocky desertification control has long been summarized from previous experiences of vegetation rehabilitation and lacks the support of systematic studies on soils of the rocky desertification ecosystem, thereby resulting in different summaries from different regions, departments and experts that are in conflict with the technical measures for rocky desertification control (Xiong et al. 2011; Su 2002; Du et al. 2011). Consequently, this non-standardized technical measurement hinders the scientific control of rocky desertification. For example, a number of controversies are imminent in the growing of plant species need significant amounts of water and nutrients, such as *Pennisetum hydridum* and *Lonicera Japonica*, in the vegetation rehabilitation of high rocky desertification. Many people including some experts in rocky desertification control believe that growing these plants is impossible because of the poor soil quality of high rocky desertification. The present results discredit this idea. Similarly, previously conducted rocky desertification controls also prove this idea wrong (Xiong et al. 2011). Such controls conducted in many regions of South China Karst including Anlong, Xingyi, Guanling, and Zhengfen (Xiong et al. 2011) demonstrate that the aforementioned plant species can grow well in high rocky desertification, which also strongly support the present results demonstrating that soil initially degenerates and then recovers with increased degree of rocky desertification, and that the soil quality of high rocky desertification is high.

Conclusions

There are significant differences of soil physical and chemical properties among different degrees of rocky desertification. With increased degree of rocky desertification, these properties initially degenerated and then recovered. And the soil quality of nil and severe degree of rocky desertification were better than all others. In the succession of soil physical and chemical properties, the key factors were organic matter content, nitrogen content, bulk density, and moisture capacity.

The exposed rocks in rocky desertification ecosystem have obvious positive action on soil nutrients accumulated. Based on this theory, the change mechanism of soil physical and chemical properties in rocky desertification process was come up by authors: At the onset of rocky desertification, soil erosion is very strong and soil nutrient is critically washed away. Additionally, the organic matter decreases because of the decrease in plant litters. So the soil degenerates. With the constant increase in rocky desertification, the supply of soil nitrogen and organic matter increases because of the remarkable increase of soil nutrients accumulation action by exposed rocks. Concurrently, the loss of soil nutrient becomes weak because the soil erosion weakens. Accordingly, the soil physical and chemical properties improve in the severe degree of rocky desertification ecosystem.

The soil quality of high rocky desertified area is better than that of potential or low degree of rocky desertification, and vegetation rehabilitation can be completely carried out through artificial afforestation in some areas with thicker soil layer. By contrast, successful rehabilitation of vegetation through artificial afforestation is very difficult beacause the soil of potential or low degree of rocky desertification is more infertile. The results of this study are useful for management of desertified karst ecosystems.

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