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A comparative study on three methods of soil quality evaluation of microtopography in the semi-arid Loess Plateau, China

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Abstract

Three soil property test data of microtopography in the semi-arid Loess Plateau were used to compare the following three soil quality evaluation methods: correlation coefficient method, factor analysis method and Nemoro index method. The results of these methods were analyzed and compared to determine the most suitable method for comprehensive evaluation of soil quality. While correlation coefficient method and factor analysis method produced similar results, Nemoro index method showed several differences from the other two methods and exhibited higher sensitivity in its assessment results. The soil quality index (SQI) parameters of three methods showed consistent scales and variation trends among the various microtopographies, and there was a highly significant linear positive correlation between the SQI parameters of any two given methods. This result suggested that the three methods were all reliable and could be employed for comprehensive assessment of soil quality of microtopography in the study region. However, the Nemoro index method involves relatively uncomplicated mathematics and is very easy to absorb, and thus should be preferentially employed when three grading standards can be identified. The factor analysis method is the next most preferable, followed by correlation coefficient method.

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Introduction

Microtopography generally refers to local topography with small-scale topographical changes. Japanese experts divide the microtopography of hilly regions into seven types: slope crests, upper side slopes, head hollows, lower side slopes, foot slopes, flood terraces and river beds (Nagamatsu and Miura, 1997). Chinese experts define the microtopography of the semi-arid Loess Plateau as local topography of varying sizes and shapes, which is formed on loess slopes by soil erosion and other geological processes and causes habitat conditions such as soil moisture and nutrients to vary at a scale greater than 1 m^2 (Zhu *et al.,* 2011). Based on this definition, the microtopography is divided into five types: gully, furrow, collapses, gently sloped terrace and scarp (Zhao *et al.,* 2010). Because microtopography is the basic constitutional unit of topography of the Loess Plateau, dynamic changes in soil quality of microtopography reflect not only the effects of soil management but also the capability of soil to be recovered or degraded; the level of soil quality determines the types of vegetation and effects of vegetation recovery in the region (Qiu *et al.,* 2009).

Soil quality assessment is one of the core components of soil quality study, and several methods of soil quality assessment exist (Kinoshita *et al.,* 2012; Liang *et al.,* 2006). Therefore, it is absolutely essential to screen the suitability of these assessment methods for soil quality evaluation of microtopography in the semi-arid Loess Plateau. No unified standard for soil quality assessment currently exists; some methods are already in practice, while others are still under review. Amongst the previous studies, Doran and Parkin employed the comprehensive soil quality index (SQI) method to evaluate soil quality elements (Hussaina *et al.,* 1999). Larson and Pierce proposed a new method to describe dynamic changes in soil quality using a system dynamics approach (Cao, 2001). Researchers from the United States Department of Agriculture and the Washington State University proposed an approach for comprehensive evaluation of soil quality, using multiple-variable indicator kriging (MVIK) method (Goovaerts, 1998; Jonathan *et al.,* 1996; Nazzareno and Michele, 2004). Xu *et al.* (2011) employed the methods of principal component analysis and discriminant analysis to study soil quality assessment indices of loess hilly regions. Bao *et al.* (2012) studied several evaluation methods for fertility changes of red soil after long-term use of fertilizers. In addition, the classification and gradation method, index method, fuzzy evaluation method, cluster analysis method, geostatistics and other relevant methods have been widely applied for quantitative evaluation of soil quality (Saviozzi *et al.,* 2001). The Nemoro index method is one of the most commonly used methods for calculating of soil quality indices, both domestic and abroad (Rahmanipour *et al.,* 2014; Zhang *et al.,* 2009).

At present, studies on evaluation methods of soil quality in microtopography are rarely reported. In this study, three extensively studied assessment methods, the correlation coefficient method, the factor analysis method and the Nemoro index method, were employed to comprehensively evaluate the soil quality of the microtopography in the semi-arid Loess Plateau.

