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Response of surface-soil quality to secondary succession in karst areas in Southwest China: Case study on a limestone slope

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ABSTRACT

Karst areas are fragile ecological environments facing serious soil quality problems. It is crucial to understand the surface-soil quality for ensuring the secondary succession of vegetation. In this study, four plots located on the same hill slope were selected, representing the four secondary succession stages of arable land, grassland, shrubs, and secondary forest, respectively. The surface-soil quality during secondary succession is assessed using the minimum dataset method. The results show that secondary succession decreased soil bulk density and total potassium content ($P < 0.05$), whereas soil organic matter, saturated hydraulic conductivity, overall porosity, and total nitrogen increased ($P < 0.05$). However, pH and capillary porosity are relatively stable. Non-capillary porosity and total phosphorus content first decreased and then increased. In addition, the mean soil quality indices increased and the difference in surface-soil quality between stages decreased with vegetation succession ($P < 0.05$). Improvement in surface-soil quality is most obvious in the early stages of secondary succession, and natural vegetation restoration can solve the land degradation problem. This study is not only helpful in understanding the changes in surface-soil quality during the secondary succession but also provides a theoretical basis for selecting ecological restoration methods in karst regions.

1. Introduction

Soil degradation caused by both human and natural factors has significantly reduced the quality of soil worldwide (Marzaioli et al., 2010; Peng et al., 2013). Soil quality problems have seriously threatened the human living environment and constrained economic development (Nabiollahi et al., 2018; Yu et al., 2018). In many areas, soil fertility has been maintained by extensive revegetation efforts (Gu et al., 2019; Raiesi and Salek-Gilani, 2020; Wang and Fu, 2020). During the secondary succession of vegetation, the roots of plants are widely distributed in the surface soil and the quality of the surface soil determines the benign plant growth (Hu et al., 2017). Therefore, studying the changes in surface-soil quality during the secondary succession of vegetation is vitally important.

Related studies have shown that secondary succession of vegetation can improve the surface-soil quality, but to a limited extent (Liu et al., 2020a, 2020b; Zethof et al., 2019). For example, Zethof et al. (2019) found a non-linear improvement in surface-soil quality during secondary succession. However, the reported changes in surface-soil quality during secondary succession do not represent the situation in karst areas, because soil formation in the limestone of karst areas is a slow process and the soil layer is shallower than in other areas (Peng and Wang, 2012; Zhao et al., 2017). With their steep slope, high annual precipitation, and poor vegetation cover, karst areas are also vulnerable to soil erosion and degradation (Peng and Wang, 2012). These unique characteristics of karst regions suggest that the surface-soil quality conditions differ from those of other regions.

Several studies have been conducted to understand the relationship between secondary succession and environmental elements in karst areas, such as the effects of several factors of secondary succession and the impact of secondary succession on environmental elements (Yi et al., 2021; Zhong et al., 2022). Some studies have focused on the impact of secondary succession on soil quality, the effects of different vegetation restoration types on soil quality (Guan and Fan, 2020; Pang et al., 2018), and the differences in the effects of vegetation restoration on surface and fissure soil quality (Yan et al., 2019). Although some studies have

Abbreviation: BD, Bulk density; CP, Capillary porosity; MDS, Minimum dataset; NCA, Non-capillary porosity; OP, Overall porosity; PC, Principal component; PCA, Principal component analysis; TK, Total potassium; TN, Total nitrogen; TP, Total phosphorus; SHC, Saturated hydraulic conductivity; SOM, Soil organic matter; SQI, Soil quality index.

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analyzed the effects of different secondary succession stages of vegetation (such as grassland and shrubs) on soil quality, they analyzed the entire soil layer, instead of only the surface layer. Therefore, the changes in the quality of the surface soil during the secondary succession of karst slopes are still unclear.

The highly sensitive and vulnerable karst ecosystem in southwest China is one of the largest exposed carbonate rock areas in the world (more than 0.54 million km^2). This area hosts 220 million people and has been selected as a major target of vegetation restoration projects (Tong et al., 2018; Qiao et al., 2021; Peng et al., 2021). The soil layer in the karst region is shallow, and the surface soil has an important influence on vegetation growth. Thus, understanding the changes in surface soil quality can help people formulate reasonable vegetation restoration strategies. In addition, shallow soil layer is not only a feature of karst mountains, but also an important feature of many rocky mountains around the world. Therefore, research in karst mountains can also help people understand the changes of soil quality in other rocky mountains with secondary succession. Then formulate appropriate ecological protection measures in various places. Thus, it is of great significance to clarify the characteristics of surface-soil quality with secondary succession in karst region.

Although some studies have been carried out on the effect of secondary succession on surface-soil quality in karst areas, how the surface-soil quality of the karst areas changes with secondary succession is still an important question that needs to be answered. Karst mountainous areas usually consist of depressions and slopes. Depressions usually have thicker soil layers and are more conducive to farming. Therefore, up to now, most of the depressions are still used as cultivated land without obvious secondary succession, so this study chose karst slope as the research object. The present study attempts to characterize the responses of the physicochemical properties of the surface soils in karst slope to secondary succession. The study was performed on four sample plots on the same slope. The soil quality indices (*SQIs*) at different stages of vegetation restoration were calculated by the minimum dataset (MDS) method, then analyzed to summarize the changes in surface-soil quality of the karst during the secondary succession. The results provide a basis for ecological restoration and management in karst slopes.

