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REDUCED SOIL QUALITY WITH CULTIVATION OF CALCAREOUS SOILS IN SUBTROPICAL CHINA KARST REGION

ZMANJŠANA KAKOVOST TAL ZARADI OBDELAVE APNENČASTIH TAL NA SUBTROPSKEM KITAJSKEM KRAŠKEM OBMOČJU

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Abstract UDC 504.12:631.61:551.435.8(510)

Mengxia Zhou, Hui Yang, Cheng Zhang, Jianhua Cao & Degen Zhu: Reduced soil quality with cultivation of calcareous soils in subtropical China karst region

Cultivation practices significantly impact soil functionality and quality, however, the effects of different cultivation durations remain inadequately quantified in the fragile karst ecosystems of southwestern China. This study employed a chronosequence approach to assess agricultural soil quality changes and identify their key drivers. Five land-use stages were selected and sampled: a natural reserve forest (NR) as a reference, recently burned land (0 a), and cultivated lands with durations of 1, 5, 15, and 30 years (1 a, 5 a, 15 a, 30 a, respectively) in the subtropical karst region of southwestern China. The soil quality index (SQI) was constructed using both the Total Data Set (TDS) and Minimum Data Set (MDS) methods. Principal component analysis (PCA) identified calcium (Ca), silt content and silicon (Si) as the key indicators within the MDS. Both TDS and MDS assessments revealed a progressive decline in SQI with increasing cultivation duration following slash-and-burn practices (R^2=0.67 between TDS- and MDS-derived SQIs), indicating that agricultural activities significantly alter soil physicochemical properties and lead to soil degradation. The observed decrease in soil quality may be explained by two main mechanisms: (1) depletion of the soil-forming matrix in shallow karst environments; and (2) accelerated loss of acid-insoluble residues due to enhanced weathering under cultivation. These findings highlight the high vulnerability of karst soils to long-term farming, where inherently limited pedogenic materials

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Mengxia Zhou, Hui Yang, Cheng Zhang, Jianhua Cao & Degen Zhu: Zmanjšana kakovost tal zaradi obdelave apnenčastih tal na subtropskem kitajskem kraškem območju

Obdelovalne prakse pomembno vplivajo na funkcionalnost in kakovost tal, ob tem pa vplivi različno dolgega trajanja obdelovanja v občutljivih kraških ekosistemih na jugozahodu Kitajske še vedno niso ustrezno opredeljeni. Avtorji so v tej raziskavi uporabili pristop kronološkega zaporedja ter na njegovi podlagi proučili spremembe v kakovosti kmetijskih tal in opredelili njihove ključne dejavnike. Izbrali in vzorčili so pet stopenj rabe zemljišč: naravni gozdni rezervat kot referenco, nedavno požgano zemljišče (0 a) in obdelovalna zemljišča, ki so se obdelovala 1, 5, 15 in 30 let (1 a, 5 a, 15 a, 30 a) na subtropskem kraškem območju na jugozahodu Kitajske. Z uporabo metod celotnega podatkovnega niza in minimalnega podatkovnega niza so oblikovali indeks kakovosti tal. Iz analize glavnih komponent je razvidno, da so kalcij, vsebnost mulja in silicij ključni kazalniki v minimalnem podatkovnem nizu. Na podlagi ocen celotnega podatkovnega niza in minimalnega podatkovnega niza je opazno postopno upadanje indeksa kakovosti tal, ob tem pa se podaljšuje trajanje obdelovanja po praksah sekanja in požiganja (R^2 = 0,67 – indeks kakovosti tal, izpeljan iz celotnega in minimalnega podatkovnega niza), kar kaže, da kmetijske dejavnosti pomembno spreminjajo fizikalno-kemijske lastnosti tal in povzročajo njihovo degradacijo. Ugotovljeno zmanjšanje kakovosti tal je mogoče razložiti z dvema glavnima razlogoma: (1) izčrpavanje matrice, ki tvori tla, na plitvih kraških območjih in (2) pospešena izguba v kislini netopnih ostankov zaradi okrepljenega vpliva vremenskih

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and intense chemical weathering collectively exacerbate quality decline. This study provides critical insights for developing sustainable land management strategies in karst regions, emphasizing the importance of practices that conserve soil fertility, reduce residue loss, and maintain essential ecosystem services. With the MDS model explaining 67% of the variance in the TDS-based SQI, it represents an efficient and practical tool for monitoring soil quality in fragile karst environments, thereby supporting evidence-based sustainable land use planning.
Keywords: soil quality index (SQI), minimum data set (MDS), total data set (TDS), cultivation, karst region.

razmer ob obdelavi tal. Te ugotovitve kažejo na veliko ranljivost kraških tal ob dolgotrajnem kmetovanju, pri čemer omejena količina pedogenih materialov in intenzivno kemično preperevanje skupaj kakovost še poslabšujeta. Ta raziskava zagotavlja ključna spoznanja za pripravo trajnostnih strategij upravljanja zemljišč na kraških območjih ter poudarja pomen praks, s katerimi se ohranja rodovitnost tal, zmanjšuje izguba ostankov in se ohranjajo bistvene ekosistemske storitve. Glede na to, da model minimalnega podatkovnega niza pojasnjuje 67 % variance indeksa kakovosti tal, izpeljanega iz celotnega podatkovnega niza, je to učinkovito in praktično orodje za spremljanje kakovosti tal na občutljivih kraških območjih ter podpira trajnostno načrtovanje rabe zemljišč, ki temelji na dokazih.
Ključne besede: indeks kakovosti tal, minimalni podatkovni niz, celotni podatkovni niz, obdelava tal, kraško območje.

1. INTRODUCTION

Karst landscapes cover 12% of the global terrestrial surface, with China containing approximately 3.44 million km^2 of karst formations (Wei et al., 2018). Notably, 83% of China's karst is located in the southwest, where ecosystems face severe challenges including intense human-land conflicts, declining land productivity, and significant soil degradation (Jiang et al., 2014; Zhang et al., 2019; Yuan, 1991). Traditional practices such as deforestation and hillslope cultivation of cash crops have exacerbated ecological degradation under sustained human pressure. This unsustainable land use pattern has fundamentally hindered rational resource utilization and agricultural sustainability (Hu et al., 2019; Lei et al., 2019; Wu et al., 2003; Wiesmeier et al., 2015; Xiao et al., 2019). Agricultural intensification is a major driver of soil nutrient depletion, with a study showing that conversion of natural ecosystems to cropland can result in up to 75% soil organic carbon (SOC) loss (Lal, 2004; Lal, 2010; Liao et al., 2018). The inherent fragility of karst ecosystems, due to low acid-insoluble residue content in carbonate bedrock, severely limits soil formation and recovery capacity. Cultivation further accelerates erosion, leaching, and organic matter loss, leading to negative soil mass balance, progressive thinning, and rocky desertification. The interplay between geological constraints and human disturbance heightens ecosystem vulnerability, underscoring the need for land management strategies that address both degradation processes and limited soil-forming potential (Li et al., 2019; Foley et al., 2005).

