Evaluating soil degradation based on earthworm community characteristics: A case study on loess soils

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Abstract

Soil degradation restricts the development of agriculture and the degree of soil degradation is related to land use type. Quick and efficient evaluation of the degree of soil degradation is needed for the timeous implementation of remedial measures to ensure soil sustainability. Earthworm community characteristics are closely related to soil management practices and soil quality and could be used for evaluation purposes. In this Loess Plateau study, the degree of soil degradation under nine different land use types (natural and planted woodland, shrubbery, and grassland, plus cropland, orchard, and abandoned land) was related to the earthworm community characteristics (density, biomass, and the Shannon-Wiener, Species richness, and Pielou's evenness indices) using a soil degradation index calculated from soil physicochemical properties determined for each land use type. The earthworm community characteristics associated with a low degree of degradation were significantly higher than those associated with a high degradation degree. Compared to the artificially managed land use types, earthworms in the natural ones showed higher biomass, density, and diversity. The earthworm density, biomass, and Shannon-Weiner index were significantly correlated with soil organic matter and total nitrogen content. These findings indicate that earthworm community characteristics can comprehensively characterise the physicochemical properties and biological characteristics of soils under different land use types. Linear correlations showed a significant relationship between the soil degradation index and the earthworm community characteristics, indicating that the latter could be used effectively to evaluate and represent the degree of degradation of soils on the Loess Plateau over a certain degradation range.

KEYWORDS

biological indicators—earthworm—diversity index—land use types—soil degradation

1 INTRODUCTION

Soil degradation is the most direct cause of soil quality decline, and its impact on ecosystems cannot be ignored (Zhang et al., 2006). Unreasonable development and utilisation of land and excessive application of chemical fertiliser and organic manure to soil to improve crop yield and quality aggravates the degree of soil degradation (Turkelboom et al., 2008; Srinivasarao et al., 2014). The aggravation of soil degradation causes a decline in ecosystem productivity, affects global climate and nutrient element cycles, and intensifies forest destruction, soil erosion, water pollution, and other such phenomena (Senjobiand and Ogunkunle, 2010; Bazhenova et al., 2013; Tang et al., 2013). However, by selecting reasonable and suitable soil degradation evaluation indices, evaluating the degree of soil degradation timeously, and implementing corresponding restoration measures, soil quality decline can effectively be slowed.

Soil fauna actively promote the material circulation process in an ecosystem through their own activities and feeding and other behaviours; thus, they significantly affect the soil quality. Moreover, there are many types of soil fauna with activities that are suitably sensitive to changes in the surrounding soil environment (Dick, 1992), and several studies have shown that soil fauna can be used as effective indicators of soil quality change. Biological monitoring using soil fauna to determine the slow toxic effect of harmful substances on environmental change can be more effectively accomplished in comparison to the use of physical and chemical indicators that are more difficult to measure. In addition, biological indicator measurement is cost effective and can be intensively implemented over large areas and long distances, even in remote places (Cole et al., 2004; Ouédraogo et al., 2004).

The earthworm, a common member of the soil macrofauna, is called the soil ecosystem engineer because earthworm activities play an important role in soil structure, nutrient cycling, and microbial composition (Blouin et al., 2013). It is known that the impact of earthworms on ecosystems changes with a change in earthworm ecotype (Kherbouche et al., 2012). At the same time, many studies have shown that the distribution of earthworm populations changes with a change in habitat (Smetk et al., 2007; Carnovale et al., 2015). Xu et al. (2013) reported that both the biomass and diversity of earthworms in a mixed planting area were significantly higher than that in an area with a single perennial plant species. In systems with different intensities of agriculture, earthworm biomass, abundance, and diversity (as measured by the Shannon index) have been found to decrease with an increase in agricultural intensity. These changes in earthworm numbers and species may be due to disturbances caused by agricultural management practices from which some of the populations failed to recover (Decaëns and Jiménez, 2002). Moreover, earthworm biomass, abundance, and diversity are closely related to soil physical and chemical properties, including soil bulk density, organic matter, and pH, and any changes in these properties will affect earthworm indicators (Perreault and Whalen, 2006; Jiménez et al., 2011). In suitable habitats, earthworm indicators increase significantly.

