

southwestern China (Huang and Cai, 2007; Xiong et al., 2009). Climate changes and anthropogenic driving forces are responsible for the development of aeolian/sandy desertification (T. Wang et al., 2013; X. Wang et al., 2013) which can cause dust storms (Wang and Jia, 2013), soil and water losses (Cerdà and Lavée, 1999), and are also playing important roles in the aggravation of karst rocky desertification (Y. B. Li et al., 2009b; Yan and Cai, 2013). This has gradually attracted the national-wide attention in China, and the government and researchers are taking active measures to meliorate rocky desertification land by sustainable management (Bai et al., 2013; Huang et al., 2008).

For example, to enforce the sustainable management of karst lands, in 2011, a *Monitoring Rules of Rocky Desertification in Hunan Province* had been issued by Hunan Provincial Bureau of Forestry, in which rocky desertification (RD) was classified into 4 grades, namely potential RD (PRD), light RD (LRD), moderate RD (MRD), and intensive RD (IRD) based on the soil depth, vegetation coverage, vegetation type and bedrock exposure according to some reported classification methods (Wang et al., 2004a; Xiong et al., 2009) with minor modifications. The changing process of karst land from one grade to another was called succession of RD here and elsewhere (Xie and Wang, 2006), which means an observable process of changes of karst ecosystem such as vegetation type, vegetation coverage, bedrock exposure, and soil depth from PRD to IRD orderly or vice versa. Furthermore, on stands investigation, we found that some karst regions with higher grades (MRD or IRD) had been enclosed for afforestation. These measures are beneficial to rehabilitation and sustainable management of karst lands.

In the process of sustainable management, it is important to determine the status of soil quality on karst regions (Deng and Jiang, 2011; Li et al., 2013), because the soil quality is of fundamental importance for agricultural production and soil fertility management (irrigation, fertilization, and cultivation) (Fallahzade and Hajabbasi, 2012), and it is also a central issue in the decisions on food security, poverty reduction and environment management (Tilman et al., 2002). Soil fertility is a major component

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of soil quality, so investigation on soil fertility could be regarded as an essential prerequisite to rationally management and utilization of karst lands. However, soil fertility changes associated with the succession of RD in the karst lands have been poorly understood (Wang and Li, 2007) due to lacking of method how to evaluate the soil on areas affected by RD. Especially, using a minimum dataset to reduce the need for determining a broad range of indicators to assess soil fertility (Yao et al., 2013) of karst lands during succession of RD have not been achieved at present.

The soil fertility depends on local climate, soil-forming conditions, eco-environment, and anthropogenic influence in different regions (Liu et al., 2006). Choosing appropriate indicators is vital to evaluate soil fertility. Those indicators that influence plant growth should be included into evaluating system. Generally, evaluating indicators are chosen empirically based on the researching fruits of predecessors. But the adaptability of soil fertility indicators should be paid close attention to karst area due to its fragile ecosystem (Fu et al., 2010). Based on the analyses of literatures and suggestions from experts on the stands investigation, we evaluated soil fertility of karst lands using 19 selected indicators.

In order to avoid information overlapping from high-dimensional datasets, dimension reduction is usually performed to get a minimum dataset. Principal component analysis (PCA) is regarded as a statistical procedure using dimension reduction to convert a set of observations with possibly correlated variables into a set of linearly uncorrelated variables called principal components (Liu et al., 2003).

The objectives of this work were: (i) to clarify how 19 selected soil fertility indicators are affected by the succession of rocky desertification, and (ii) to identify some reasonable and sensitive indicators to evaluate soil fertility of karst lands with different RD grades.

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PRD were lower than fertility scores of LH2 and LY2 for LRD, and fertility scores of LH3, XH3 and XS3 for MRD. Fertility scores of LY4 and SD4 for IRD were far lower than those of other sites. In summary, integrated fertility scores fluctuated with different sampling sites for different RD grades.

To facilitate comparison, the means of integrated fertility scores were calculated (Fig. 2). The sequencing of the mean scores was PRD > MRD > LRD > IRD. The difference between fertility scores of PRD and those of IRD was very significant ($p = 0.008$), and the difference between fertility scores of LRD and those of IRD was significant ($p = 0.023$). However, fertility scores of PRD vs. LRD ($p = 0.622$), PRD vs. MRD ($p = 0.160$), LRD vs. MRD ($p = 0.692$), and MRD vs. IRD ($p = 0.416$) were not significantly different.

3.3 Correlation of integrated fertility scores with evaluating indicators

We analyzed the correlation of integrated soil fertility scores with the 19 evaluating indicators (Table 5). The results demonstrated that the integrated fertility scores were strongly and significantly correlated to TOC, TN, TP, CEC, MBC, MBN, MBP and BD ($p < 0.01$), were significantly correlated to TK, AK, FUN, FMC, and TOP, but were insignificantly correlated to pH, AP, BAC, ACT, CMC, and CAP.