Soil is a vital natural resource that integrates physicochemical and biological properties, underpinning biological productivity, environmental quality, and ecosystem stability (Shukla et al., 2006). Soil quality reflects the inherent capacity of soil to function within ecosystem boundaries and serves as a sensitive indicator for monitoring functional changes, predicting ecological recovery, succession dynamics, and system resilience (Doran and Parkin, 1994). SQI has become a widely used integrative tool for assessing ecosystem health, especially in fragile karst environments (Li et al., 2012). Effective ecological restoration in this region depends on indicators that are both sensitive to change and scalable across landscapes. However, standardized SQI development remains challenging due to soil heterogeneity and the need for context-specific assessment protocols aligned with land-use goals (Zhang et al., 2011; Karlen and Stott, 1994; Mukherjee and Lal, 2014; Qi et al., 2009). For instance, indicator selection for agricultural systems focused on productivity differs from that for conservation-oriented systems emphasizing erosion control (Karaca et al., 2021; Griffiths et al., 2010). Current frameworks classify soil quality indicators into two types: (1) inherent properties (e.g., texture, mineral composition), which define baseline soil potential, and (2) dynamic properties (e.g., organic matter content, microbial biomass), which reflect short-term management effects (Qi et al., 2009; Andrews et al., 2002). Effective evaluation requires synergistic consideration of both categories, yet persistent challenges remain in establishing universally applicable indicators across diverse ecological and anthropogenic gradients (Doran and Parkin, 1994; Rahmanipour et al., 2014; Schnitzer et al., 2006). The MDS approach addresses this need by identifying a concise set of key parameters, enabling efficient monitoring without redundancy. This is particularly relevant in shallow karst soils, where limited depth and low formation potential constrain recovery and require precise assessment. By incorporating key geochemical factors (e.g., Ca, Si) and indicators of human impact (e.g., soil organic carbon, silt loss), a karst-specific MDS can capture major drivers of soil degradation (Wei et al., 2018;

Zhang et al., 2021). When used to compute an SQI, this framework facilitates targeted evaluation and early detection of soil decline, supporting science-based land restoration and sustainable management in these vulnerable ecosystems (Bünemann et al., 2018).

Site-specific soil quality assessment provides a critical scientific basis for understanding pedogenic processes and designing sustainable land management strategies in ecologically sensitive zones, especially karst regions with vegetation vulnerability (Zhang et al., 2021). In this study, conducted under the distinctive geological and agricultural conditions of the karst areas, soil indicators from citrus orchards of different cultivation ages are examined. The aims are: (1) to establish a standardized soil quality evaluation framework identifying diagnostic indicators that reflect systemic soil quality patterns in karst plantation ecosystems; (2) to assess the influence of cultivation duration on soil quality through comprehensive scoring; and (3) to compare soil indicators across different cultivation years to identify key factors constraining soil sustainability in karst ecosystem. The results will provide a valuable reference for sustainable land management and the enhancement of ecosystem service functions in karst regions.

2. MATERIALS AND METHODS

2.1 STUDY SITES

This study was conducted at the Field Scientific Observation and Research Station of Southwest Karst Rocky Desertification, under the Ministry of Science and Technology (110°32′27″ E, 25°12′33″ N), located in Dengming village, approximately 30 km southeast of Guilin city, Guangxi Zhuang Autonomous Region (Figure 1a). The site features a typical peak-cluster depression landscape, and a subtropical monsoon climate, with a mean annual temperature of 18.6 °C and mean annual precipitation ranging from 1800 to 2000 mm (Xie et al., 2018). Between 60% and 70% of the precipitation occurs during the monsoon season from April to September. The dominant soil type is classified as Leptosols (Rendzic Leptosols according to WRB 2014 classification), which is a typical calcareous soil formation of karst bedrock environments (IUSS Working Group, 2014). The enclosed karst depression was originally covered by a nature reserve forest consisting of shrubs and trees in the absence of anthropogenic disturbance. The area was cleared using fire, starting from the base of the depression and moving upslope, to establish citrus orchards for economic purposes.

2.2 SOIL SAMPLING

A space-for-time substitution approach was employed to select sampling sites (Yang et al., 2019a). Soil sampling was conducted in July 2018. The selected plots represented different durations of citrus trees (0 years, 0 a; 1 year, 1 a; 5 years, 5 a; 15 years, 15 a; 30 years, 30 a) (Figure 1b), along with a nature reserve forest plot (NR) serving as a reference control. To minimize confounding factors, all plots were chosen based on similar environmental conditions, lithology, soil type, and historical land use prior to cultivation. Three replicate plots were established for each of the 0 a, 1 a, 5 a, 30

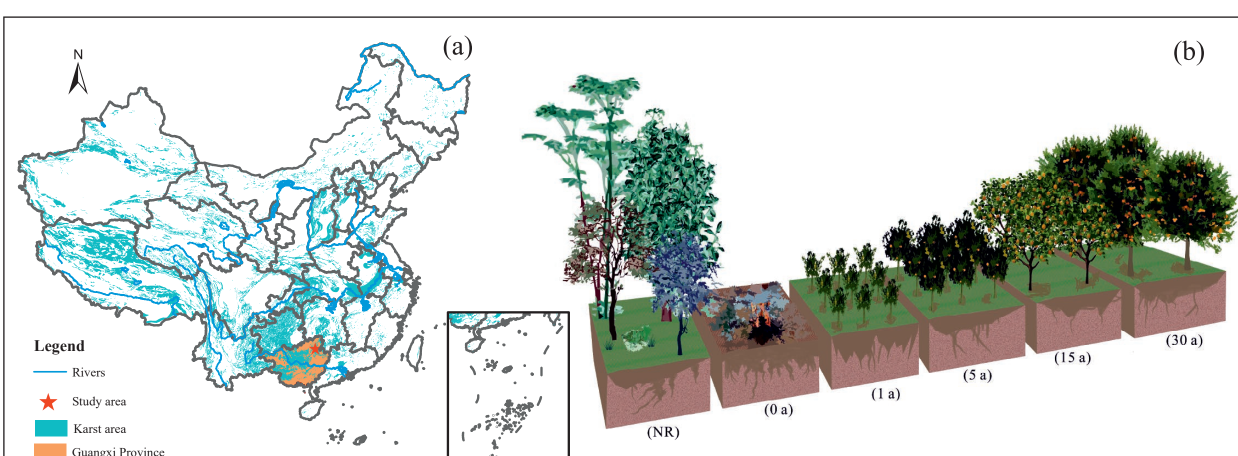

Figure 1: Location of sampling sites in Guilin County, Guangxi Zhuang Autonomous Region.

