OPTIMAL INDICATORS FOR MICROTOPOGRAPHY-ORIENTED SOIL QUALITY ASSESSMENT IN SEMIARID REGIONS OF THE LOESS PLATEAU, CHINA
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中国黄土高原半干旱区微地形土壤质量评价指标筛优

Ph.D. Stud. Yaojun Bo [1,2] , Prof. Ph.D. Qingke Zhu [1], Ph.D. Stud. Weijun Zhao [1]
[1] College of Soil and Water Conservation, Beijing Forestry University / China; [2] College of Life Sciences,Yulin University / China
Tel: +86 153 8912 0000; E-mail: byj212@126.com

Abstract: *This study was aimed to identify optimal indicators for microtopography-oriented soil quality assessment. Twenty-two soil physicochemical and biological parameters were investigated at 93 sampling points in five different microtopographic units in semiarid regions of the Loess Plateau, where the principal functions of eroded agriculture soils are related to productivity and anti-erosion ability. The selection of soil quality indicators was accomplished using a combination of sensitivity analysis, principal component analysis, and stepwise regression. The indicators used for microtopography-oriented soil quality assessment were found to be moderately sensitive with no high sensitivity. Moderately sensitive soil quality indicators including the levels of sucrase activity (SA), available phosphorus (AP), total nitrogen (TN), soil organic matter (SOM), and urease (UA) are the major objectives of soil quality restoration and regulation in the study area. The 22 soil physicochemical and biological parameters indicative of soil quality were grouped into seven soil quality factors; SOM, water-holding capacity, total phosphorous (TP), total potassium (TK), soil water content, capillary porosity, and AP. Optimal indicators for microtopography-oriented soil quality assessment in the study area were identified as; SOM, TN, SA, UA, AP, TP, CaCO3, APA, and TK. Among these, the SOM level was the key indicator for characterizing soil quality in relation to microtopography in the semiarid loess region. This study provides reference information for the conservation of agricultural soils and improvement of low-yield farmlands in semiarid regions of the Loess Plateau. This will enable better agricultural decisions by the residents and aid decision making by the government according to local conditions.*

Keywords: *microtopography; soil quality; assessment indicators; semiarid loess region*

摘要: *针对黄土高原半干旱区侵蚀农业土壤最主要的功能-生产力和抗侵蚀能力,运用敏感性分析、 主成分分析和逐步回归分析法,对5种微地形93个样点的22项土壤属性指标进行了筛选。结果表明: 研究区各微地形土壤质量指标敏感性适中，无高度敏感指标。蔗糖酶、速效磷、全氮、有机质和脲酶为中度敏感指标，是土壤质量恢复与调控的主要目标。研究区微地形土壤的22项理化及生物属性指标可以被归纳为7个土壤质量因子，即有机质因子、持水量因子、全磷因子、钾因子、水分因子、孔隙因子和速效磷因子。黄土高原半干旱区微地形土壤质量评价指标为有机质、全氮、蔗糖酶、脲酶、速效磷、全磷、*$CaCO_3$*、碱性磷酸酶和全钾，其中，有机质是表征黄土高原半干旱区微地形土壤质量的关键指标。本研究为农业土壤保育、低产地改良及因地制宜地指导农业生产提供科学依据。*

关键词: *微地形；土壤质量；评价指标；黄土高原半干旱区*

INTRODUCTION

The semiarid region of China’s Loess Plateau comprises undulating ridges and hills with crisscrossing ravines and gullies. In this region, soil erosion is one of the primary causes of soil quality degradation[1]. In recent years, ecological restoration measures such as returning farmland to forest or grassland and enclosures for natural vegetation rehabilitation have been implemented, which to some extent have mitigated the exacerbation of water and soil loss[2]. However, the situation of soil erosion remains severe. The action of water erosion not only forms erosion gullies but also fragments slopes into microtopographically diverse landforms such as collapse, gullies, furrows, gently sloped terraces, scarps, and other units[3] (Fig. 1). Soil quality is a comprehensive reflection of soil physicochemical and biological properties, which integrally measures the ability of the soil to supply the nutrients necessary for life and produce biological materials; to accommodate, degrade, and purify pollutants and maintain ecological balance; and to impact and improve the health of plants, animals, and human beings[4]. Despite the widely recognized importance of soil quality for sustainable human development, there is

引言

作黄土高原半干旱区梁峁起伏、沟壑纵横，土壤侵蚀成为该区土壤质量退化的主要原因之一[1]，近年来该区退耕还林还草及封禁等措施的实施缓解了水土流失的加剧，但土壤侵蚀仍然严峻[2]，在水力侵蚀作用下不仅形成各种侵蚀沟，而且把坡面分割成不同碎块，形成变化多端的微地形地貌如塌陷、切沟、浅沟、缓台和陡坎[3]（图1）。土壤质量是土壤在一定生态系统内提供生命必需养分和生产生物物质的能力,容纳、降解、净化污染物质和维护生态平衡的能力,影响和促进植物、动物和人类生命安全和健康的能力之综合量度,是土壤理化及生物属性的综合反映[4]。尽管土壤质量对于人类可持续发展的重要性已得到广泛认同,但是土壤学家至今未能就如何评价土壤质量达成共识[5]。土壤质量评价的目

presently a lack of consensus on how to assess soil quality[5]. Soil quality assessment aims to comprehensively analyze all aspects of soil functions in a wide scope, including the ability to maintain biological productivity, environmental quality, and plant and animal health[6]. The major goal of assessment lies in the understanding of agricultural soils for effective management and protection. Because soil quality cannot be measured directly, assessment of soil quality becomes necessary. A first step in soil quality assessment is to establish a measurable indicator system that can comprehensively reflect the quality of agricultural soils. Because of the diverse utilization patterns and regional variability of soil resources, different indicators have been used for assessing soil quality but no assessment indicators are commonly accepted [7-9]. The characterization theory and method as well as the assessment indicators for soil quality are currently the main subject of soil quality assessment research internationally and domestically[10-13]. However, few studies have been reported on soil quality indicators oriented to microtopography. Additionally, the existing soil quality assessments have largely used indicators artificially selected rather than statistically screened out from a large number of soil physicochemical and biological indicators [10, 14, 15]. The artificially selected indicators are inevitably subjective and arbitrary to some extent.