2. Materials and methods

2.1. Overview of the study area

The sample site is located in Guanling County, Anshun City, Guizhou Province (25°34′–26°05′N, 105°15′–105°49′E). Guanling County (area 1468 km^2) is a typical karst landscape area with complex landform types and extensive distribution of carbonate rocks. Serious stony desertification is the main ecological problem of the county. The karst landscape comprises 83.83% of the total area (only 16.17% is covered by non-karst landscapes). The Guanling area mainly experiences a humid mid-subtropical monsoon climate with an average annual temperature of 16.2 °C and abundant rainfall (1205.1–1656.8 mm per year, concentrated between June and August).

2.2. Plot setting

The study was conducted in July of 2019. For a spatial (rather than temporal) analysis, we selected four land types representing the four stages of secondary vegetation succession, namely, arable land, secondary grassland, secondary shrubs, and secondary forest land. To better reflect the changes in surface-soil quality during the vegetation succession and to eliminate the influence of environmental factors, all sample plots were located on the same slope (Fig. 1), with an elevation

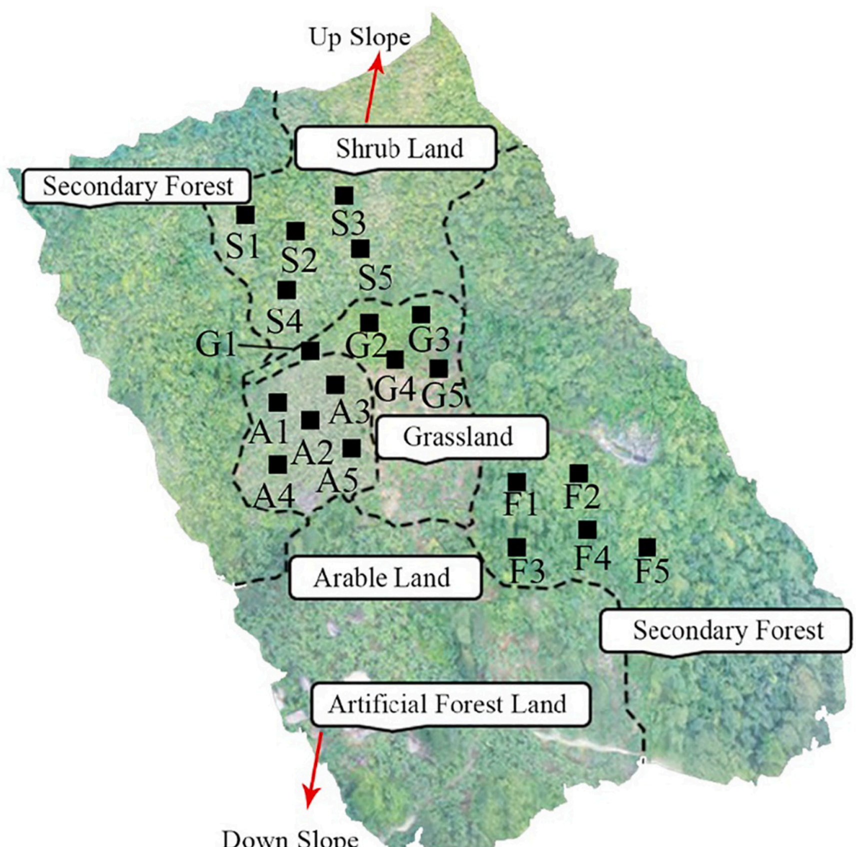

Fig. 1. Distribution map of the sample plots: arable land plots (A1–A5), grassland plots (G1–G5), shrub land plots (S1–S5), and secondary forest plots (F1–F5).

of ~700 m, aspect of NE orientation, and a slope of ~25°. The vegetation information of the different secondary vegetation succession stages was given in Table 1. The distribution of karst soils was extremely uneven, with uneven distribution of soil thickness, and the thickness of soil layers in the sample sites was about 5 to 40 cm. The soil type of the sample site is Cambisols (WRB., I.W.G, 2014) and the lithology is limestone.

Because the exposed bedrock is common in the experimental site, it is difficult to adopt the method of regular sampling. The soil samples were collected at four soil depths (0–5, 5–10, 10–15, and 15–20 cm) in each secondary succession sample plot. The physical and chemical properties of each soil sample were than analyzed. First, we randomly select a series of sampling points according to the aerial image of the sample plot by the unmanned aerial vehicle. If the selected sampling point is bare rock or the soil layer is thin or thick, we believe that this point cannot represent the general situation on this slope. Because the soil thickness of 30–40 cm is the general condition of the soil thickness of this slope. We then move the sampling point appropriately based on experience, with a soil thickness of 30–40 cm serving as the criterion. Random sampling combined with empirical judgment enables us to select representative sampling points in such karst slopes where the bedrock is exposed and soil thickness varies greatly. If regular or random sampling is carried out mechanically, a large sampling error may be introduced.