a, and NR sites. Given that the 15 a represents a critical transitional period within the 5 a to 30 a timeline, five sampling points were selected for this age group. At each sampling point, the 1 m × 1 m quadrats were randomly placed, maintaining a minimum distance of 5 m between quadrats. Soil depth across the study area ranged from 20 to 50 cm, with an organic layer thickness of 1 - 3 cm (Wang et al., 2022). Soil samples were collected from the 0-10 cm layer within each quadrat. After removing surface litter, visible gravel, roots, and organic debris, three subsamples were combined to form one composite sample per quadrat. A total of 20 soil samples were collected across six land-use types (5 citrus orchard ages and one natural forest), with 3 - 5 replicate plots per type. All samples were transported to the Key Laboratory of Karst Dynamics, Ministry of Natural Resources. The soils were air-dried and sieved for subsequent physical and chemical analyses (Yang et al., 2019a).

2.3 ANALYSIS OF SOIL PROPERTIES

Soil pH was determined in a 1:2.5 (w/v) soil-water suspension using a Digital Millivolt pH Meter-2 detector (DMP-2 mV/pH, Quark Ltd., Nanjing, China). SOC and total nitrogen (TN) were analyzed using a Sercon SL C/N elemental analyzer after pretreatment with 1 mol/L HCl to remove inorganic carbon. The contents of recalcitrant organic carbon (ROC) and recalcitrant organic nitrogen (RON) were determined based on the residual C and N after NaClO oxidation. Dissolved organic carbon (DOC) was determined by shaking soil with deionized water at a 1:5 (w/v) ratio and analyzed with a Total Organic Carbon analyzer (Shimadzu Corporation) (Yang et al., 2019b). The contents of Ca, magnesium (Mg), phosphorus (P), iron (Fe), aluminum (Al) and Si were quantified using total X-ray fluorescence spectroscopy (SPECTRO Analytical Instruments GmbH) (Yang et al., 2021). Soil texture was analyzed with a laser diffraction particle size analyzer (Beckman Coulter LS-230, Brea, CA, USA) after removing organic matter with H_2O_2 and carbonates with dilute HCl (Yang et al., 2021). Soil bulk density (SBD), soil water content (SWC), and field water holding capacity (FWHC) were determined using the core method (Bao et al., 2000).

2.4 MDS ESTABLISHMENT AND SOIL QUALITY EVALUATION

The MDS was constructed to evaluate soil quality by systematically selecting and integrating key soil indicators from a full set of physical and chemical properties. The procedure consisted of four steps: (1) identifying the representative indicators of soil quality; (2) scoring these indicators using a standard scoring function (SSF); (3) assigning weights to each indicator through PCA method; (4) integrating the weighted scores to derive a comparative SQI value for comparison.

2.4.1 Indicator selection

Representative indicators were selected based on their direct relevance to soil quality (Qi et al., 2009). These included soil fertility parameters (C, N, P), trace elements (Fe, Al, Si),base cations (Ca, Mg) which are particularly relevant in calcareous soils (Muneer et al., 1989; Rowley et al., 2018). Additionally, physical properties such as SBD and FWHC, which influence root development and plant growth (Plante et al., 2018). Soil texture was also included due to its role in organic matter stabilization. The TDS initially contained 19 indicators reflecting soil properties and management effects.

The coefficient of variation (C.V) and value ranges of these properties were calculated (Table S1) to assess spatial variability and sensitivity. PCA was applied to identify key indicators, retaining only principal components (PCs) with eigenvalues greater than 1 and variables with factor loadings more than 0.65. Where multiple indicators loaded highly on the same PC, correlation analysis was used to eliminate redundancy (*P* < 0.05), retaining only those that were either strongly correlated or represented unique soil functions. This process ensured the MDS was both representative and non-redundant.

2.4.2 Indicator scoring

A standard scoring function (SSF) was used to normalize all indicators to a uniform scale (0-1) to mitigate differences in units and magnitudes (Karlen and Stott, 1994; Li et al., 2013). Indicators were classified into three categories based on their functional relationship with soil quality, and scored using the following equation:

$$f(x)=\begin{cases}0.1 & x<L\\ 0.1+0.9\times\dfrac{x-L}{U-L} & L\le x\le U\\ 1 & x>\mathrm{U}\end{cases}$$

$$f(x)=\begin{cases}0.1 & x<L\\ 1-0.9\times\dfrac{x-L}{U-L} & L\le x\le U\\ 1 & x>\mathrm{U}\end{cases}$$

$$f(x)=\begin{cases}0.1 & x<L_1, x>U_2\\ 0.1+0.9\times\dfrac{x-L}{U-L} & L\le x\le U\\ 1-0.9\times\dfrac{x-L}{U-L} & U_1\le x\le L_2\\ 1 & L_2<x\le U_2\end{cases}$$

Here, $f(x)$ is the normalized score (0.1 to 1); x is the monitored value; and L and U represent the lower and upper threshold values, respectively.

2.4.3 Weight assignment
Weights for each indicator in both TDS and MDS were determined based on communality derived from factor analysis (FA) (Shukla et al., 2006). The weight of an indicator was calculated as the ratio of its communality to the sum of the communalities of all indicators.

2.4.4 Integration of soil quality index
The SOI was computed for both TDS and MDS using the following formula:

$$SQI = \sum_{i}^{n} W_i \times S_i$$

Where SQI is the soil quality index ranges from 0 to 1, W_i is the weight of each indicator, S_i is the score, and n is the number of indicators.

2.5 STATISTICAL ANALYSES
One-way analysis of variance (ANOVA) was used to test all the parameters and soil quality indexes. When significant differences were detected, the Duncan's multiple range test ($P < 0.05$) was applied for mean separation. Two-tailed Pearson product-moment correlation analysis was conducted to explore relationships between soil indicators. All statistical analyses were performed using SPSS 19.0 software (SPSS Inc., Chicago, USA), while data visualization was carried out with Origin 2021 software (OriginLab Corporation, Northampton, MA, USA). Three replicates were prepared for independent laboratory testing and statistical analysis.