Materials and Methods

Study sites: The study area comprised the Hejiagou catchments of Wuqi County, Yan'an. The catchments stand 1233–1890 m above sea level and experience a semi-arid continental monsoon climate. The area has an average annual temperature of 7.8°C, an accumulative temperature ($\geq$10°C) of 2817.8°C, an average annual sunshine of 2400 hr, a frost-free period of 96–146 days and an average annual evaporation of 400–450 mm (Bo *et al.,* 2014). The topography is gully and hilly, and the vegetation transitions from forest steppes into 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 (Zhou *et al.,* 2013).

Sample collection and preparation : In July 2012, the number of soil sampling sites of different microtopographies of the study area were determined depending on their topographical characters, topographical distribution and the sizes of its microtopographies as follows (Fig. 1): 30 sampling sites in the furrows, 12 sampling sites in the gullies, 18 sampling sites in the collapses, 9 sampling sites on the gently sloped terraces and 9 sampling sites on the scarps, for a total of 78 sampling sites. Three sites were chosen as control sampling sites in the undisturbed areas of each microtopography, for a total of 15 control soil sampling sites. Soil sampling was conducted in three soil layers: 0–20, 20–40 and 40–60 cm. The soil sampled from three soil layers at three neighboring sampling points were mixed and prepared as one soil sample by quartering, for a total of 93 soil samples. 500 g of each soil sample was air dried, pulverized and sieved (with 1 mm mesh and 0.25 mm mesh) in a campus-based lab for future use.

Measurement of soil parameters: The following soil parameters were determined using conventional methods (Feng *et al.,* 2010; Bouma, 2002). Total nitrogen(TN) was determined by semi-trace Kjeldahl method; total phosphorus (TP) was determined by NaOH liquation and molybdenum blue colorimetry; total potassium (TK) was determined by NaOH liquation and flame photometry; available nitrogen (AN) was determined by alkaline hydrolysis and diffusion; available phosphorous (AP) was determined by extraction with 0.5 mol l^{-1} $NaHCO_3$ and silica-molybdenum blue colorimetry; available potassium(AK) was determined by extraction with NH_4OAc and flame photometry; soil organic matter(SOM) was determined heated potassium dichromate oxidation; pH was measured by potentiomerically using a pH meter; cation exchange capacity(CEC) was determined by NaOAc flame photometry; and $CaCO_3$ was determined by NaOH-neutralized titration.

Statistical analysis: The study employed Excel 2010 and SPSS 20.0 for data processing, drawing and statistical calculation. The data presented was average across 0–60 cm soil.

Selection of assessment indexes: Screening of assessment indices was the base of soil quality assessment (Islam and Weil, 2000; Mairura *et al.,* 2007). The indicators commonly involved physical, chemical and biological features. This study selected ten soil indices for comprehensive evaluation of soil quality in microtopography of the semi-arid Loess Plateau: SOM, TN, TP, TK, rapidly AN, rapidly AP, rapidly AK, pH value, CEC and $CaCO_3$.

Membership calculation of assessment indicators: Being expressions of mathematical relation between different assessment indictors and their long-term effects on crop growth curves, membership functions characterized by fuzziness and continuity are widely adopted to standardize original data of different assessment indicators (nondimensionalize the data), i.e., membership calculations (Fu *et al.,* 2011; Xu *et al.,* 2011; Zhang *et al.,* 2011). The study relied on relevant previous research achievements to determine membership functions for indicators (Badiane *et al.*, 2001; Bai *et al.,* 2010; Crabtree and Bayfield, 1998; Wang and Gong, 1997), revealing that SOM, TN, TP, TK, AN, AP, AK and CEC had S-type membership functions; pH had parabolic membership functions; $CaCO_3$ contents presented a reverse S-type membership function.