4 Discussions

4.1 Effects of succession of RD on soil fertility

Soil fertility, as the basis of soil quality, directly affects the productivity of land. In return, land use type and frequency influence the soil quality (Ozgoz et al., 2013). The aggravation of RD is not only caused by anthropogenic factor (land overuse), but also by climate (S. Li et al., 2009). Degradation of phytocommunity (tree → tree/shrub → shrub → shrub/grass → grass) results in homogenized community structure, decrease of biomass and litter fall, and reduction of plant nutrition such as soil

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organic matter, total N and so on. The altered soil ecosystem leads to microorganism population reducing and microbial degradation of litter fall decreasing, so that C, N, and P retentions in soil decrease (Lu et al., 2014). First two components (Table 4) were identified as “*water/air permeability and water-holding capacity component*” and “*organic matter component*”, so water/air permeability, water-holding capacity, and organic matter content would be affected strongly by the aggravation of RD. Thus, the aggravation of RD leads to soil hardening, bulk density enlarging, water/air permeability worsening, and water-holding ability of surface soil decreasing would happen, then the strong surface runoff causes great loss of N, P, and K nutrients (Peng and Wang, 2012). In one word, multiple affects above eventually lead to integrated soil fertility decreasing with the aggravation of RD.

4.2 Discordance between soil fertility level and RD grade

Soil fertility fluctuated remarkably with different sampling sites and with different RD grades. Soil fertility levels were not always consistent with RD grades, for instance, the average fertility of MRD was greater than that of LRD (Fig. 2). This might be ascribed to: (i) the classification method of RD is not so satisfactory as expected. The actual soil fertility could not be only explored from soil depth, vegetation coverage, bedrock exposure and vegetation type. For some karst areas (MRD or IRD), although their vegetation covers are less than those of LRD, their surface fertile soil might accumulate in a low-lying zone when eroded by rainfall chronically, hence some soil with higher RD grade would have greater fertility, (ii) difference of soil fertility also caused by regional variation. Local climate, soil-forming conditions, and the way and extent of anthropogenic intervention were different from one region to another (Clemens et al., 2010). Soil fertility in one region for MRD might be greater than that in another region for LRD. When we investigated on stands, we found that the majority of PRD regions had better vegetation because they had been enclosed for afforestation to avoid anthropogenic interference. Most of IRD regions became abandoned land without any agricultural production due to seriously degrading soil fertility. In contrast, both LRD

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and MRD regions with moderate fertility were not strictly protected. Perhaps residue burning had caused degradation of tree/shrub to shrub/grass or animal grazing had led to residue mineralization, recycling of faeces, and incrementing soil nutrients. They were usually utilized to cultivate timber forests or non-wood forests. As a result, the anthropogenic interference to LRD or MRD certainly reached the highest level. Human activity is one of key driving factors of RD (Y. B. Li et al., 2009; Xiong et al., 2009), and RD grade varies among land use types (Li et al., 2006). Thus, reducing human activities and taking measurements such as mountain closure, forest reservation and plantation might be definitely important to control expanding of RD area, which could be learned from natural vegetation rehabilitation to control soil erosion on the Loess Plateau (G. Zhao et al., 2013a; X. Zhao et al., 2013), (iii) self-organization of soil environment improves soil fertility. With gradual deterioration of soil fertility, soil animals and microorganism at some stage (MRD) increase the speed of litter fall breakdown by disintegrating tissue and fixing the nutrients to acclimate the degrading environment (Barot et al., 2007). Thus, the fertility of MRD soil is likely greater than that of LRD soil.

4.3 Sensitive indicators to evaluate soil fertility in RD lands

Selecting appropriate indicators will guarantee the accuracy of evaluating results. Generally, evaluating indicators are chosen empirically based on the researching fruits of predecessors. Some physiochemical (Ozgoz et al., 2013), microbial biomass (Paz-Ferreiro and Fu, 2013), and enzymatic activity properties (Pajares et al., 2011) had been chosen to assess the soil quality. On the basis of scientific reliability, defining a minimum dataset for evaluating soil fertility can cut down the number of indicators and reduce evaluating cost.

Soil organic matter (used interchangeably with TOC), as the major source of several nutrients, exerts numerous positive effects on soil physiochemical properties, as well as soil's capacity to provide regulatory ecosystem services. N, P, and K are often referred to the primary macronutrients in soil for plants' growth. CEC is used as a measure of fertility and nutrient retention capacity. BD, as an indicator of soil compaction, reflects