3. RESULTS

3.1 SOIL PHYSICAL AND CHEMICAL PROPERTIES
Soil texture analysis (Table 1) revealed no significant differences ($P > 0.05$) in clay and silt contents across the various cultivation durations. In contrast, sand content at 5 a, 15 a and 30 a of cultivation differed significantly from other stages ($P < 0.05$). Overall, prolonged cultivation was associated with a decrease in sand content and a concurrent increase in clay and silt fractions. This trend suggests the progressive accumulation of fine particles, likely attributable to processes such as erosion, deposition, or selective loss of coarser materials.

Table 1: Response of variation of the soil texture to cultivation.

	Clay (%)	Silt (%)	Sand (%)
NR	25.53±2.93a	47±1.99a	27.40±4.68a
0 a	30.13±2.01a	46.3±2.40a	23.54±4.18ab
1 a	33.87±2.53a	50.67±2.47a	15.48±4.05bc
5 a	27.97±9.04a	64.6±8.94a	7.45±0.63c
15 a	39.08±7.54a	54.24±5.28a	6.66±2.56c
30 a	31.4±9.35a	63.1±7.79a	5.50±2.16c

Note: Different lowercase letters indicate significant differences at $P < 0.05$.

The physicochemical properties of soil indicators across different cultivation durations were shown in Figure 2. The pH values ranged from 5.34 to 7.40, with a mean value of 6.46, showing a gradual shift from neutral-alkaline to acidic conditions over time. Throughout the 30 years cultivation period, SOC varied from 16.74 to 84.73 $g \cdot kg^{-1}$ (the mean value is: 49.85 $g \cdot kg^{-1}$) , while TN ranged from 2.04 to 8.04 $g \cdot kg^{-1}$ (mean value: 4.81 $g \cdot kg^{-1}$). Both SOC and TN exhibited significant reductions, declining by 80.24% and 74.67%, respectively. Similarly, DOC decreased by 75% over the same period. Despite the sharp declines in soil carbon and nitrogen with increasing cultivation time, the C/N ratio showed no significant difference ($P > 0.05$) during the early stage of cultivation. However, after 15 years of cultivation, the C/N ratio differed significantly ($P < 0.05$) from the initial values.

Calcium content was the highest in NR, followed by the initial stage (0 a), and gradually decreased with longer cultivation duration, reaching its lowest level at 30 a. Significant differences were observed across cultivation stages. Soil Mg content followed a trend similar to that of Ca, with peak values observed at 0 a. Phosphorus content peaked at 15 a and 30 a, differing significantly from other stages ($P < 0.05$). The Si content (derived from SiO_2) exhibited a fluctuating trend, decreasing initially and then increasing, with the lowest value recorded at 5 a. In contrast, the concentrations of Fe and Al, representing soil Fe and Al oxides, accumulated over time, reaching a maximum at 15 a, before slightly decreasing at 30 a.

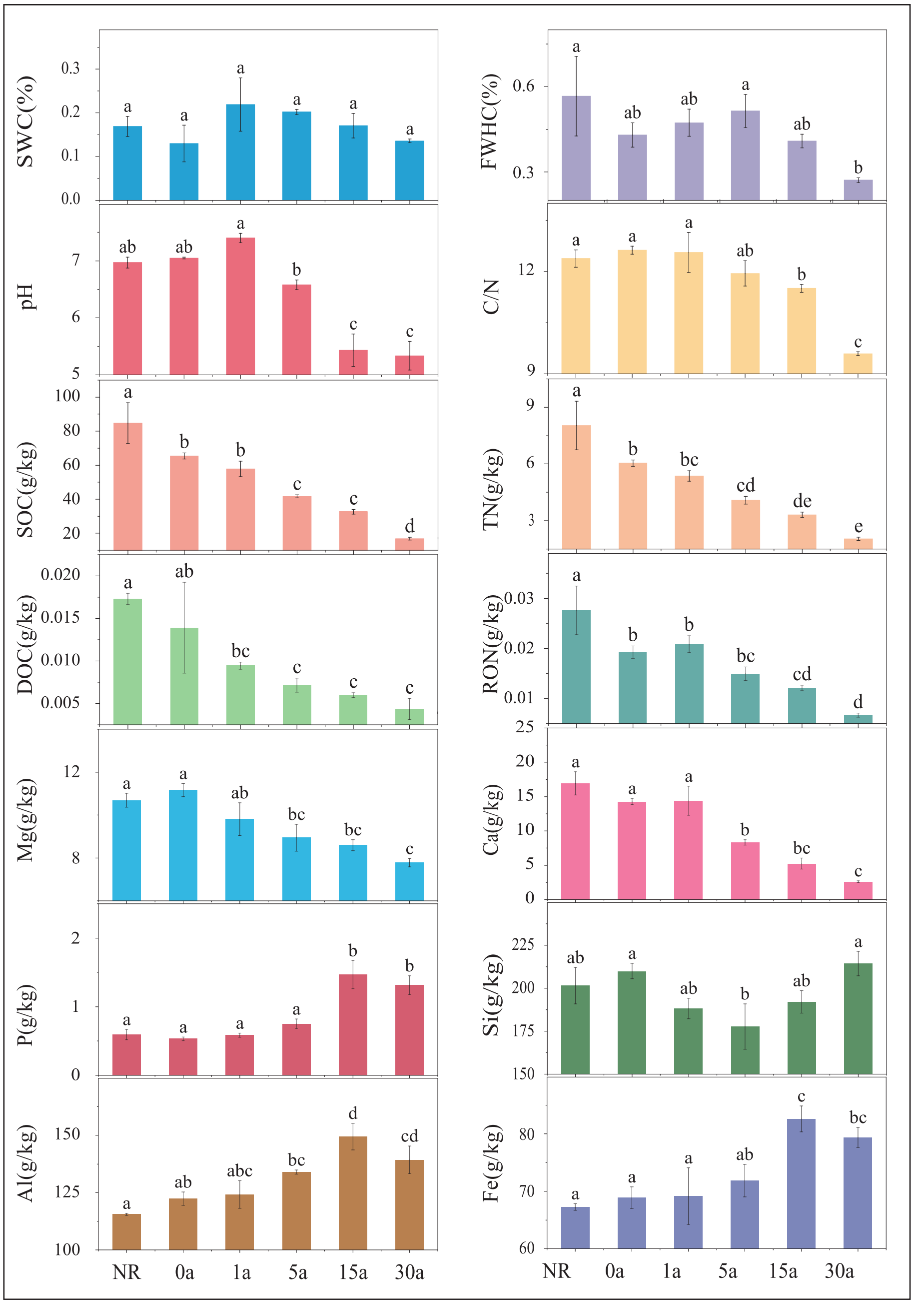

Figure 2: Soil physical and chemical indicators under different stages of cultivation.