Determination of weight: The correlation coefficient method is so named for its weight calculation. Weight was determined as

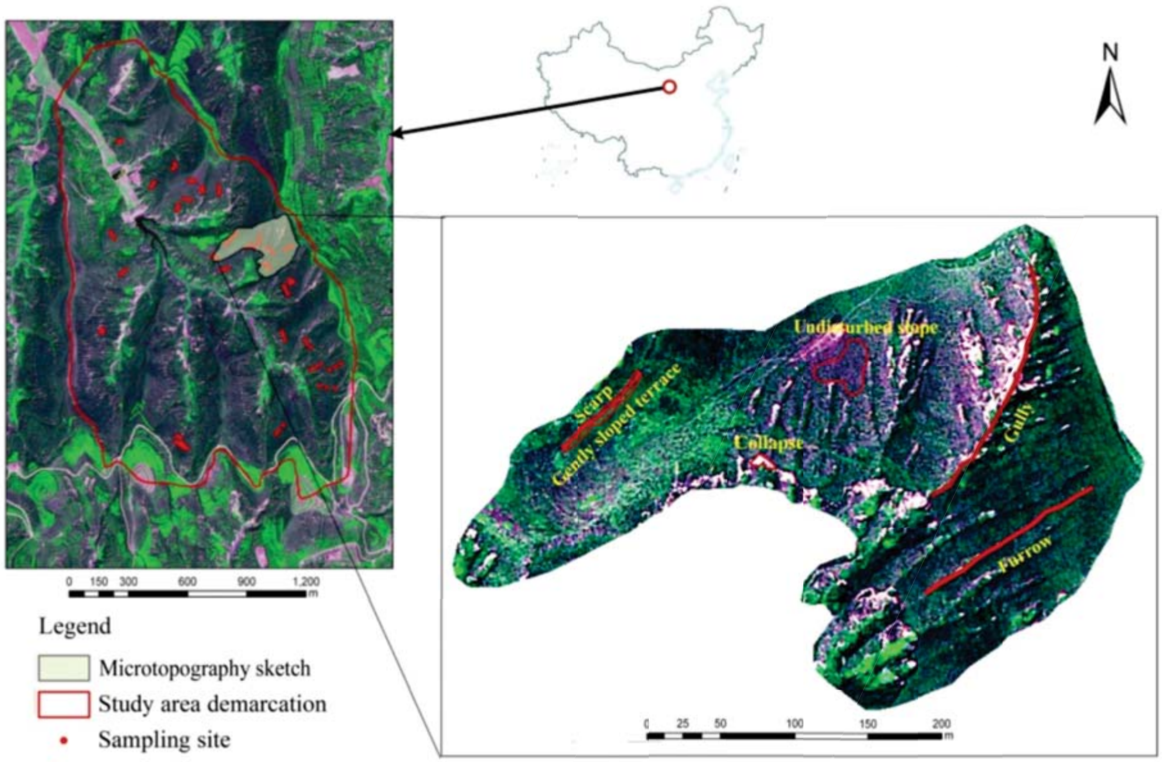

Fig. 1 : Microtopography sketch and sampling sites (Digital Orthophoto Map from QuickBird Image)

follows: the correlation coefficient between every two assessment indices were calculated, and then mean values of correlation coefficients between each index was determined. The mean value of each assessment index divided by the sum of mean values of all indiced, expressed as percentage, was taken as weight of the corresponding index, with all weights summing up to 1 (Bao *et al.*, 2012).

The factor analysis method is also named for its weight calculation. Weight was determined as follows: the common factor variance (communality) of each assessment index was calculated by factor analysis method. The ratio (percentage) of common factor variance of each index to the total sum of all common factor variances was calculated and converted into a figure between 0 and 1, which was then employed as the weight of each single assessment index; all the weights summed to 1 (Bouma, 2002).

Both correlation coefficient method and factor analysis method employ the membership function for the unitary processing of data, and therefore they are classified as fuzzy methods for comprehensive evaluation. The comprehensive soil quality index (SQI) was calculated using the formula based on the principle of the fuzzy mathematical additive-multiplicative method (Bouma, 2002). SQI value ranges between 0 and 1. A higher SQI value indicates better soil quality and vice versa.

Calculation of soil quality indices using Nemoro index method: To eliminate the effect of dimension differences among various soil quality parameters, calculation of partial quality coefficient SQI_i can be used in addition to the usual process of establishing a membership function and dividing it by standard deviation or abundance standard (single standard) (Kan and Wu, 1994).