In semiarid regions of the Loess Plateau, the unique erosive environment and microtopographical diverse landscape have caused serious soil degradation and erosion. Therefore, quality restoration, conservation, and directed cultivation of agricultural soils become an important work for agricultural eco-environmental construction in semiarid loess regions. This present study has the following objectives: (1) to identify microtopography-oriented soil quality factors from 22 soil physicochemical and biological indicators of soil quality in semiarid regions of the Loess Plateau; (2) to analyze the effects of the diverse microtopography on soil quality factors; and (3) and to screen out optimal indicators for microtopography-oriented soil quality assessment in the semiarid loess region. The results will provide reference information for agricultural soil quality assessment and its variation patterns and rational sampling, and will aid agricultural soil management

MATERIAL AND METHOD

Study site

The study area comprised the Hejiagou catchments of Wuqi County, Yan'an City and the northern Shaanxi Province, China (36°33′33″–37°24′27″N and 107°38′57″–108°32′49″ E). The catchments stand at 1233–1890 m above sea level and have a semiarid continental monsoon climate. The area has an average annual temperature of 7.8°C, an accumulative temperature (≥10°C) of 2817.8°C, 2400 average annual sunshine hours, a frost-free period of 96–146 days and an average annual evaporation of 400–450 mm[3]. The topography is gully and hilly, and the vegetation is a transition from forest steppes to grasslands. Since 1998, the catchments have been closed to facilitate the rehabilitation of vegetation, and the primary vegetation now consists of herbaceous communities accompanied by sparse undershrubs and tree saplings, as well as arbor species on valley bed lands.

Sample collection and preparation

The number of soil sampling sites of the different microtopographies of the study area were determined depending on its topographical characters, topographical distribution and the sizes of its microtopographies as follows (Figure 1 and Table 1): 30 sampling sites in the furrows, 12 sampling sites in the gullies, 18 sampling sites in the

标是在更为广泛的范围内综合分析土壤各个方面的功能,包括保持生物生产力、环境质量以及动植物健康的能力[6],目的在于正确认识农业土壤,从而有效管理和保护农业土壤。然而,土壤质量不能够直接测定,要进行土壤质量评价,首先必须确定可测定的、全面反映农业土壤质量的评价指标体系。 由于对土壤资源利用方式的多样性及所处区域的差异,土壤质量的评价指标也不一样,目前尚无公认的评价指标[7-9]。 有关土壤质量表征的理论和方法、 土壤质量评价指标是当前国际土壤质量研究的热点,也是我国土壤质量研究的重点[10-13]。目前国内有关微地形土壤质量指标方面的研究报道较少,多数研究者在土壤质量评价中所采用的评价指标是人为确定的,而不是从大量表征土壤理化生物属性的指标中筛选出的 [10, 14, 15],难免带有一定的主观随意性。

黄土高原半干旱区特殊的侵蚀环境造就了严重退化的侵蚀土壤,对微地形农业土壤质量恢复、保育和定向培育成为该区农业生态环境建设的重要内容。本研究的目的是（1）从22项土壤属性中识别微地形土壤质量因子；（2）分析微地形对土壤质量因子的影响；（3）筛选出黄土高原半干旱区微地形土壤质量评价指标。以期为该区农业土壤质量评价及其变异规律研究、科学取样及农业土壤管理等提供理论依据。

材料与方法

试验区概况

研究区位于陕西延安市吴起县合家沟流域(N36°33′33″-37°24′27″，E107°38′57″- 108°32′49″)，海拔1233-1890m， 属半干旱温带大陆性季风气候。 年均温7.8℃，≥10℃积温2817.8℃；年均日照数2400h，无霜期96-146d；年均降雨478.3mm， 蒸发量 400-450mm[3]。 属典型黄土丘陵沟壑区， 植被为森林草原向草原过渡类型，自1998年开始封育，现自然恢复植被以草本群落为主，零星分布有小灌木及乔木幼苗，沟底现少量乔木树种。

土壤样品采集与处理

根据研究区地貌特征和微地形实际面积确定采样点数(图1和表1)：浅沟30个、切沟12个、塌陷18个、缓台9个、陡坎9个，共78个；每类微地形原状坡对照3个，计

collapses, nine sampling sites on the gently sloped terraces and nine sampling sites on the scarps, making a total of 78 sampling sites. Three sites were chosen as control sampling sites in the undisturbed areas of each microtopography type, making a total of 15 control soil sampling sites. Soil sampling was conducted at 0–20 cm, 20–40 cm, and 40–60 cm. The soils sampled from the three soil layers at three neighboring sampling points were mixed and prepared as one soil sample by quartering, to a total of 93 soil samples.

A 500-g portion of each soil sample was air-dried, pulverized and sieved to 1 mm and 0.25 mm in a campus-based lab for future use.