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the loosen extent and permeability of soil. MBC, MBN, and MBP, reflects the number and activity of soil microorganism, and the status of soil environment, although they only have a little content in soil with the mean ratios of MBC to TOC (0.61%), MBN to TN (2.16%), and MBP to TP (0.95%) in this study (extracting from Table 2). It was reported that the microbial activity directly influences soil ecosystem stability and fertility (Pascual et al., 1997). Soil biochemical, microbiological and biological properties are more suitable than physical and/or chemical properties to estimate soil quality and soil degradation (Paz-Ferreiro and Fu, 2013). And it is widely recognized that a good level of microbiological activity is crucial for maintaining soil quality (de la Paz Jimenez et al., 2002; Pascual et al., 2000; Visser and Parkinson, 1992), because microbial turnover is a driving force for transformation and cycling of organic matter to plant nutrients in soils (Chen and He, 2002; Fontaine et al., 2003). For instance, the changes in MBC is a sensitive index of changes in the content of soil organic matter (García-Orenes et al., 2010; Powlson et al., 1987), and it is useful for determining microbial population size to evaluate natural and degraded systems (Soulas et al., 1984). The strong and positive correlation between MBC and TOC (Table 3) indicated that MBC was a sensitive index to indicate the dynamics of soil organic carbon (Liu et al., 2012). Inorganic N and P needed by vegetation are mainly obtained from mineralization of organic matter in soil microbial degradation system (Hopkins et al., 2011; Ros et al., 2011). The changes in MBN and MBP can also indicate the fluctuation of soil fertility (Powlson et al., 1987). Thus, these indicators deserve pre-researching before getting a minimum dataset.

Furthermore, TOC, TN, TP, CEC, MBC, MBN, MBP, and BD were strongly and significantly correlated to the integrated soil fertility ($p < 0.01$) (Table 5). But TN was highly correlated to TOC with $r = 0.936$ (Table 3). Thus, we can put forward that TOC, TP, CEC, MBC, MBN, MBP, and BD might be reasonable and sensitive indicators to estimate soil fertility in RD region. They could be included in the minimum dataset of evaluating indicators for RD.

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Table 5. Correlation analysis of integrated fertility scores (*F*) with soil indicators.

	pH	TOC	TN	TP	AP	TK	AK	CEC	MBC	MBN
<i>F</i>	0.111	0.497 ^b	0.571 ^b	0.465 ^b	-0.105	0.145 ^a	0.179 ^a	0.764 ^b	0.503 ^b	0.480 ^b
	MBP	BAC	FUN	ACT	BD	CMC	FMC	CAP	TOP	
<i>F</i>	0.445 ^b	0.424	-0.295 ^a	-0.091	-0.679 ^b	0.449	0.528 ^a	0.077	0.679 ^a	

^a Significant (two-tailed) at $p \leq 0.05$ level.
^b Significant (two-tailed) at $p \leq 0.01$ level.

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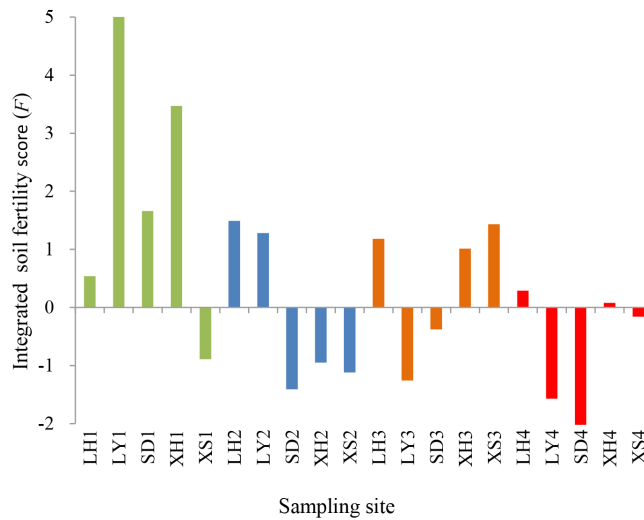


Figure 1. Integrated soil fertility scores of 20 studied plots. LH, LY, SD, XH, and XS are the sampling plots standing for Longhui, Lianyuan, Shaodong, Xinhua, and Xinshao counties at central Hunan province, China, respectively. The green, blue, orange, and red bar refer to potential, light, moderate, and intensive rocky desertification, respectively.

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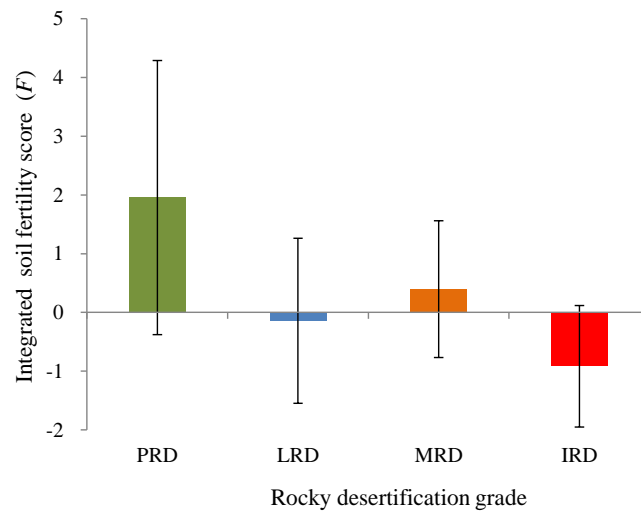


Figure 2. Average scores of integrated soil fertility of 20 studied plots. PRD, LRD, MRD, and IRD refer to potential, light, moderate, and intensive rocky desertification, respectively. Paired difference were analyzed as p (LRD) = 0.114, p (MRD) = 0.347, and p (IRD) = 0.120 compared to PRD.