After data standardization using this method, SQI_i values ranged between 0 and 3. The advantages of this method were as follow: there was a high degree of comparability between values of same parameter; partial quality coefficients of various attributes of same grade were relatively close, showing a high degree of comparability and if the measured values exceeded the upper limit, the corresponding partial quality coefficients no longer increased, which reflects the reality that plants do not always impose the highest possible demand on soil attributes. In the present study, SQI was calculated using the modified formula of Nemoro (Fu *et al.*, 2011).

Results and Discussion

As shown in Fig. 2, the SQIs of the study region determined using the three assessment methods showed lowest

SQI for the scarps and highest SQI for the gently sloped terraces, consistent with the findings of Zhang *et al.* (2011) in Northern Shaanxi Province. The SQIs of gullies and collapses were higher than those of the undisturbed slopes and furrows. The $SQI_{Co.}$ sequence was as follows: gently sloped terraces (0.554) > gullies (0.540) > collapses (0.538) > furrows (0.485) > undisturbed slopes (0.482) > scarps (0.448). The $SQI_{Fa.}$ sequence was as follows: gently sloped terraces (0.551) > gullies (0.537) > collapses (0.536) > furrows (0.490) = undisturbed slopes (0.490) > scarps (0.459). However, the differences among microtopographies in terms of $SQI_{Co.}$ and $SQI_{Fa.}$ are not significant. The $SQI_{Ne.}$ sequence was as follows: gently sloped terraces (1.137) > gullies (1.105) > collapses (1.067) > undisturbed slopes (1.040) > furrows (1.013) > scarps (0.986). Differences between scarps and gently sloped terraces and gullies were significant. The sequence of $SQI_{Co.}$, $SQI_{Fa.}$ and $SQI_{Ne.}$ generally tend to be consistent. Using the data of undisturbed slopes as control, SQI_{Co} of the gently sloped terraces, gullies, collapses and furrows were 14.94%, 12.03%, 11.62% and 0.62% greater, respectively, while SQI_{Co} of scarps was 7.05% less. $SQI_{Fa.}$ values of gently sloped terraces, gullies and collapses were 12.45%, 9.59% and 9.39% greater than the control, respectively, while $SQI_{Fa.}$ of furrows were the same as control and $SQI_{Fa.}$ of the scarps was 6.33% less. $SQI_{Ne.}$ of the gently sloped terraces, gullies and collapses were 9.33%, 6.25% and 2.60% greater than control, respectively, while $SQI_{Ne.}$ of the furrows and scarps were 2.60% and 5.19% less, respectively.

The descriptive statistics in Table 1 indicate that the mean values, standard deviations (SD), ranges and coefficient of variation (CV) of SQI_{Co} were all relatively close to those of the $SQI_{Fa.}$, indicating the high consistency and universality of the correlation coefficient method and the factor analysis method for the assessment of soil quality in the microtopographies. The mean value of $SQI_{Ne.}$ is approximately twice that of $SQI_{Co.}$ and $SQI_{Fa.}$. When the mean values are different, the CV better reflect the dispersion degree of the data, as unlike the SD, they eliminate the impacts of differences in unit and/or mean value (Yu et al., 2010). Therefore, the dispersion degree of data, as reflected by Nemoro index method, was relatively lower than that reflected by correlation coefficient method or factor analysis method was consistent with the results of Rahmanipour *et al.* (2014).

In conclusion, the assessment method had little effect on the variation trends of the SQIs among various microtopographies of the study region. As a whole, SQIs of collapses, gullies and gently sloped terraces were higher than