15个。 采样层次为0-20cm、20-40cm和 40-60cm， 选取 3个相邻样点按四分法取各层混合样，共采样93个。

每个土样采集约500g带回实验室风干、研磨、过筛(1mm和0.25mm)后备用。

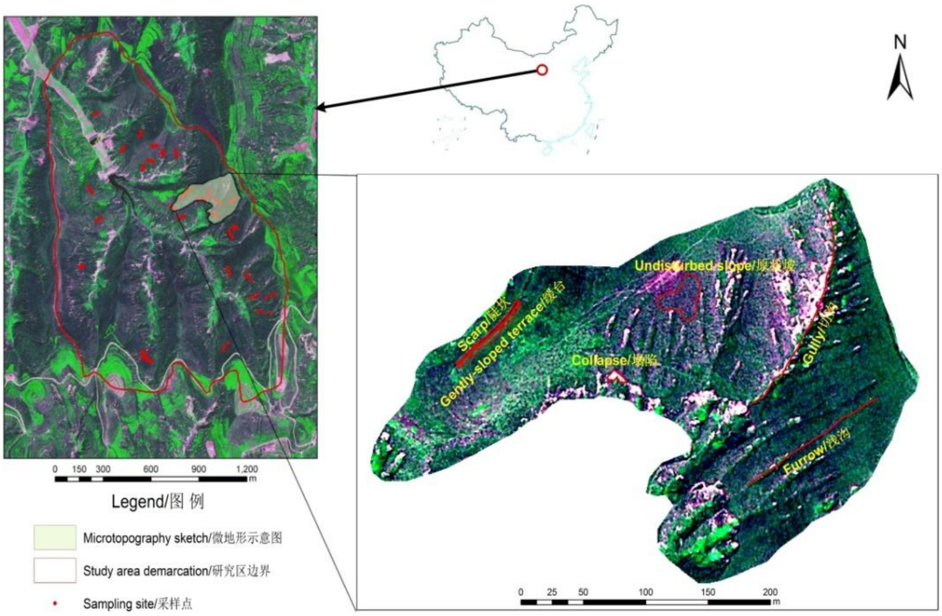

Fig. 1 - A sketch of the microtopography (QuickBird image) of the study area

Table 1 / *表1*

Basic status of the study plots

Sample number	*Microtopography*	*Altitude* [m]	*Degree of slope* [°]	*Slope position*	*Slope aspect*
30	*Furrow*	1358-1413	12-37	U9，M12，L9	A6，U3，SA18，SU3
12	*Gully*	1399-1419	23-27	U3，M9	A6，SA3，SU3
18	*Collapse*	1351-1383	12-20	M12，L6	A6，SA12
9	*Gently-sloped terrace*	1342-1365	17-27	M9	U3，SU6
9	*Scarp*	1396-1416	38-43	M9	A3，U3，SA3
15	*Undisturbed slope*	1341-1423	17-36	U3，M9，L3	A3，U3，SA6，SU3

Note: U, M, and L mean upper, middle, and lower positions, respectively; and A, U, SA, and SU mean adret, udbac, semi-adret, and semi-udbac, respectively. The numbers in the description of slope position and slope aspect are the number of samples

Soil parameter measurements

Eight soil physical parameters [16] were determined where the bulk density (BD), maximum water-holding capacity (MaxWHC), minimum water-holding capacity (MinWHC), and capillary water-holding capacity (CWHC) were measured by ring shear testing, while the soil water content (SWC) was measured by oven drying. The other soil parameters were calculated using the following formulae:

土壤质量指标测定方法

物理指标[16]8个。容重、最大持水量、最小持水量和毛管持水量用环刀法；含水量用烘干法。部分物理指标计算如下：

$$\Psi = \Psi^1 + \Psi^2 \tag{1}$$

$$\Psi^1 = c \times \rho \tag{2}$$

$$\Psi^2 = (c_{\max} - c) \times \rho \tag{3}$$

where,
Ψ, Ψ^1 and Ψ^2 are the total capillary porosity (TCP, %), capillary porosity (CP), and non-capillary porosity (NCP), respectively, c is the CWHC, ρ is the BD of the soil (g/cm^3), and c_{max} is the MaxWHC.

Ten soil chemical parameters [17] were analyzed as follows: Total nitrogen (TN) by the semi-trace Kjeldahl method; total phosphorus (TP) by NaOH liquation and molybdenum blue colorimetry; total potassium (TK) by NaOH liquation and flame photometry; available nitrogen (AN) by alkaline hydrolysis and diffusion; available phosphorous (AP) by extraction with 0.5 mol L^{-1} $NaHCO_3$ and silica-molybdenum blue colorimetry; available potassium (AK) by extraction with NH_4OAc and flame photometry; soil organic matter (SOM) by heated potassium dichromate oxidation; pH was measured by potentiometry using a pH meter; cation exchange capacity (CEC) was determined by NaOAc flame photometry; and $CaCO_3$ by NaOH-neutralized titration.

Four soil biological parameters [18] were determined, as follows: the sucrase activity (SA) by 3, 5-dinitrosalicylic acid colorimetry; the alkaline phosphatase activity (APA) by disodium phenyl phosphate colorimetry; the catalase activity (CA) by permanganate titration; and the urease activity (UA) by citric acid colorimetry.

Assessment indicator selection principles

(1) Principle of pertinence

Soil quality not only depends on the major functions, type, and region of the soil, but also relies on external factors such as microtopography and soil management measures[19]. Because of different demands for soil functions, clarification of the assessment objectives is necessary (i.e., specific soil functions and problems) when selecting indicators of soil quality. In the erosive environment of microtopographically diverse semiarid loess regions, fertility quality is of greater importance to soil quality than environmental quality and health quality. This is because fertility quality directly relates to the soil water carrying capacity for vegetation and the restoration capacity of vegetation, thus having implications for eco-environmental restoration and re-construction in the semiarid loess regions. In this region, soil fertility quality is mainly constrained by water and soil loss; thus, vegetation restoration and re-construction (e.g., SOM) is an important aspect of soil quality assessment.