2.3. Soil Quality Index

Following the selection of physical and chemical indicators, the following considerations were made: we chose soil bulk density (BD) to represent the change in soil looseness during secondary succession, and total porosity (TP), capillary porosity (CP) and non-capillary porosity (NCP) to represent the soil's aeration and structural condition, respectively. Saturated hydraulic conductivity (Ks) is mostly used to reflect the change in infiltration performance during secondary succession. To reflect the changes in surface-soil fertility during secondary succession, we primarily use the indexes of soil organic matter content (SOM), total nitrogen (TN), total phosphorus (TP), and total potassium (TK). Soil pH is mostly used to show how the soil pH changes during secondary succession.

Individual soil properties are difficult to correctly assess when evaluating soil quality, but the SQI can integrate different soil properties to provide a comprehensive evaluation of soil quality (Andrews et al., 2003). Currently, this method is commonly used for evaluating soil quality in karst areas (Guan and Fan, 2020; Zhang et al., 2019; Zhang et al., 2021). There are two primary methods for calculating SQIs: total data set and minimum data set. Compared with the total data set method, the MDS method can select the most representative soil indicators and reduce data redundancy (Andrews and Carroll, 2001; Karaca et al., 2021). Previous studies in karst areas have shown that the MDS method can adequately represent the total data set and be used for evaluating soil quality in the area (Pang et al., 2018; Zhang et al., 2021). As a result, a SQI was established in this study using the MDS method to evaluate the surface-soil quality during secondary succession in this study.

The SQI was calculated in three steps as follows: (1) select the MDS; (2) score the parameters in the MDS method; and (3) merge the scores and calculate the *SQI*. The minimal dataset indicators were selected in a principal component analysis (PCA). First, the principal components (PCs) with eigenvalues ≥1 that explained more than 5% of the total variables were selected. For each PC, only the factors with absolute loading values within 10% of the highest factor loading were selected (Brejda and Karlen, 2000). Then, when more than one indicator was retained in one PC, whether other indicators should be removed was checked in a Pearson's correlation analysis. If any two indicators in a PC were correlated (correlation coefficient > 0.6), we selected the indicator with the highest weighted indicator.

The selected MDS indicators were then scored on a 0–1 scale using a nonlinear scoring function, namely, the sigmoidal function was performed as follows (Andrews et al., 2002):

$$S = a \bigg/ \left[1 + \frac{x}{x_0}\right]^b \tag{1}$$

where S is the score of the soil indicator, a is the maximum score (1.0), x and x_0 denote the value of an indicator and its average value, respectively, and b is the value of the the equation's slope. The curves with slopes of −2.5 and 2.5 were defined as the “more is better” and “less is better” curves, respectively. The *SQI* was calculated as follows (Zhang et al., 2019):

$$SQI = \sum_{i=1}^{n} S_i W_i \tag{2}$$

where W_i and S_i are the weight and score of soil indicator i, respectively, determined by PCA and Eq. (1), respectively. n is the number of selected indicators in the MDS method.

2.4. Determination of physical and chemical properties of soils

Soil BD, SHC, OP, NCP, and CP were measured using the conventional core method with a volume of 100 cm^3 (Gu et al., 2019; Peng et al., 2020). The soil SOM was measured using the $K_2Cr_2O_7$–H_2SO_4 oxidation method (Islam and Weil, 1998). The soil pH was measured at a soil to water ratio of 1:5 (PHS-320 acidity meter, Chengdu, China). Soil TN was measured by an elemental analyzer (K1100, Shandong, China). The total phosphorus (TP) was measured using an ultraviolet spectrophotometer (UV752N, Shanghai, China). Then the total potassium (TK) was measured in a flame photometer (FP6440, Shanghai, China).

2.5. Data analysis

Differences among the physicochemical and *SQI* values of the soils in different vegetation succession stages and different layers were assessed by one-way analyses of variance followed by the least-significant

Table 1
Basic profiles of experimental plots.

Secondary succession stages	Arable land	Grassland	Shrub Land	Secondary Forest
Vegetation coverage (%)	40%	70%	85%	95%
Mean tree height (m)	2	0.7	3.4	15
Root distribution (g/m^3)	0.9	6.5	4.5	3.8
Main species	Corn	*Blumea balsamifera* (Linn.); *Ageratum conyzoides* Sieber ex Steud; *Arthraxon hispidus* (Thunb.)	Cipadessa cinerascens (Pellegr.) Hand -Mazz; *Albizia kalkora* (Roxb.) Prain;Mallotus japonicas var. floccosus (Muell. Arg.)	Radermachera sinica (Hance) Hemsl; Toona sinensis (A. Juss.) Roem
Restored years	0 (not restored)	3	8	25

difference comparison test. Results were considered significant at the $P < 0.05$ level. The datasets were tested for equal norms and variances, and if necessary, were transformed to meet the assumption of the analytical analysis. If the data failed to meet the two conditions, they were instead analyzed by the non-parametric Kruskal–Wallis test. The soil property indicators and their weights were selected by PCA. All analyses were performed using SPSS 19.0 statistical software, and the graphs were generated using R.