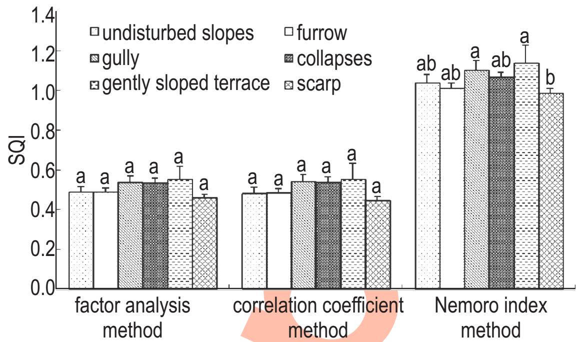

Fig. 2 : Soil quality indices of various assessment methods

those of undisturbed slopes, furrows and scarps. The difference in $SQI_{Co.}$ and $SQI_{Fa.}$ between different microtopographies were not significant, while differences in SQI_{Ne} were significant. The mean values of SQI_{Co} and SQI_{Fa} were relatively close and each were approximately half of the mean value of SQI_{Ne}. However, the dispersion degree of SQI_{Ne} was relatively lower than that of $SQI_{Co.}$ and $SQI_{Fa.}$.

As shown in Table 1 and Fig. 2, the correlation coefficient method and factor analysis method were similar in terms of calculated SQIs (0.389–0.685) and did not show significant difference among microtopographies, especially in terms of consistency (mean values of $SQI_{Co.}$ and SQI_{Fa} being 0.505 and 0.507, respectively) and variation trends of SQI values. This result suggests that relatively high consistency and universality existed between the correlation coefficient method and factor analysis method of assessment which was, consistent with previous findings of Zheng *et al.* (2010) on the loess Plateau. The SQIs obtained by Nemoro index method (0.882–1.274) was obviously higher than the SQIs from the former two methods, with a low dispersion degree (low variable coefficient) and significant differences observed among the microtopographies. Irrespective of assessment method employed, the variation trends of SQI values were consistent, i.e., SQI values of the collapses, gullies and gently sloped terraces were higher than those of undisturbed slopes, furrows and scarps, and SQI values of the gently sloped terraces and scarps were lowest and highest, respectively, which is in agreement with actual soil quality. This result suggests that all the three methods were suitable for evaluation of soil quality of microtopography of the region. It is worth mentioning that relatively higher SQI values of Nemoro index and significant differences calculated among various microtopographies can widen grade gaps of soil quality among different

Table 1 : Descriptive statistics of $SQI_{Co.}$, $SQI_{Fa.}$ and $SQI_{Ne.}$

Assessment method	Sampling number	Mean	SD	Range	CV (%)
$SQI_{Co.}$	31	0.505	0.073	0.296	14.55
$SQI_{Fa.}$	31	0.507	0.064	0.257	12.71
$SQI_{Ne.}$	31	1.049	0.091	0.392	8.71

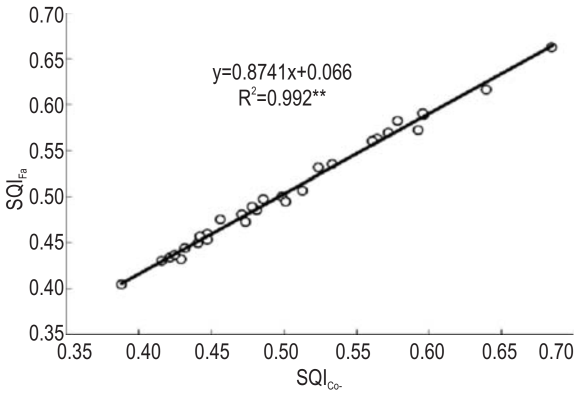

Fig. 3 : SQI correlation between correlation coefficient method and factor analysis method

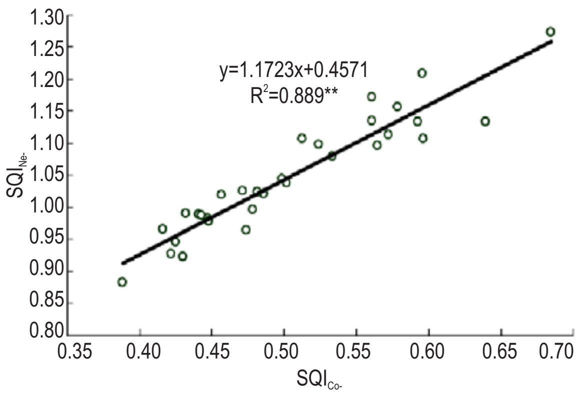

Fig. 4 : SQI correlation between correlation coefficient method and Nemoro index method