(2) Principle of regionality

Soil quality has regional characteristics under different environmental conditions [20]. The spatial difference in soil quality should be reflected by the assessment indicators selected, and local conditions should be taken into consideration for establishing assessment indicators with regional representativeness. In relation to microtopography, soil quality is determined by the extent of erosion, and soil quality variations are closely related to the erosion process. In the semiarid loess regions, soil quality assessment should highlight the particularity of the erosive environment and reflect the condition and variation patterns of agricultural soil quality under different conditions of microtopography and erosion intensity.

(3) Principle of sensitivity combined with stability

Soil quality indicators are required to sensitively reflect the variations in soil erosion, tillage management, and utilization patterns. However, soil quality indicators should remain relatively stable within a certain period, rather than a higher sensitivity meaning better indicators.

Statistical analysis

Descriptive statistics (coefficient of variation and relative range) and principal component analysis were

式中，

Ψ是总孔隙度(%)，Ψ^1 为毛管孔隙度，Ψ^2为非毛管孔隙度，c 为毛管持水量，ρ为容重，c_{max}为最大持水量。

化学指标10个[17]。速效氮：碱解扩散法；速效磷：0.5mol/L $NaHCO_3$ 浸提钼蓝比色法； 速效钾：NH_4OAc浸提火焰光度法；全氮：半微量凯氏法；全磷：NaOH熔融钼蓝比色法；全钾：NaOH熔融火焰光度法；有机质：重铬酸钾容量外加热法；CEC：NaOAc火焰光度法；$CaCO_3$：NaOH中和滴定法.

pH值(2.5:1)：酸度计电位法；生物学指标[18]4个。蔗糖酶：3，5-二硝基水杨酸比色法； 碱性磷酸酶： 磷酸苯二钠比色法；过氧化氢酶：高锰酸钾滴定法；脲酶：柠檬酸比色法。

评价指标选取原则

（1）针对性原则

土壤质量不仅依赖于土壤的主要功能、类型和所处的地域,也依赖于外界因素,如微地形和土壤管理措施等[19]。由于人们对土壤功能的需求不同,在选取土壤质量表征指标时,要明确土壤质量评价目标,即针对土壤哪方面功能、何种问题而进行。就黄土高原半干旱区微地形侵蚀环境下的土壤而言,其肥力质量较之环境质量和健康质量显得更为重要。因为肥力质量直接关系到土壤植被承载力和植被恢复能力,对黄土高原半干旱区的生态环境恢复重建具有重要意义。黄土高原半干旱区土壤肥力质量主要受制于水土流失,因此植被恢复重建(如土壤有机质等)是土壤质量评价的重要方面。

（2）区域性原则

不同环境条件下土壤质量有其区域特点[20],指标选取应反映这种空间差异,因地制宜地设立具有区域代表性的指标。微地形土壤质量取决于受侵蚀程度,其质量变化与侵蚀过程密切相关。在黄土高原半干旱区,土壤质量评价要突出其侵蚀环境的特殊性,反映不同微地形与侵蚀强度下土壤质量状况及变化规律。

（3）敏感性与稳定性兼顾原则

土壤质量指标应能较灵敏地反映土壤侵蚀、耕作管理及利用方式的变化,但并非越灵敏越好,而是应当在一定时间内相对稳定。

统计分析方法

用SPSS20.0软件对试验数据进行描述性统计(计算出各

performed in SPSS 20.0 (IBM SPSS Inc., Chicago, IL, USA). Stepwise regression was performed in DPS 7.55 (Data Processing System designed by Tang). Statistical analysis was carried out using mean data of soil parameters at 0–60 cm depth.

Principal component analysis is an important method for multivariate analysis. It essentially involves optimal integration, simplification, and dimensionality reduction of high-dimensional variable systems, and objectively determines the weight of each index to avoid subjective arbitrariness. The focus of comprehensive assessment via principal component analysis is to integrate a multi-objective problem into a single index form both scientifically and objectively point of view. Because soil quality is affected by a variety of factors, principal component analysis provides a practical method for soil quality assessment. Standardization of soil quality assessment indicators is needed to eliminate their effects of inconsistency and being dimensionless on factor loading. In this study, membership functions of soil quality assessment indicators and soil functions were established, and the degree of membership for soil quality assessment indicators was calculated using a single-factor assessment model. In this way, the measured values of soil quality assessment indicators were converted to values between 0 and 1 for normalizing the dimensionless factors of the assessment indicators. Based on a matrix of correlation coefficients, principal component analysis was performed after varimax rotation. The communality of each assessment indicator was derived from the factor loading matrix, which reflects the relative contribution of the indicator to overall variability in soil quality. The weights of individual assessment indicators were converted to values between 0 and 1 by calculating the percentage of individual communality in the sum of communality.

Stepwise regression is an effective method for selection of optimal assessment indicator(s) from a regression equation containing all indicators under the conditions of both-enter-and-exit models and successive elimination of non-significant factors [21]. In the present study, regression analysis (i.e., stepwise regression) was performed with the first, second, third, and fourth principal components (PA1 to PA4, i.e., sample factors with the highest scores in principal component analysis) as the dependent variables, and original variable values of single or multiple indicators that affect each principal component as the independent variables. Stepwise regression was carried out through the *F*-test using the maximum correlation coefficient principle. The principal components selected to characterize soil quality were further analyzed through stepwise regression to choose the one with greatest variability in relation to microtopography. Additionally, the assessment indicators (i.e., soil parameters) that constitute each principal component were subjected to stepwise regression to identify the one with the highest variability in relation to microtopography. Finally, optimal soil quality assessment indicators and the key soil quality characterization indicator were identified.