Note: Error bars corresponded to the standard deviation (SD). different letters indicate significant differences among different stages of cultivation (one-way ANOVA followed by Duncan's test, $P<0.05$).

3.2 ESTABLISHMENT OF MDS UNDER PCA

The PCA results (Table S2) showed that the first four PCs with eigenvalues >1 collectively explained 81.593% of the total variance in soil indicators. Based on the MDS selection criteria, Ca exhibited high factor loadings in PC1 and was strongly correlated with SOC, TN, C/N, DOC, RON, P, FWHC, Mg, P, Al, Fe, and SBD (Figure S1). Consequently, Ca was selected as a representative indicator for MDS. Similarly, Silt was chosen from PC2, and Si from PC3. The pH value in PC4 was excluded because it had a low factor loading (< 0.6). Ultimately, Ca, Silt and Si were selected to constitute the MDS.

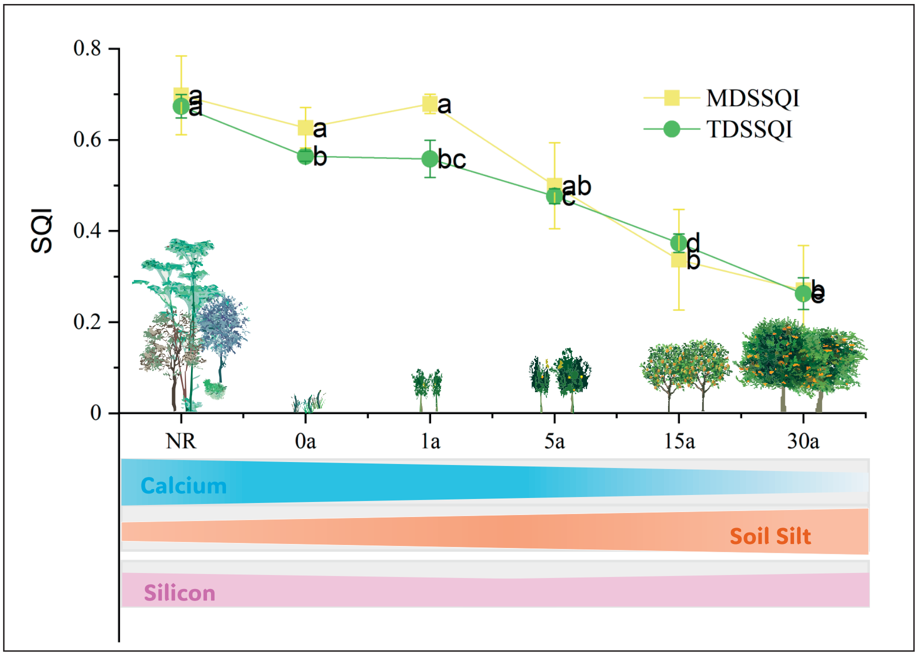

Figure 3: Mean values of SQI based on TDS and MDS methods.

3.3 EVALUATION OF SQI WITH THE TDS AND MDS METHODS

The SQI values calculated using the TDS method (Figure 3) ranged from 0.26 to 0.67 and showed highly significant variation ($P < 0.05$) across cultivation durations. The no-tillage site exhibited the highest SQI, followed by 0 a. The SQI decreased with increasing cultivation time, with the lowest value observed at 30 a. Using the MDS method, SQI values ranged from 0.27 to 0.70 and showed no significant differences among NR, 0 a and 1 a ($P > 0.05$), but these indicators were statistically distinct from those at 5 a, 15 a and 30 a ($P < 0.05$). The highest SQI value under the MDS method was also observed in NR, followed by 1 a, differing slightly from the TDS method. The SQI value for 0 a fell between NR and 1 a. In summary, soil quality in the study area declined progressively from NR to 30 a of cultivation. The SQI values derived from both the TDS and MDS methods generally followed the same ranking from the highest to lowest across different cultivation stages.

Linear regression analysis was employed to evaluate the relationship between SQI values derived from the MDS and TDS methods. The results (Figure S2) indicated a significant positive correlation between the two sets of SQI values, with a coefficient of determination (R^2) of 0.67 ($P < 0.01$).

3.4 LIMITING SOIL INDICATORS FOR SOIL QUALITY

A radar diagram was used to visualize the score of all soil parameters, helping to identify key indicators that limit soil quality (Figure 4). The plotted lines corresponding to different cultivation durations intersect the axes, projecting the scores of each indicator onto the diagram. Intersections near the outer edges of the radar indicate higher soil quality, while those closer to the center reflect poorer soil quality. The results revealed that NR had the highest soil quality under the TDS method. As cultivation duration increased, the radar profile converged toward the center, indicating a progressive decline in soil quality. The lowest soil quality was observed after 30 years of cultivation, with major limiting factors including Ca, Mg, C and N contents, FWHC, and SBD. At 15 a, soil quality was primarily constrained by Fe and Al oxides. For 5 a, soil texture, particularly clay and silt content, was

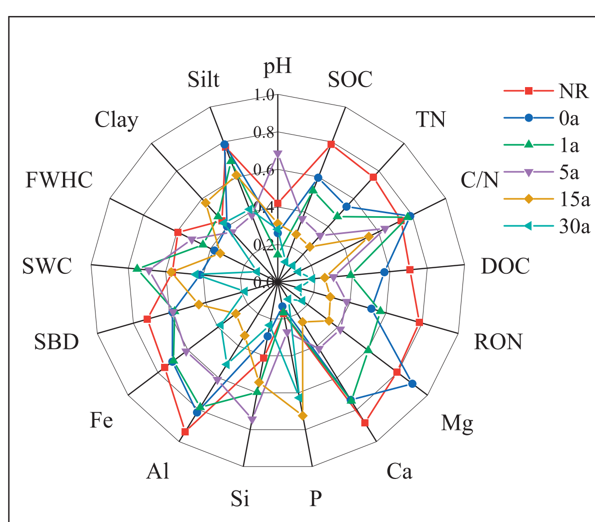

Figure 4: The limiting factors of soil quality index for SQI.

the main limiting factor. After 1 year of cultivation, pH was the dominant constraint, while SWC and P were the significant limiting factors at the initial stage (0a). With increasing cultivation duration, parameters such as SOC, TN, C/N, DOC, RON, Ca, and Mg showed consistent reduction toward the center of the diagram. The greatest declines were observed in Ca and Mg, followed by soil carbon and nitrogen components (including SOC, DOC, TN and RON), indicating that long-term cultivation in karst areas accelerates the depletion of organic matter and base cations, leading to progressive degradation of soil quality.