3. Results

3.1. Physical indicators of surface soils in different secondary succession stages

The BD was significantly higher on arable land than on secondary forest land ($P < 0.05$), but was not significantly different on grassland and shrub land (Fig. 2a). The mean BD values increased in the reverse order of secondary succession: secondary forest < shrub land < grassland < arable land. The BD did not significantly differ among the four

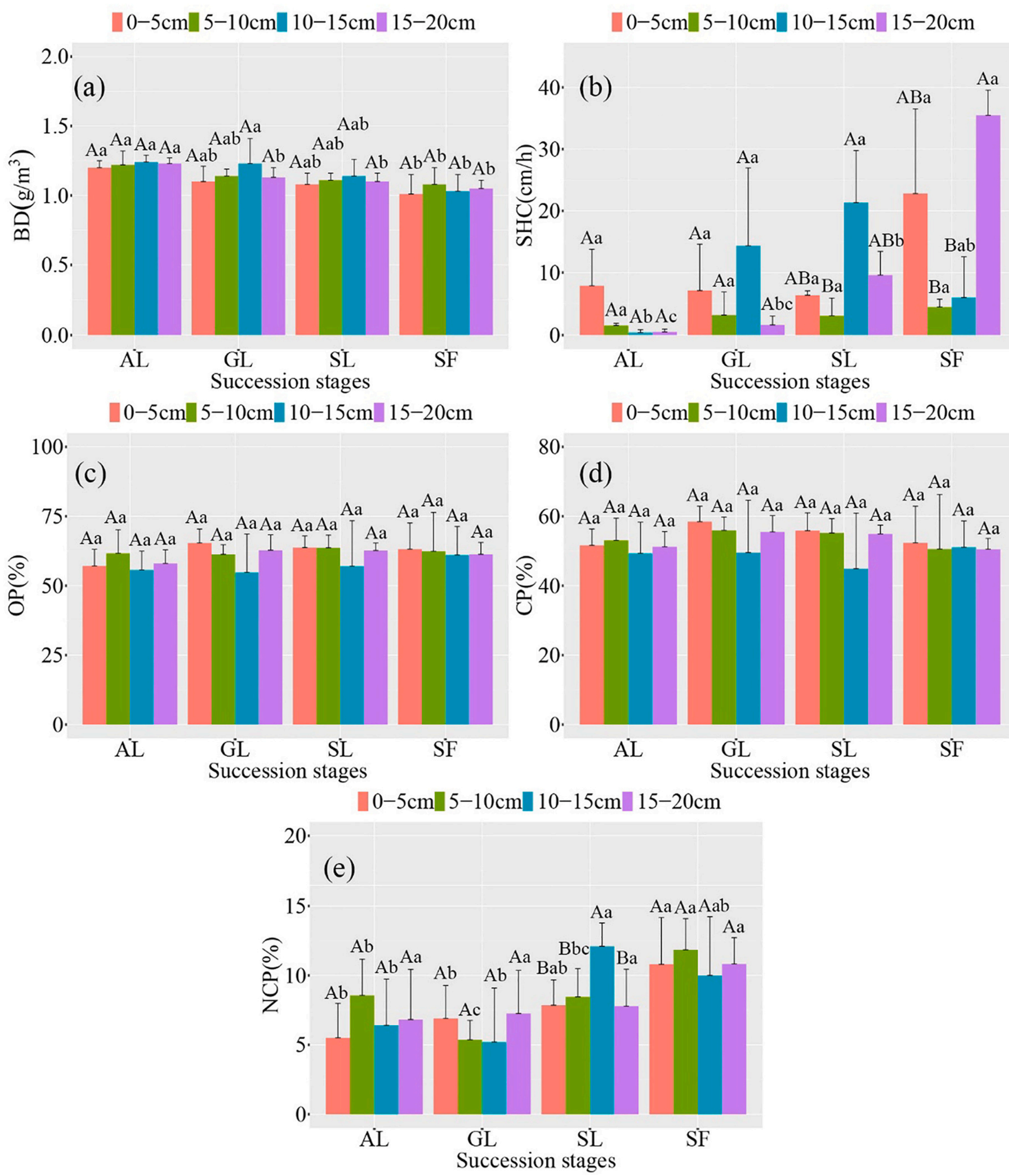

Fig. 2. Soil physical indicators in different stages of secondary succession at different soil depths: 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm. Error bars correspond to the standard deviations. AL: Arable land; GL: grassland; SL: shrub land; SF: Secondary forest. BD indicates bulk density; SHC indicates saturated hydraulic conductivity; OP indicates overall porosity; CP indicates capillary porosity; NCP indicates non-capillary porosity. Different uppercase lower-case letters indicate significant difference under soil depths ($p < 0.05$), different lower-case letters indicate among different secondary succession stages at the same depth ($p < 0.05$). The same below.