RESULTS AND ANALYSES

Sensitivity of soil quality indicators

Soil properties vary with microtopography and the variation rate of soil parameters is relatively high. The assessment of soil quality is not only closely related to soil functions but also sensitive to microtopographic differences. Here CV was used as the criterion to evaluate the sensitivity of soil quality indicators. A greater CV value means that the indicator is more sensitive to the variations in microtopography. Table 2 summarizes the descriptive statistics of the 22 soil physicochemical and biological

测定指标的变异系数和相对极差)、主成分分析，用DPS7.55软件进行逐步回归分析。本研究采用0-60cm土层均值数据。

主成分分析是一种重要的多元分析方法，其本质是对高维变量系统进行最佳综合与简化降维，同时客观地确定各个指标的权重，避免主观随意性，而综合评价的焦点是如何科学、客观地将一个多目标问题综合成一个单指标形式。考虑到土壤质量影响因子众多的特点，采用主成分分析法是一种较为可行的评价方法。为了消除评价指标量纲的不同对因子荷载的影响，需要将评价指标标准化，本研究通过建立评价指标与土壤功能之间的隶属函数，利用单因素评价模型计算出评价指标的隶属度，将评价指标的实测值转换为介于0-1之间的数值，实现指标量纲归一化。然后，基于评价指标相关系数矩阵，经过方差最大化旋转后进行主成分分析。由因子荷载矩阵求得土壤各评价指标的公因子方差，其值大小表示该项指标对土壤质量总体变异的贡献，由此求得各项指标的权重值(通过计算各个公因子方差占公因子方差总和的百分数，将权重值转换为0-1的数值)。

逐步回归分析法就是在遵循“有进有出和逐次剔除不显著因子”的条件下从包含全部指标的回归方程中来挑选最优评价指标的一种有效方法[21]。本研究采用回归分析中的逐步回归分析法，分别以主成分分析当中第1、第2、第3和第4主成分样本因子得分最高的为因变量，以影响每个主成分的指标(一个或几个)原始变量值为自变量，逐步进行F值检验，采用调整相关系数R最大为原则，进行逐步回归分析。通过回归分析，对主成分分析所筛选出的表征土壤质量的主成分进一步分析，从而选择出在不同微地形之间差异最大的主成分。同时，对构成各主成分的土壤属性指标进行回归分析，选择出在不同微地形之间差异最大的指标，最终确定微地形土壤质量评价指标以及表征微地形土壤质量的关键指标。

结果与分析

土壤质量指标敏感性分析

不同微地形具有不同的土壤属性，土壤属性指标值变化速率差异较大。土壤质量评价指标不仅与土壤功能关系密切，而且对不同微地形类型的差异反应敏感。用变异系数作为指标敏感性判据，变异系数越大，该指标对微地形的差异反应越敏感。表2是研究区样地理化和生物指标描述性统计结果，在22项指标中，蔗糖酶的变异系数最大，其次是速效磷、全氮、有机质、脲酶、非毛管孔隙度、碱性磷

parameters in the study area. Among these, SA had the greatest CV, followed by AP, TN, SOM, UA, NCP, APA, AN, AK, SWC, CA, TP, TK, $CaCO_3$, and CEC levels; pH and CP had the smallest CVs. Additionally, AP level had the largest relative range, followed by SA, TN, UA, APA, SOM, NCP, AN, AK, SWC, CA, TK, CEC, $CaCO_3$, MinWHC, and TP levels; pH and CP levels had the smallest relative ranges.

酸酶、速效氮、速效钾、含水量、过氧化氢酶、全磷、全钾、$CaCO_3$和CEC，pH和毛管孔隙度的变异系数最小；以速效磷的相对极差最大，其次是蔗糖酶、全氮、脲酶、碱性磷酸酶、有机质、非毛管孔隙度、速效氮、速效钾、含水量、过氧化氢酶、全钾、CEC、$CaCO_3$、最小持水量和全磷，以pH和毛管孔隙度的相对极差最小。

Table 2 / *表2*

Sensitivity analysis of soil quality indicators (sorted by coefficient of variation, CV)

Soil quality indicators	*Samples*	*Range*	*Min.*	*Max.*	*Mean*	*Standard deviation*	*CV* [%]	*Relative range*
SA	31	8.49	1.02	9.51	4.81	2.56	53.22	1.77
AP	31	5.12	0.93	6.05	2.70	1.14	42.22	1.90
TN	31	0.62	0.14	0.76	0.36	0.15	41.67	1.72
SOM	31	8.39	2.91	11.3	5.84	2.42	41.44	1.44
UA	31	13.31	2.36	15.67	8.45	3.42	40.47	1.58
NCP	31	6.9	3.50	10.40	5.74	1.76	30.66	1.20
APA	31	1.38	0.55	1.93	0.90	0.26	28.89	1.53
AN	31	34.99	16.73	51.72	31.61	8.44	26.70	1.11
AK	31	74.9	52.87	127.77	84.40	21.25	25.18	0.89
SWC	31	7.87	4.67	12.54	8.83	2.06	23.33	0.89
CA	31	0.4	0.36	0.76	0.63	0.10	15.87	0.63
TP	31	0.17	0.46	0.63	0.54	0.07	12.96	0.31
TK	31	10.29	13.49	23.78	17.56	2.20	12.53	0.59
$CaCO_3$	31	58.59	139.89	198.48	164.97	19.97	12.11	0.36
CEC	31	4.42	6.48	10.9	8.74	1.05	12.01	0.51
MinWHC	31	10.71	25.97	36.68	31.93	2.13	6.67	0.34
MaxWHC	31	10.84	37.22	48.06	41.97	2.66	6.34	0.26
CWC	31	8.23	33.88	42.11	37.46	1.77	4.73	0.22
BD	31	0.22	1.15	1.37	1.26	0.05	3.97	0.17
TCP	31	8	49.73	57.73	52.81	1.86	3.52	0.15
CP	31	4.66	45.07	49.73	47.18	1.24	2.63	0.10
pH	31	0.24	8.33	8.57	8.48	0.06	0.71	0.03