All the studies mentioned above showed that earthworms are sensitive to changes in soil management and physicochemical properties, which can effectively represent the degree of change in soil-related properties in response to soil degradation. The degree of soil degradation is known to be closely related to the degree of human disturbance, the soil management approach, and changes in soil physicochemical properties. To assess the degree of soil degradation using earthworm community characteristics as indicators, it is necessary to clarify the relationship between earthworm community characteristics and different degrees of soil degradation. A clear earthworm indicator significance needs to be established to effectively reflect the degree of soil degradation or remediation in order to improve soil sustainability. Based on this need, the purpose of this study was to (1) determine the soil physiochemical properties under different degrees of soil degradation in an area on the Loess Plateau, (2) explore the relationship between the degree of soil degradation and various earthworm community characteristics (biomass, density, and diversity index) that could be used as indicators, and (3) study the feasibility and limitation of using earthworms as indicators to evaluate the degree of soil degradation.

2 MATERIALS AND METHODS

2.1 Site description

The study area was located at the Yeheshan Provincial Nature Forest Reserve (34°31.76′N, 107°54.67′E), Fufeng County, Shaanxi Province, China. The altitude of the Forest Reserve is 449–1,662 m a.s.l, and it covers an area of approximately 10,996 ha. The mean annual precipitation is 580 mm and the average temperature is 21°C. The annual distribution of precipitation is mainly concentrated in summer and autumn, accounting for 79.8% of the annual total. The soil layer in the study area is relatively thick, and the groundwater depth varies between 50 and 80 m. The soil type is a silty loam according to the United States Department of Agriculture classification system.

2.2 Experimental design and earthworm sampling

In the study area, nine field plots with different land use types were selected for earthworm sampling: natural woodland (NW), natural shrubbery (NS), natural grassland (NG), planted woodland (PW), planted shrubbery (PS), planted grassland (PG), cropland (CL), orchard (OL), and abandoned land (AL). The basic characteristics and soil properties of all field plots are shown in Tables 1 and 2, respectively. A 30 × 30 m quadrat was established inside each field plot. Five soil samples were randomly collected along the diagonal profile to a depth of 25 cm in each plot. Earthworms were separated from the soil by hand-sorting in the field. The earthworm samples were then stored in plastic boxes containing soil, taken to a laboratory, and placed on moist filter paper for 24 h to facilitate gut emptying. The earthworms were then transferred to 95% ethanol for preservation (Wang et al., 2018). A binocular dissecting microscope equipped with double-tube anatomical lenses was used to examine and identify the earthworms to the species level (Yin, 1998). Thereafter, the earthworms were cleaned using distilled water, patted dry, and weighed for biomass determination. Earthworms that could not be identified were removed from the samples and excluded from further analysis.

Soil samples were collected from the 0–20-cm layer in each sample plot, after removal of the surface impurities, and subsequently evenly mixed. In addition, soil cores were collected from the same layer using a 100-cm^3 cutting ring for determination of bulk density (BD) and total porosity (TOP). After removal of roots and other impurities, the soil samples were air-dried and then sieved through a 2-mm mesh. The soil organic content (SOC), cation exchange capacity (CEC), and microbial biomass carbon (MBC) and nitrogen (MBN) content were determined using the external heating potassium dichromate, ammonium acetate exchange, and chloroform fumigation extraction methods, respectively. Total nitrogen (TN), total phosphorus (TP), and total potassium (TK) were measured using a continuous flow analyser (F-410; British). The soil pH was measured in a soil-water suspension at a ratio of 1:2.5 (soil:water) using an ion meter (Lei-ci PXSJ-216F; Shanghai REX Instrument Factory, China). The alkali absorption titration method was used to determine soil respiration (SR). The content of water-stable aggregates of different grain sizes was determined using a Yoder-type wet sieving apparatus. The mean weight diameter (MWD) of the soil aggregates was calculated using the following equation:

$$\mathrm{MWD} = \sum_{i=1}^{n} (\bar{x}_i w_i) \tag{1}$$

where $\bar{x}_i$ is the mean diameter of each size fraction, and w_i is the proportion of the total sample weight.

2.3 Data analysis

The earthworm diversity was characterized using the Shannon-Wiener, Species richness, and Pielou's evenness indices, calculated as follows:

Shannon-Wiener index: $$H' = -\sum_{i=1}^{s} P_i \ln P_i \quad (2)$$

Species richness index: $$S = 1 - \sum_{i=1}^{s} P_i^2 \quad (3)$$

Pielou's evenness index: $$E = H'/\ln s \quad (4)$$

where, P_i is the proportion of group i to the total number of individuals in the group, and s is the number of groups.