soil depths at any secondary succession stage. The SHC was significantly higher ($p < 0.05$) in secondary forests than in the three previous successional stages (Fig. 2b). The mean SHC values increased in the order of secondary succession, and significantly differed between the 5–10 cm and 10–15 cm soil depths, whereas in the secondary forest stage, the SHC significantly differed between the 15–20 cm and 5–10/10–15 cm soil depths. The mean OP values also increased in the order of secondary succession, but the differences were not significant (Fig. 2c). Moreover, the OP was not significantly different among the four soil depths of the topsoil layers in any secondary succession stage. The mean CP values did not significantly vary among the secondary successional stages, but its maximum and minimum values were found in the secondary forest stage and arable stage, respectively (Fig. 2d). In contrast, the NCP significantly differed among the arable, shrub and secondary forest stages of secondary succession (Fig. 2e). The mean NCP values was largest in the arable stage, followed by secondary forest and grassland, and was smallest in the shrub stage. In general, the BD showed a decreasing trend during the vegetation secondary succession, while the SH, OP and CP showed overall increasing trends and the NCP showed no overall trend.

3.2. Chemical indicators of the surface soils in different secondary succession stages

The SOM was significantly lower in the arable stage than in the other

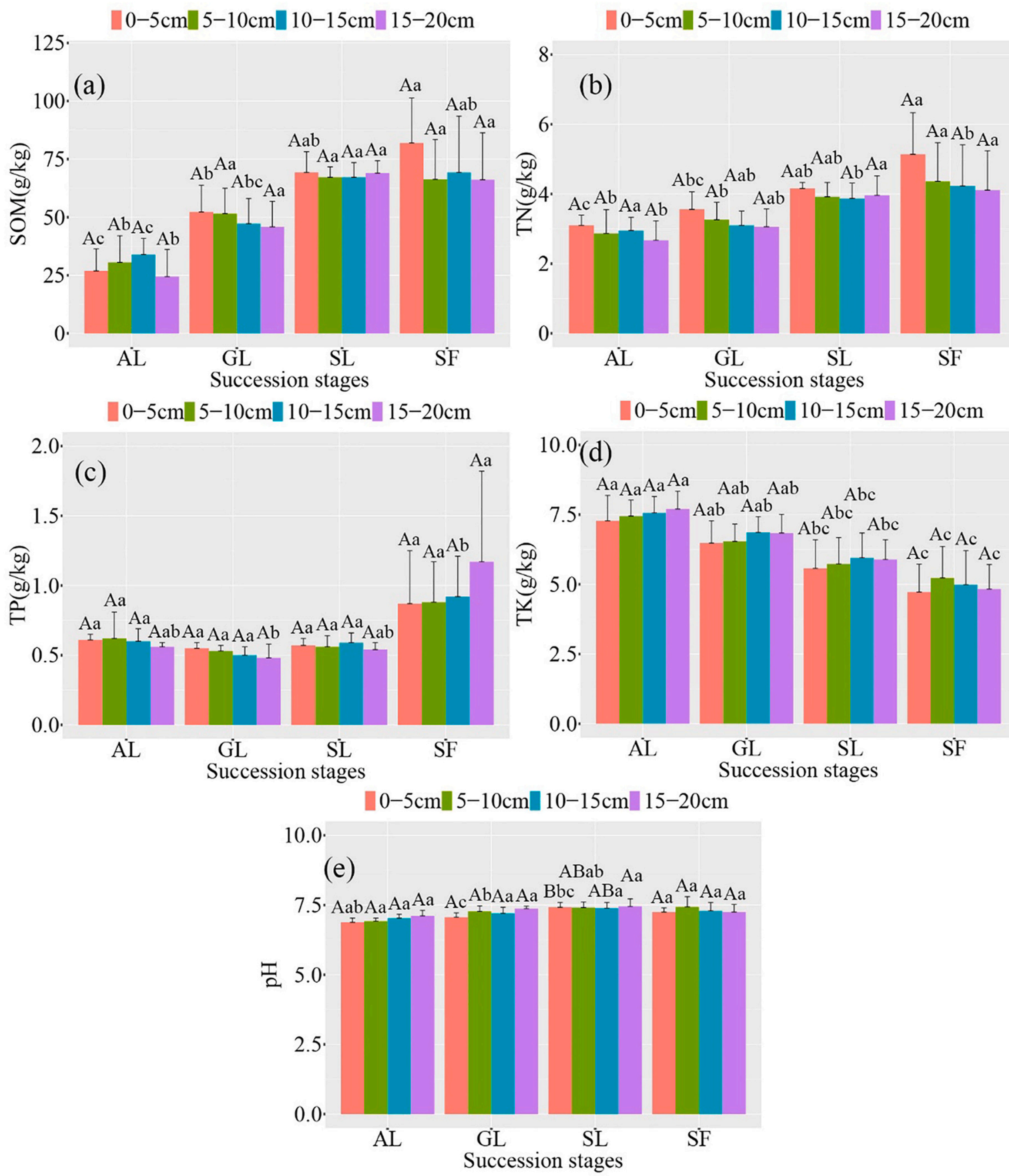

Fig. 3. Soil chemical indicators in different stages of secondary succession and different soil depths: 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm. Error bars correspond to the standard deviations. SOM indicates soil organic matter content; TN indicates total nitrogen content; TP indicates total phosphorus content; TK indicates total potassium content; pH indicates soil pH.