To distinguish the differences in their sensitivity, the soil quality indicators were classified into four groups according to their coefficients of variation, i.e., highly sensitive, moderately sensitive, poorly sensitive, and insensitive indicators (Table 3). There are no highly sensitive indicators used for assessing soil quality in the study area; SA AP, TN, SOM, and UA levels were moderately sensitive; NCP, APA, AN, AP, SWC, CA, TP, TK, $CaCO_3$, and CEC levels were poorly sensitive; and minWHC, MaxWHC, CWHC, BD, TCP, CP, and pH levels were insensitive indicators.

为区分各指标敏感性差异，根据变异系数大小将其划分为高度敏感、中度敏感、低度敏感和不敏感指标。从表3的土壤质量评价指标敏感性分析可知，研究区无高度敏感指标；蔗糖酶、速效磷、全氮、有机质和脲酶为中度敏感指标；非毛管孔隙度、碱性磷酸酶、速效氮、速效钾、含水量、过氧化氢酶、全磷、全钾、$CaCO_3$和CEC为低度敏感指标；最小持水量、最大持水量、毛管持水量、容重、总孔隙度、毛管孔隙度和pH为不敏感指标。

Table 3 / *表3*

Sensitivity classifications of soil quality indicators

Sensitivity	*CV* [%]	*Soil quality indicators*
Highly sensitive	*⩾100*	*None*
Moderately sensitive	*40-100*	*SA、AP、TN、SOM、UA*
Poorly sensitive	*10-40*	*NCP、APA、AN、AK、SWC、CA、TP、TK、$CaCO_3$、CEC*
Insensitive	*⩽10*	*MinWHC、MaxWHC、CWC、BD、TCP、CP、pH*

Microtopography-oriented soil quality factors

In this study, 22 soil physicochemistry and biological parameters were used as the initial indicators of soil quality assessment. In the principal component analysis, the principal components were selected by considering the eigenvalues (>1) and cumulative contribution (>85%).

微地形土壤质量因子

本研究选取了包括土壤物理、化学和生物学在内的22项指标作为初始评价指标，利用主成分分析中特征值大于1和累计贡献率大于85%选取主成分。由表4可知，7个主成分累积贡献率接近86%，说明7个彼此独

There are seven principal components with a cumulative contribution close to 86% (Table 4). These seven independent principal components thus can explain nearly 86% of the total variability in soil quality, satisfying the requirement for information extraction. PA1 (35.11%) had factor loadings >0.8 for SOM, AN, SA, pH (negative loading), and UA levels, and >0.7 for TN level; all these indicators were highly significantly correlated with SOM. Thus, PA1 was assigned to a SOM factor. PA2 (12.95%) had factor loadings >0.8 for MaxWHC and BD (negative loading), and >0.7 for CWHC and MinWHC. These indicators all related to soil WHC. Thus, PA2 was defined as a WHC factor. PA3 (12.71%) had greater factor loadings for TP (>0.8) and $CaCO_3$ levels (>0.7). Because TP and $CaCO_3$ levels are strongly correlated, PA3 was assigned to a TP factor. PA4 had relatively high factor loadings for strongly correlated TK and APA levels. Thus, PA4 was assigned to a TK factor. PA5 had relatively high factor loading for SWC and thus was defined as an SWC factor. PA6 had relatively high factor loading for CP, thus was defined as a CP factor. PA7 had a relatively high factor loading for AP level, thus was defined as an AP factor.

立的主成分可解释近86%的总体变异性，满足信息提取要求。其中，第1主成分(35.11%)与有机质、速效氮、蔗糖酶、pH（负荷载）和脲酶的因子荷载大于0.8，与全氮的因子荷载大于0.7，而且这些指标均与有机质有极显著的相关性，因此可将第1主成分称为有机质因子。第2主成分(12.95%)与最大持水量和容重（负荷载）的因子荷载大于0.8，与毛管持水量和最小持水量的因子荷载大于0.7，这4个指标均是反映土壤持水量的指标，因此可以将第2主成分称为持水量因子。第3主成分(12.71%)与全磷（>0.8）和$CaCO_3$（>0.7，负荷载）的荷载较高，全磷和$CaCO_3$具有较高的相关性，可将该主成分命名为全磷因子。第4主成分与全钾和碱性磷酸酶的荷载较高，全钾和磷酸酶具有较高的相关性，可将该主成分命名为全钾因子。第5主成分与土壤含水量具有较高的荷载，因此称为水分因子。第6主成分与毛管孔隙具有较高的荷载，因此称为孔隙因子。第7主成分与速效磷具有较高的荷载，因此称为速效磷因子。

Table 4 / *表4*

Variance rotation matrix, contribution percentages, and weights of the initial indicators used for microtopography-oriented soil quality assessment