4. DISCUSSION

4.1 SOIL QUALITY INDEX METHODS AND SELECTED SOIL INDICATORS

Cultivation significantly alters soil physicochemical properties, highlighting the importance of a comprehensive understanding of soil quality for sustainable land management. The selection of appropriate soil parameters is critical for accurately assessing soil quality. Soil quality indices have gained widespread recognition due to their reliability and precision (Doran and Parkin, 1994; Zhang et al., 2011; Griffiths et al., 2010; Andrews et al., 2002). However, identifying the most representative soil indicators remains a challenge. While the TDS method provides more comprehensive evaluation, the Minimum Data Set (MDS) method offers practical advantages by minimizing data redundancy, reducing time, and lowering costs (Zhang et al., 2019; Raiesi, 2017).

In this study, 17 soil variables were analyzed using TDS, while three key parameters, Ca, Silt and Si were selected for MDS through PCA to minimize redundancy. The MDS served as a robust composite index, effectively reflecting soil nutrients, soil structure, and pedogenic processes. The strong positive correlation (R^2=0.67) between MDS and TDS methods highlights their comparable accuracy in assessing soil quality. Notably, the MDS method, despite relying on fewer indicators, achieved performance similar to the more exhaustive TDS approach. This suggests that Ca, Silt, and Si in the MDS are robust indicators for quantifying the impacts of cultivation on soil quality in karst areas, offering an efficient alternative to the TDS method.

4.2 EFFECT OF GEOLOGICAL BACKGROUND ON SOIL QUALITY

The geochemical characteristics of calcareous soils in karst regions are fundamentally influenced by their origin in carbonate bedrock, which leads to naturally high levels of Ca and Mg. Elevated CO_2 levels in water, atmosphere and soil promote the dissolution of carbonate minerals, releasing Ca^{2+} and enhancing its bioavailability in these soils (Yang et al., 2021). Over time, however, prolonged rainfall leads to intense leaching and decalcification, gradually depleting base cations.

Soil organic carbon is a well-established indicator of soil quality (Schnitzer et al., 2006; Griffiths et al., 2010; Davari et al., 2020; Huang et al., 2021), and it was highly weighted in the PCA results of our findings (Table S2). A significant correlation between Ca and SOC was observed, likely due to their symbiotic relationship (Yang et al., 2018; Rowley et al., 2018). Calcium forms organo-mineral complexes such as calcium humate with soil organic matter, improving soil structural stability and promoting organic matter accumulation (Muneer and Oades, 1989a, b, c). Additionally, Ca^{2+} form multivalent cationic bridges between organic ligands and soil mineral surfaces, effectively protecting SOC from microbial decomposition (Rowley et al., 2018). Beyond its structural role, Ca is also an essential plant nutrient, positively impacting on net primary productivity (NPP) and thus increasing above- and belowground biomass inputs to soil organic matter (Carmeis Filho et al., 2017; Haynes and Naidu, 1998). Moreover, changes in Ca^{2+} can modulate bacterial community composition and function, influencing soil carbon and nitrogen cycling (Tang et al., 2019). In the calcareous soils of karst area, Ca emerged as a dominant indicator of soil quality due to its high contribution in PCA, strong association with SOC, and regulatory role in microbial processes (Yang et al., 2019b).

Soil formation in karst regions involves two main processes: carbonate dissolution and subsequent bedrock weathering (Wang et al., 1999). In these environments, Si is primarily found in quartz and silicate minerals, which have low solubility under subaerial conditions. Consequently, Si accumulates in residual mineral fractions, contributing to the stability of weathered rock residues (Lasaga, 1984; White et al., 1996). The Si:(Fe+Al) ratio (Figure S3) serves as an indicator of weathering intensity in carbonate rocks (Sugitani et al., 1996). This ratio initially decreased with cultivation age but increased after 30 years, suggesting that carbonate dissolution dominated early soil formation stages, accompanied by allitization. In later stages, however, the decreasing MgO and CaO contents-typical of carbonate rocks, indicated extensive leaching due to high CO_2 and water levels. This process also caused weathering and decomposition acid-insoluble residues containing Ca and Mg (host minerals include amphibole, plagioclase, montmorillonite, and chlorite, etc.). The depletion of base cations such as Ca^{2+} and Mg^{2+} may reduce soil buffering capacity, thereby enhancing susceptibility to acidification driven by agricultural inputs or root exudates, contributing to an increase in SiO_2 (Si being a component of quartz and silicate) and decreased Fe_2O_3 and Al_2O_3 (Al from silicate and aluminum oxides and Fe from hornblende, chlorite, and iron oxides). These trends reflect the weathering of acid-insoluble residues due to cultivation. Carbonate weathering occurs more slowly than dissolution. In this study, acid-insoluble residues weathered only in the advanced stages of cultivation, with human activities accelerating both soil-forming processes. Consequently, Si was included in the MDS as mineralogical evidence of soil formation through carbonate weathering, indicating that soil derived from weathered carbonate rocks, widespread in southwest China, are an important source of soil in karst areas.

4.3 EFFECT OF CULTIVATION ON SOIL QUALITY

Agricultural practices are likely to reduce the content of soil organic matter, alter soil structure, decrease porosity and increase soil bulk density (Jones, 1971; Jonas et al., 2016). In this study, most soil physicochemical properties exhibited statistically significant differences, indicating that cultivation has disturbed the soil, contributing to property changes and substantial impacts on soil function (Davari et al., 2020; Jaiyeoba, 2003; Khormali et al., 2009).

The highest levels of SOC and TN were observed in NR, but reclamation and agricultural operations caused severe losses of SOC and TN. These losses were influenced by the degree of human disturbance and the annual harvesting of citrus, which removed C and N from the nutrient cycle (Yang et al., 2019a; Jaiyeoba, 2003; Wang et al., 2021). Additionally, fire-based reclamation can degrade soil aggregate structure and microbial communities in a short time scales, further contributing to SOM loss (Jones et al., 2016; Jaiyeoba, 2003). The imbalance between limited organic inputs and increased mineralization rates under tillage resulted in a net decline in SOC over time (Jones, 1971).

Soil pH decreased by nearly two units with prolonged cultivation, indicating progressive acidification of the initially alkaline calcareous soils. This shift is attributed to several factors: (1) root exudation of organic acids by citrus plants, (2) accumulation of phenolic compounds from litter decomposition, and (3) nitrification of ammonium-based fertilizers (Zhang et al., 2000; Chatterjee et al., 2017). Acidification reduces base saturation and cation exchange capacity, further compromising soil buffering and fertility.