three stages (Fig. 3a). The mean SOM values increased in the order of secondary succession: arable land < grassland < shrub land< secondary forest, but did not significantly differ among the four depths of surface soil in any secondary succession stage. The TN significantly differed between arable land and shrubs/secondary forests (Fig. 3b). The mean TN values increased in the order of secondary succession. The TP significantly differed between the shrub and secondary forest stages (Fig. 3c). The mean TP values also followed the secondary succession stages. The TK significantly differed between arable land and shrub land/secondary forests (Fig. 3d). The maximal mean TK values was found in arable land, grassland and shrub land, whereas the minimal mean TK values was found in the secondary forest stage. Significant pH differences were found between the arable land and grassland stages (Fig. 3e). The mean pH was highest in secondary forest, followed by arable land and shrubs, and was lowest in grassland. In general, SOM, TN and TP showed increasing trends during the secondary succession, while TK showed a decreasing trend and the pH showed an overall upward trend.

3.3. Soil quality index evaluation of surface soils during secondary succession

The PCA of all measurements showed that the three main PCs with eigenvalues ≥1 explained 78.98% of the total variance (Table 2). In PC1, the main weighted indicators were SOM, BD and TN. Because SOM was well correlated (correlation coefficients >0.6; see Fig. 4) with BD and TN, the SOM with a high weighting factor was selected in PC1. Meanwhile, CP was selected in PC2 owing to its high loading factor in that component. SHC was the only suitable factor in PC3. In the MDS method, the *SQI* was thus computed as a function of SOM, CP, and SHC. After calculating the weights in a PCA (Table 3), the *SQI* was calculated by Eq. (3):

$$SQI = 0.61SOM + 0.25CP + 0.14SHC. \tag{3}$$

The *SQI* significantly differed ($P < 0.05$) among the secondary succession stages (Fig. 5). The mean *SQI* values of the surface soils increased in the order of secondary succession: arable land (0.24) < grassland (0.43) < shrub land (0.54) < secondary forest (0.55). The *SQI* difference between two adjacent stages was considered to represent the changing status of the surface-soil quality during the secondary succession. From the arable to grassland stages, grassland to shrub stages, and shrub to secondary forest stages, the *SQI* changed by 0.19, 0.11, and 0.01, respectively. As the secondary succession advanced, the soil quality significantly improved while the inter-stage difference in *SQI* gradually decreased. Specifically, the *SQI* change was highest between arable land and grassland, and lowest between shrub land and secondary forest.

Table 2
Principal component analysis of the soil quality indicators.

Principal component	PC-1	PC-2	PC-3
Eigenvalues	4.83	1.94	1.13
Variation (%)	48.30	19.37	11.31
Cumulative (%)	48.30	67.67	78.98
SOM	0.95	−0.07	0.04
TN	0.88	−0.31	−0.14
TP	0.70	−0.28	−0.31
TK	−0.79	0.18	0.26
pH	0.46	−0.38	0.60
BD	−0.92	−0.23	0.11
OP	0.58	0.77	0.04
CP	0.38	0.91	−0.01
NCP	0.64	−0.29	0.15
SHC	0.29	0.13	0.75

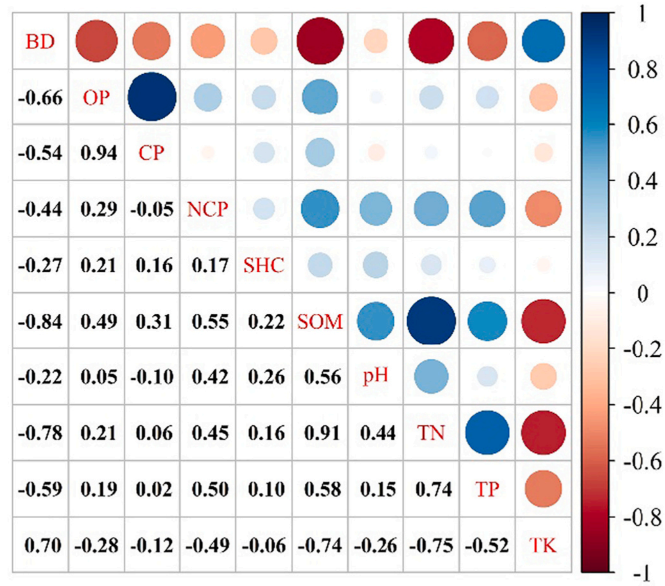

Fig. 4. Correlation coefficients of soil properties in different secondary succession stages (circle sizes indicate the goodness of the correlations, and colors indicate the sign of the correlation: blue for positive and red for negative). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Parameters of normalization equations of the scoring curves.