Assessment indicator	***Principal component***							***Communality***	***Weight***
	1	***2***	***3***	***4***	***5***	***6***	***7***		
SOM	0.863	0.285	0.290	-0.157	0.210	-0.098	-0.083	0.896	0.047
AN	0.859	0.326	0.170	0.036	-0.068	0.000	-0.053	0.882	0.047
SA	0.844	0.218	-0.136	0.207	-0.159	0.055	-0.079	0.855	0.045
pH	-0.829	-0.035	0.045	0.069	-0.207	0.098	-0.160	0.773	0.041
UA	0.819	0.314	-0.016	0.288	-0.149	-0.125	-0.153	0.914	0.048
CP	-0.014	0.246	-0.021	-0.226	0.108	0.870	0.216	0.928	0.049
TCP	0.318	0.673	-0.232	-0.004	0.031	-0.028	0.455	0.816	0.043
SWC	-0.063	-0.166	0.031	0.006	0.921	0.130	0.048	0.900	0.048
MinWHC	-0.032	0.739	0.186	0.342	0.255	0.312	-0.296	0.949	0.050
AP	0.049	-0.121	0.238	-0.004	-0.011	-0.153	-0.858	0.834	0.044
AK	0.150	0.214	0.640	0.035	0.423	0.199	-0.274	0.773	0.041
NCP	0.326	0.522	-0.202	0.099	-0.118	-0.528	0.420	0.899	0.048
TN	0.753	0.198	0.176	-0.308	0.028	0.167	0.320	0.863	0.046
TP	0.051	-0.196	0.824	0.101	0.078	0.110	-0.090	0.756	0.040
TK	-0.119	0.130	0.176	0.845	0.080	-0.325	-0.038	0.890	0.047
BD	-0.414	-0.822	-0.062	-0.112	0.097	0.028	0.005	0.873	0.046
CEC	0.266	0.285	0.000	-0.438	0.630	-0.065	-0.033	0.745	0.039
$CaCO_3$	-0.127	-0.127	-0.732	-0.010	0.340	0.376	0.098	0.834	0.044
CWC	0.319	0.778	0.066	-0.064	-0.041	0.476	0.115	0.958	0.051
APA	0.369	0.167	-0.023	0.725	-0.306	0.034	0.086	0.793	0.042
CA	0.602	0.201	0.311	0.109	0.096	0.299	0.410	0.778	0.041
MaxWHC	0.424	0.854	-0.072	0.050	-0.061	-0.026	0.256	0.986	0.052
Eigenvalue	7.72	2.85	2.80	2.07	1.33	1.12	1.01		
***Variance* [%]**	35.11	12.95	12.71	9.39	6.03	5.08	4.61		
***Cumulative* [%]**	35.11	48.06	60.76	70.15	76.18	81.27	85.88		

Microtopography-oriented soil quality assessment indicators

Non-significant factors were successively eliminated through stepwise regression as follows:

微地形土壤质量评价指标

采用逐步回归分析法逐次剔除一些不显著因子，方程如下：

$$Y_{\text{SOM factor}} = -6.274 + 3.938X_1 + 0.032X_2 + 0.820X_3 + 4.158X_4 + 4.252X_5 \tag{4}$$

$F = 466.269^{**}$, $Df = (5, 25)$, and $R_a = 0.994$ (adjusted correlation coefficient)

$F=466.269^{**}$ $Df=(5, 25)$ $R_a=0.994$(调整相关系数)

where: X_1 = TN, X_2 = AN, X_3 = pH, X_4 = SA, and X_5 = UA; the partial correlation coefficients of X_1 to X_5 were 0.545 (p = 0.0016), 0.139 (p = 0.4892), 0.069 (p = 0.7320), 0. 659 (p = 0.0003), and 0.665 (p = 0.0001), respectively. These results show that to the SOM factor, TN, SA, and UA had a greater contribution than the remaining two indicators.

式中：X_1－全氮，X_2－速效氮，X_3－pH，X_4－蔗糖酶，X_5－脲酶；X_1、X_2 、X_3 、X_4和X_5的偏相关系数(括号中为显著性)分别为0.545 (p=0.0016)、0.139 (p=0.4892)、0.069 (p=0.7320)、0.659(p=0.0003)和0.665 (p=0.0001)。可见，在全氮、速效氮、pH、蔗糖酶和脲酶5个有机质因子主要指标中，全氮、蔗糖酶和脲酶的贡献较大。

$$Y_{WHC\ factor} = -28.501 + 0.359X_1 - 0.327X_2 + 3.960X_3 \quad (5)$$

F = 384.241^{**}, Df = (3, 27), R_a = 0.987 (adjusted correlation coefficient)
where: X_1 = BD, X_2 = MinWHC, and X_3 = CWHC; the partial correlation coefficients of X_1 to X_3 were 0.350 (p =0.069), -0.387 (p = 0.077), and 0.625 (p = 0.0003), respectively. These results demonstrate that among the WHC factors, CWHC made a greater contribution than the remaining two indicators.

F= 384.241^{**} Df=(3, 27) R_a=0.987(调整相关系数)
式中：X_1－容重，X_2－最小持水量，X_3－毛管持水量；X_1、X_2和X_3的偏相关系数(括号中为显著性)分别为 0.350 (p=0.069)、-0.387 (p=0.077)和 0.625 (p=0.0003)。 可见，在容重、最小持水量和毛管持水量3个持水量因子主要指标中，毛管持水量的贡献较大。

$$Y_{TP\ factor} = -0.1402 + 0.004X_1 \quad (6)$$

F = 174.302^{**}, Df = (1, 29), R_a = 0.923 (adjusted correlation coefficient)
where: X_1 = $CaCO_3$, and the partial correlation coefficient of X_1 was 0.925 (p = 0.0001). Thus, $CaCO_3$ was the greatest contributor to the indicators of the TP factor.