Soil texture is a reliable indicator of soil properties, including erosion potential, pore structure and permeability (Plante et al., 2006). Silt and clay particles have larger surface areas than sand, giving them strong sorption properties and facilitating the formation of soil aggregates. In organically rich soils, these particulars combine with organic material to form stable aggregates, resulting in high water retention, permeability, and homogeneity. Conversely, dispersed clay particles can clog soil pores during droughts, leading to soil slumping and reduced agricultural productivity (Ferreras et al., 2000; Six et al., 2000). Thus, silt content serves as a critical physical indicator of soil structure, and its decline has significant implications for soil chemical and biology. Khormali et al. (2009) have reported differences in soil texture, attributing increased silt content in the surface layer following deforestation to erosion and the loss of clay. In this study, the gradual rise in soil silt content with extended cultivation reflects accelerated physical fragmentation of soil particles, contributing to a finer-grained soil texture. An increase in silt content may indicate enhanced physical disaggregation due to tillage, which could elevate the susceptibility of soil to water erosion, particularly in sloping landscapes characteristic of karst regions. The observed increases in clay and silt content contrast with typical agricultural systems, possibly reflecting ongoing weathering of carbonate bedrock or localized deposition in this karst landscape, justifying the inclusion of silt in the MDS analysis.

The SQI of NR was significantly higher than that of all cultivated treatments, confirming that prolonged agriculture has degraded soil quality. This finding aligns with numerous studies highlighting that frequent tillage and harvesting over time may contribute to soil structure degradation and a loss of soil organic matter inputs (Schnitzer et al., 2006). In contrast, revegetation processes have been shown to improve soil structure and soil properties (Zhang et al., 2019; Huang et al., 2021; Xiao et al., 2017; Rojas et al., 2016). Soil quality is influenced by multiple factors, including lithology, land use, vegetation type and human activity (Zhang et al., 2019), with varying constraints at different cultivation stages. Compared to NR, there was a significant loss of SOM in the 0a treatment following burning. Continuous cultivation led to the leaching of Ca and Mg from karst soils, undermining the stability of SOM (Yang et al.2019b). This process is accompanied by an increase in the clay and silt content of the soil, leading to greater soil compaction and reduced water and nutrient retention capacity, which all adversely affect agricultural production. Based on the soil factors selected by MDS, it is reasonable to conclude that the sharp decline in soil quality of artificial forest land in karst areas is primarily due to two factors: (1) Geological constraints: the low abundance of acid-insoluble residuum in carbonate bedrock limits the potential for new soil formation; (2) Anthropogenic acceleration: cultivation practices intensify erosion, SOM loss, and weathering, pushing soils toward irreversible degradation.

5. CONCLUSION

This study demonstrates that agricultural cultivation exerts a profound and time-dependent degradation effect on soil quality in karst ecosystems. Key findings include: (1) Soil quality exhibits a progressive decline with increasing duration of cultivation, highlighting the substantial adverse impact of farming on the soil physicochemical properties and overall quality of the soil. (2) The MDS method identified Ca, silt and Si as pivotal indicators for quantifying tillage's effect on soil quality. (3) The severe soil degradation in the karst area is attributed primarily to the inherently low abundance of acid-insoluble residues in the carbonate bedrock which limits soil formation coupled with human activities that disrupt pedogenic processes. In summary, integrating cultivation effects into SQI evaluations fosters a robust linkage between soil quality metrics and agricultural management practices. This study provides a scientific basis for developing targeted strategies aimed at promoting sustainable soil management, restoring soil fertility, and enhancing ecosystem services in fragile karst environments.

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SUPPLEMENT

Table S1: The C.V and range of sensitive soil indicators.

	Min	Max	Mean	S.E	Coefficient of variation	Range
ROC	0.1	1.37	0.549	0.34	0.619	1.27
Sand	1.55	36.66	13.571	10.066	0.742	35.11

Table S2: Principal component analysis of soil quality indicators.

Soil quality indexes	1st principal component		2nd principal component		3rd principal component		4th principal component	
	Capacity	Weight	Capacity	Weight	Capacity	Weight	Capacity	Weight
pH	0.08	0.007	-0.512	0.01	-0.02	0.005	0.564	0.136
SOC	**0.942**	0.087	0.177	0.035	0.028	0.007	-0.199	0.048
TN	**0.913**	0.084	0.214	0.042	0.013	0.003	-0.227	0.055
C/N	**0.82**	0.076	-0.149	0.029	0.288	0.068	0.11	0.027
DOC	**0.795**	0.073	0.228	0.044	-0.232	0.055	0.206	0.05
RON	**0.889**	0.082	0.193	0.038	0.184	0.043	-0.265	0.064
SWC	0.215	0.02	-0.414	0.081	**0.622**	0.146	-0.238	0.058
FWHC	**0.645**	0.059	-0.384	0.075	0.309	0.073	0.395	0.095
Mg	**0.79**	0.073	0.233	0.045	-0.121	0.028	0.23	0.056
Ca	**0.955**	0.088	0.108	0.021	-0.022	0.005	-0.141	0.034
P	**-0.823**	0.076	0.267	0.052	0.298	0.07	-0.003	0.001
Si	-0.007	0.001	-0.108	0.021	**0.779**	0.183	-0.277	0.067
Al	**0.815**	0.075	-0.196	0.038	-0.382	0.09	-0.125	0.03
Fe	**0.8**	0.074	-0.24	0.047	-0.173	0.041	-0.145	0.035
Clay	-0.121	0.011	**0.633**	0.124	0.332	0.078	0.508	0.123
Silt	0.442	0.041	**0.803**	0.157	0.229	0.054	0.123	0.03
SBD	**0.792**	0.073	-0.265	0.052	0.215	0.051	0.381	0.092
Variance contribution /%	50.822		12.527		10.295		7.95	
Cumulative variance contribution /%	50.822		63.349		73.644		81.593	