Parameter	SOM	CP	SHC
Average (x0)	54.31	52.49	18.43
Slope (b)	−2.50	−2.50	−2.50
Weighting value	0.61	0.25	0.14

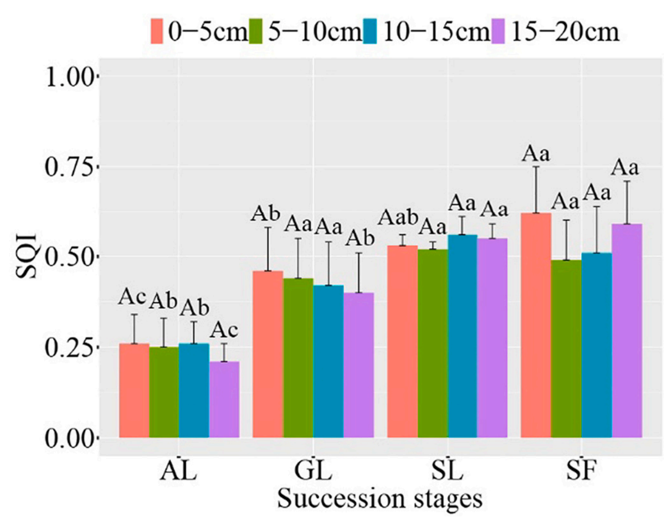

Fig. 5. *SQI* changes at different soil depths (0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm) throughout the secondary succession stages (AL: Arable land; GL: grassland; SL: shrub land; SF: Secondary forest).

4. Discussion

4.1. Processes of changes in the physical and chemical properties of surface soils during secondary succession

The BD was highest in the surface soil of arable land and decreased during the later stages of secondary succession. Low BD is important for the cycling of water, air and nutrients (Tesfahunegn et al., 2011; Mora and Lázaro, 2014). On arable land, the high BD can be attributed to human tillage activities. Maize growing in arable land absorbs organic matter and large amounts of nutrients from the soil, which is not sufficiently replenished by the small amount of surface litter; accordingly, the sources of SOM are diminished and the capacity is maximized on arable land. Meanwhile, the TP and SHC were smallest on arable land, indicating poor permeability and water holding capacity on this land. The secondary succession of vegetation increases the plant species diversity and canopy density, thus altering the apoplastic inputs and fine root biomass, which in turn change the soil properties (Hu and Lan, 2020; Schedlbauer and Kavanagh, 2008). The decreasing BD trend during the secondary succession was mainly attributable to increase of apoplastic material in the surface soil and the enhanced action of plant roots, which increased the pore space and capacity of the surface soil. The accumulated apoplastic material and enhanced root action also change the permeability and water-holding capacity of the surface soil during the secondary succession. Therefore, the SHC and TP showed an increasing trend during the secondary succession. In general, secondary succession of plants improves the surface soil BD, SHC, and TP.

The SOM, TN, and TP increased during the secondary succession, and most of the chemical property values were smaller in the arable stage than in later stages. Plant litter increases the SOM content and other soil nutrients (Rutigliano et al., 2009). The SOM, TN, and TP in the surface soil were also lower in the arable stage than in other stages, mainly because arable land is more influenced by human activities and the accumulation of dead fallen matter is low, meaning that low levels of organic matter enter the soil. As growing crops are large nutrient consumers, they reduce the TN and TP in the surface soil. On the contrary, the TK was higher in the surface soil of the arable land than in later stages. The TK levels were probably raised by fertilization. In later stages of the succession, the SOM and nutrients in the surface soil overall increased as the biomass and canopy characteristics matured. For example, grassland has larger biomass than arable land and the soil surface becomes covered by herbaceous plants after drying, which can accumulate as dead material. The canopy structure of shrubs and secondary forests is complex, and a thick layer of dead and fallen leaves covers the surface soil. Litter in the surface soil layer facilitate the accumulation of SOM and nutrient elements, which in turn facilitate the recovery of vegetation. In contrast, the TK content of the surface soil mass decreased from grassland to secondary forest, possibly because more potassium was consumed by the increased plant biomass in later stages. Overall, the secondary succession of plants improved the organic matter and nutrients in the surface soil. Secondary succession can improve the chemical properties of the surface soils in karst areas with shallow soils and fragile ecological environments, assisting the recovery of vegetation.

In general, the other stages of the secondary succession improve most of the physicochemical properties of the soils in the study area compared to the arable stage. After secondary vegetation succession, plant roots and litter can improve the physical properties of the soil thereby enhancing the permeability and water holding capacity of the soil. This can slow the generation of surface runoff and thus prevent soil degradation. Additionally, the litter that covers the surface soil can also increase the nutrient content of the soil, thus improving soil fertility. Soils with good physical and chemical properties are conducive to plant growth, which is beneficial to the secondary vegetation succession on karst slopes.

4.2. Response of surface-soil quality to secondary succession

Overall, the quality of the surface- soil and the entire soil layer (Zhang et al., 2019; Zhang et al., 2021) did not show significant differences. This is primarily attributed to the slow pace of soil formation and the shallow soil layer in the karst areas (Yang et al., 2014; Zhang et al., 2020a), indicating that soil properties do not show obvious vertical differences as they do in non-karst areas. However, if we compare the changes in each vegetation succession stage, some differences can still be seen. The surface-soil quality changed significantly from the arable land stage to the grassland stage (Fig. 5), while the soil quality of the entire layer changed slightly (Zhang et al., 2021). This shows that the early succession stage mostly affects the surface-soil quality, and the impact on the entire soil layer takes a longer time to exhibit significant effect.