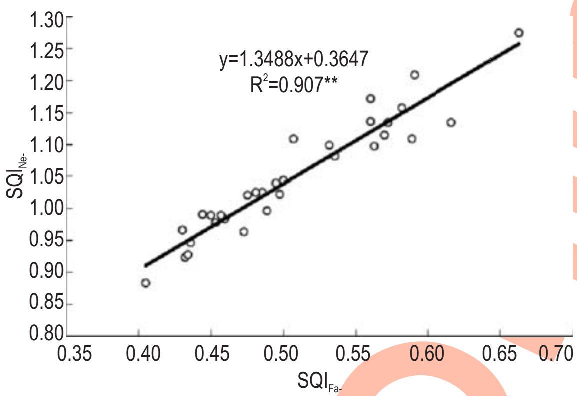

Fig. 5 : SQI correlation between factor analysis method and Nemoro index method

microtopographies, which is consistent with the results of Xu *et al.* (2005) on hilly Loess Plateau. Therefore, Nemoro index method, to make comparisons among microtopographies, was superior to correlation coefficient method and factor analysis method.

To verify the correctness of results of three evaluation methods, SQIs calculated by three methods were used for correlation analysis. If the correlation coefficient between two variables was close to 1, a high degree of linear relationship existed between them (Bao et al., 2012; Yu et al., 2010). Fig. 3–5 (the correlation coefficient r is the square root of R^2) show extremely significant linear positive correlation between $SQI_{Co.}$ and $SQI_{Fa.}$, $SQI_{Co.}$ and $SQI_{Ne.}$, and $SQI_{Fa.}$ and $SQI_{Ne.}$, with correlation coefficients being 0.996, 0.943 and 0.952, respectively. Therefore, an extremely significant linear positive correlation existed between any two of $SQI_{Co.}$, $SQI_{Fa.}$ and $SQI_{Ne.}$ (a=0.01, r=0.456); moreover, mutual transformations of three SQIs could be realized by linear regression equations provided in the figures. This correlation verifies reliability, suitability and universality of the three methods for assessment of soil quality in microtopography.

When three grade scales can be identified for all soil indexes, the Nemoro index method is recommended, but if three grade scales cannot be accurately identified for all soil indexes, only the factor analysis method and the correlation coefficient method can be used. However, the Nemoro index method requires only basic mathematical knowledge and is easy to understand. In addition, the selection of rational grade scales is vital to comprehensive soil quality assessment when using the three methods, as these grade scales affect both the SQI values and the correlations among the three methods. It is also worthy of further study and discussion.

A significant linear positive correlation existed between any two of the three methods of soil quality assessment ($SQI_{Co.}$, $SQI_{Fa.}$ and $SQI_{Ne.}$), with correlation coefficients between the methods close to 1 (all above 0.94). This result indicates the reliability of mutual verification among the three assessment methods, consistent with previous findings of Bao *et al.* (2012) and Qu *et al.* (2013). The linear mutual transformation relationship among the three methods (as shown by linear equations in Fig. 3–5) provide quantitative transformation relationship for various soil quality assessment systems. As factor analysis method is presently the most widely used method, it can be employed to calculate soil quality indices for correlation coefficient method and Nemoro index method, thereby establishing soil quality grades under the various soil quality assessment systems. In addition, for all the three methods, the calculated SQI values for collapses, gullies and gently sloped terraces were higher than those of undisturbed slopes, furrows and scarps. The values and variation trends of the SQIs among various microtopographies were relatively close, especially between $SQI_{Co.}$ and $SQI_{Fa.}$, a result which fully reflects and verifies the reliability, universality and suitability of the three assessment methods.

Nemoro index method showed highest sensitivity among other methods analyzed, which is consistent with previous findings of Bai *et al.* (2010) in water-wind erosion region of the Loess Plateau area and Rahmanipour *et al.* (2014) in agricultural lands of Qazvin Province, Iran. All the three assessment methods were reliable and suitable for comprehensive evaluation of soil quality of the semi-arid Loess Plateau.

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