F=174.302^{**} Df=(1, 29) R_a=0.923(调整相关系数)
式中：X_1－$CaCO_3$，X_1的偏相关系数(括号中为显著性)为0.925 (p=0.0001)。可见，$CaCO_3$在全磷因子指标中贡献较大。

$$Y_{TK\ factor} = 9.318 + 0.183X_1 \quad (7)$$

F = 80.601^{**}, Df = (1, 29), R_a = 0.851 (adjusted correlation coefficient)
where: X_1 = APA, and the partial correlation coefficient of X_1 was 0.856 (p = 0.0001). Thus, APA was the major contributor to the indicators of the TK factor.

F=80.601^{**} Df=(1, 29) R_a=0.851(调整相关系数)
式中：X_1－碱性磷酸酶， X_1的偏相关系数(括号中为显著性)为0.856 (p=0.0001)。 可见， 碱性磷酸酶在全钾因子指标中贡献较大。

DISCUSSION

The variability of soil quality indicators reflects the environmental sensitivity of soil properties. Thus, coefficients of variation can be used for sensitivity classification of microtopography-oriented soil quality assessment indicators in semiarid regions of the Loess Plateau. The present results show that SA, AP, TN, SOM and UA levels are moderately sensitive indicators for soil quality assessment, which are the major objectives of soil quality restoration and regulation. Here, soil biological parameters demonstrate great potential for use as soil quality assessment indicators. Being affected by the uniform texture of the loess parent materials, soil quality assessment indicators used in this study have low or no sensitivity. Over-high sensitivity of soil quality assessment indicators is not conducive to comprehensive assessment of soil quality and development of appropriate measures for agricultural soil management. For microtopography-oriented quantitative assessment of agricultural soil quality in the loess region of northern Shaanxi, it is recommended that moderately sensitive and some poorly sensitive indicators are selected but insensitive indicators are eliminated.

According to the results of the principal component analysis and stepwise regression combined with the correlations and sensitivity grades of the soil parameters, nine optimal indicators suitable for microtopography-oriented soil quality assessment in semiarid regions of the Loess Plateau were screened out including SOM, TN, SA, UA, AP, TP, $CaCO_3$, APA and TK levels. Of these, SOM is the key indicator for characterizing soil quality in diverse microtopographic units in semiarid regions of the Loess Plateau.

讨论

土壤质量指标的变异性是土壤属性对环境敏感性的反映。可用变异系数对陕北黄土区微地形土壤质量指标的敏感性进行分级，蔗糖酶、速效磷、全氮、有机质和脲酶为土壤质量评价的中度敏感指标，是土壤质量恢复与调控的主要目标，其中土壤生物学指标反映了其作为土壤质量评价指标的巨大潜力。受黄土母质质地均一性的影响，土壤质地的表征指标属低度敏感或不敏感指标。但土壤质量评价指标并非越灵敏越好，如果过于灵敏反而不利于综合评价土壤质量和制定相应的农业土壤管理措施。在定量评价陕北黄土区微地形农业土壤质量时，可选择中度敏感指标和部分低度敏感指标，不敏感指标予以剔除。

综合以上主成分和逐步回归分析结果，结合各土壤属性指标之间的相关性和指标的敏感性分析，可以筛选出适宜黄土高原半干旱区微地形土壤质量评价指标为有机质、全氮、蔗糖酶、脲酶、速效磷、全磷、$CaCO_3$、碱性磷酸酶和全钾和9个，其中，有机质是表征黄土高原半干旱区微地形土壤质量的关键指标。

CONCLUSIONS

This study is the first to investigate microtopography-oriented soil quality assessment indicators in semiarid regions of the Loess Plateau. Results show that the levels of sucrase activity, available phosphorus, total nitrogen, soil organic matter, and urease activity were moderately sensitive indicators for microtopography-oriented soil quality assessment, which are the major objectives of soil quality restoration and regulation in the study area. Soil biological parameters are moderately to poorly sensitive indicators that have great potential for use in microtopography-oriented soil quality assessment. Therefore, potential soil functions can be fully played as long as rational measures are implemented for conservation of agricultural soils, improvement of soil structure, and promotion of soil microbial activities. For the quantitative assessment of soil quality in the study area, it is recommended that moderately sensitive indicators and some poorly sensitive indicators are selected, with insensitive indicators eliminated.

This study identifies optimal indicators(SOM, TN, SA, UA, AP, TP, $CaCO_3$, APA, and TK) for microtopography-oriented soil quality assessment in semiarid regions of the Loess Plateau through stepwise regression and principal component analysis combined with correlation analysis of selected soil parameters and sensitivity analysis of soil quality indicators. The work lays a solid foundation for future microtopography-oriented vegetation allocation and ecological construction and provides a reference for conservation of agricultural soils, improvement of low-yield farmlands, and guidance of agricultural production according to local conditions in semiarid loess regions.

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结论

本研究率先对黄土高原半干旱区微地形土壤质量指标进行研究。蔗糖酶、速效磷、全氮、有机质和脲酶作为微地形土壤质量评价的中度敏感指标，是土壤质量恢复与调控的主要目标。土壤生物指标属于中度敏感和低度敏感指标，对微地形土壤质量评价具有巨大潜力。因此，只要进行合理保育农业土壤、改善土壤结构及促进微生物活动就能发挥其土壤潜能。在研究区定量评价土壤质量时,宜选择中度敏感指标和部分低度敏感指标，不敏感指标予以剔除。通过主成分和逐步回归分析，结合各土壤属性指标之间的相关性和指标的敏感性分析确定黄土高原半干旱区微地形土壤质量评价指标（有机质、全氮、蔗糖酶、脲酶、速效磷、全磷、$CaCO_3$、碱性磷酸酶和全钾）。为微地形后续植被配置及生态建设研究打下坚实的基础，为该区农业土壤保育、低产地改良及因地制宜地指导农业生产提供科学依据。

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