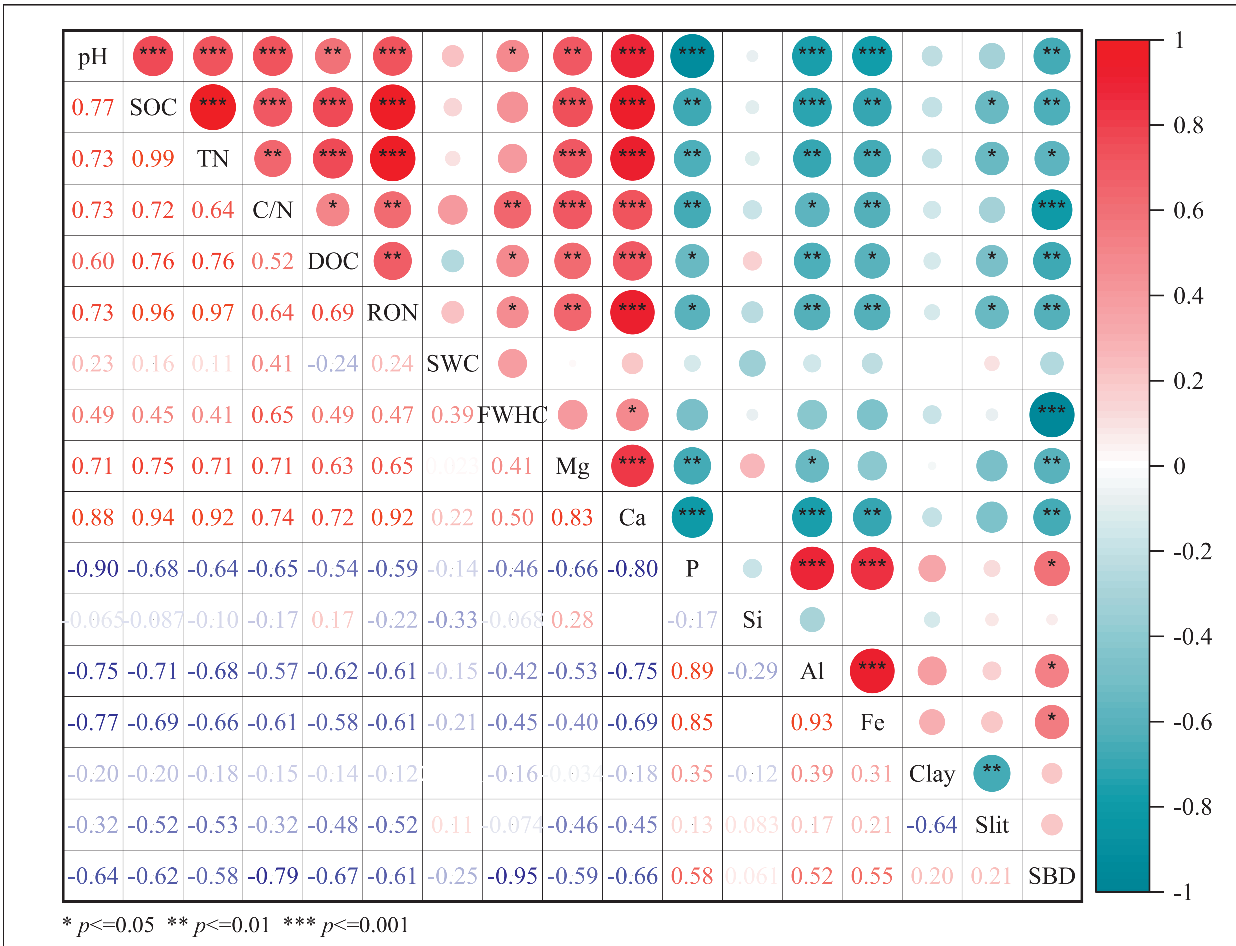

*Figure S1: Correlogram of the dataset. *** correlation is significant at P ≤0.01 level; ** correlation is significant at P <0.01 level; * correlation is significant at P <0.05 level.*

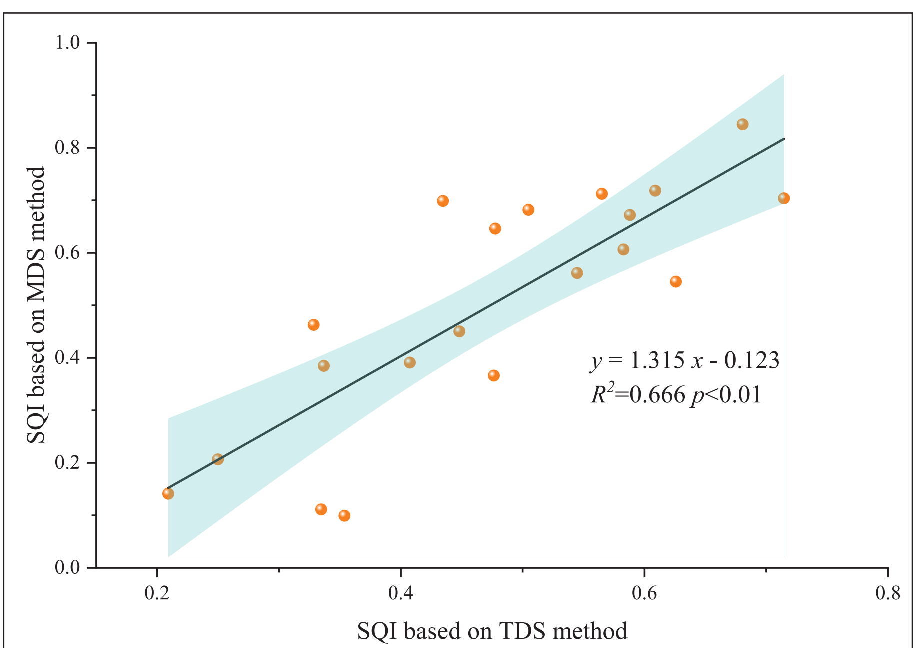

Figure S2: Linear regression of SQI based on TDS and MDS methods.

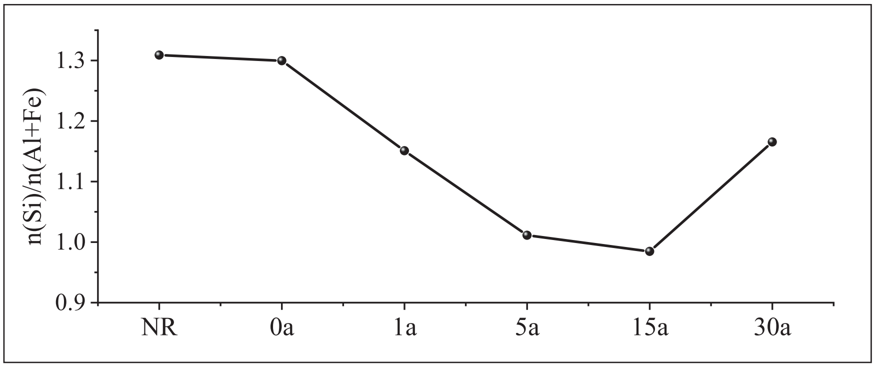

Figure S3: Weathering indices.