The primary factors affecting the surface-soil quality and the entire soil layer quality also showed differences. Our study shows that soil organic carbon is the most important factor affecting surface-soil quality during succession (Table 3). Other studies have shown that if the subsoil layer is considered, although organic carbon is still the most influential factor, its influence degree decreases and that of nutrients such as available nitrogen and available potassium increases (Zhang et al., 2021). For fissure soil, the influence of nutrients such as nitrogen, phosphorus, and potassium will further increase, and the influence of soil texture will also become more important (Yan et al., 2019). Therefore, we should fully recognize the importance of soil organic carbon accumulation caused by vegetation secondary succession (Zhang et al., 2020b) to improve the quality of surface soil. In the early stages of vegetation restoration, when formulating vegetation restoration strategies, plant species and restoration modes that are conducive to the accumulation of litter should be considered.

4.3. Implications of changes in surface-soil quality during secondary succession for vegetation restoration

Abundant precipitation coupled with unreasonable human activities in the karst region in southwest China have intensified the soil erosion, incurring a high risk of land degradation (Tang et al., 2019; Shi et al., 2019; Wang et al., 2019a; Yue et al., 2020). Natural and artificial vegetation restoration are widely used for recovering ecological environments in karst regions (Wang et al., 2019b). However, artificial vegetation restoration may negatively impact on the environment. For example, large-scale plantation forest will increase the consumption of soil water, risking soil drought and stifling the growth of other vegetation (Su and Shangguan, 2018). Therefore, other options for improving soil quality may be more appropriate.

The study areas controlled by subtropical monsoon climates are mild and wet, and even when the vegetation is degraded by external causes, vegetation succession will restore the quality of the surface soil. Humid conditions favor new secondary succession that prevents soil degradation. The changes in surface-soil quality during secondary succession showed that the greatest differences occurred between arable land and grassland, indicating that the surface-soil quality was most obviously improved at the beginning of the succession. Therefore, in this study area with good precipitation conditions, natural restoration is a suitable choice for improving the soil quality, especially in the early stage of natural vegetation succession. In areas with more serious soil quality problems, promoting the natural succession of arable land to grassland can best improve the surface-soil quality.

4.4. The complexity of soil quality at different lithological conditions

Most of the mineral nutrients in the soil (such as phosphorus and iron) come from the bedrock (Morford et al., 2011). In karst areas, limestone contains more weathered residual minerals than dolomite, which results in soils with higher nutrient content (Liu et al., 2020a; Sun et al., 2002). Therefore, the soil quality of the soil formed after the weathering of different types of carbonate rocks is different. Even if it belongs to limestone or dolomite, the purity of lithology is different; the mineral composition and clay mineral content are inconsistent, which will lead to differences in soil quality and thickness. Thus, the karst area has strong spatial heterogeneity and complex lithological conditions. In this study, the sample plot is located on a karst slope where the lithological conditions are relatively pure limestone. Therefore, the results of this study are mostly applicable to karst slopes where the lithological conditions are relatively pure limestone, and the results of this study are not necessarily applicable to karst slopes with other lithological conditions.

5. Conclusion

This study assessed the changes in soil quality of a karst area during secondary succession by calculating the SQI of the surface soils based on the MDS method and using limestone slopes as a case study. The physicochemical properties of the surface soils were improved during the secondary succession and the differences in surface-soil quality tended to decrease between the stages of the succession, being largest from cropland to grassland and smallest from shrub to secondary forest. During the secondary succession process, although the *SQI* values of the surface soil were higher in secondary forest than in the previous three stages, the soil quality was most obviously improved from the arable stage to the grassland stage. In conclusion, natural vegetation restoration can effectively improve the surface-soil quality in the management of land degradation. The present study characterized the change in soil quality in the surface layer during the secondary succession of vegetation in karst areas, but how the soil quality changes in the deeper soil layers during secondary succession is an interesting future topic.

In our experimental design, we hope that all plots are on one slope, which can avoid differences in lithology, climate, and other factors. This resulted in insufficient duplication at the sample plot level, which may limit the broad implications of the results. Considering the complexity of environmental factors in the karst mountainous region, a single case study cannot fully illustrate the changes in surface-soil quality with vegetation restoration. Therefore, we need to sample and analyze several karst areas under different environmental conditions to comprehensively assess the impact of secondary succession on surface-soil quality.

CRediT authorship contribution statement

Weihong Yan: Writing – original draft, Formal analysis, Visualization, Investigation, Methodology, Software. **Qiuwen Zhou:** Conceptualization, Writing – review & editing, Supervision, Project administration, Resources, Funding acquisition. **Dawei Peng:** Methodology. **Yingzhong Luo:** Formal analysis. **Meng Chen:** Investigation. **Yuan Lu:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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