The soil degradation index (SDI) can be used to quantitatively assess soil degradation for different land use types. The calculation is based on the assumption that all land use types are transformed from a certain land use type, which is regarded as the benchmark. The difference of each selected soil property (expressed as a percentage) between each land use type and the benchmark land use type was determined and averaged for calculation of the SDI, using the following equation (Islam and Weil, 2000):

$$SDI = \left[\left(P_1 - P'_1\right)/P'_1 + \left(P_2 - P'_2\right)/P'_2 + \cdots + \left(P_n - P'_n\right)/P'_n\right] \times 100\%/n \quad (5)$$

where, P_1, P_2, …, P_n are the values of soil properties under other land use types; P'_1, P'_2, …P'_n are the values of different soil property parameters under the benchmark land use type; and n is the number of selected soil properties. In this study, the NW was selected as the benchmark land use type. Twelve soil properties (BD, TOP, MWD, SOC, TN, TP, TK, MBC, MBN, pH, SR, and CEC) were used to compute SDI. As higher soil BD and pH usually indicates the degradation tendency of the soil, inverse values of BD and pH were used in the calculation. The SDI of the different plots is shown in Figure 1.

Analysis of variance (ANOVA) was used to determine the effects of soil degradation on earthworm abundance and diversity. Differences were considered significant at $p < 0.05$. The relationship between earthworm indicators and soil properties was determined using Pearson's correlation analysis. Principal component analysis (PCA) of earthworm community structure was conducted based on the earthworm indicators under different degrees of soil degradation using CANOCO 5.0 (Biometris, Wageningen, Netherlands). The Spearman correlation coefficient was used to determine linear correlations between the degree of soil degradation and the earthworm index. All statistical analyses were performed using SPSS 20.0 software (SPSS Inc., Chicago, IL, USA). GraphPad Prism version 8 for Windows (GraphPad Software, La Jolla, CA, USA) was used to create the figures.

3 RESULTS

3.1 Composition of earthworm communities

Seven earthworm species belonging to three families and six genera were identified, including four epigeic earthworms (*Drawida gisti gisti, Drawida japonica japonica, Amynthas pingi pingi*, and *Eisenia foetida*), two endogeic earthworms (*Metaphire guillelmi* and *Allolobophora longa*) and one epi-endogeic earthworm (*Lumbricus rubellus*; Table 3). There were differences in both the composition and abundance of earthworm communities among the different land use types (Figure 2). All seven of the earthworm species captured in the experiment were found in the NW, NS, PW, PS, and NG plots. *Metaphire guillelmi* was the dominant species in all these plots, and accounted for 60.3%, 53.3%, 61.5%, 57.5%, and 21.5% of individuals in the NW, NS, PW, PS, and NG plots, respectively. *Eisenia foetida* (42.8% and 65.3%) was the dominant species in the PG and AL plots which contained all the other earthworm species except

L. rubellus in the PG plot and *A. longa* in the AL plot. Five and four earthworm species were identified in the CL and OL plots, respectively. *Drawida gisti gisti* was the dominant species in the CL (69.5%) and OL (74.1%) plots. The earthworm ecological categories differed among the different land use types. All three earthworm ecotypes occurred in the NW, NS, PW, PS, NG, and AL plots, in the following order of abundance: epigeic > endogeic > epi-endogeic. The PG and CL plots did not have any epi-endogeic earthworms, whereas the OL plot contained only the epigeic ecotype.

3.2 Earthworm biodiversity, biomass, and density

The Shannon, Species richness, and Pielou's evenness indices for each land use type are shown in Figure 3. All three indices varied consistently among the different plots in the following order: NW > NS > NG > PS > PW > CL > PG > AL > OL. There were significant differences in the Shannon index among the different plots ($p < 0.05$), except between the AL and PG, PS and NG, and PS and PW plots. The Shannon, Species richness, and Pielou's evenness indices for the NW plot were 3.542, 0.802, and 0.834, respectively. The values of all three indices for the OL plot were significantly lower than those for the other plots ($p < 0.05$). In particular, compared with the NW plot, the Shannon, Species richness, and Pielou's evenness indices for the OL plot were significantly lower by 69.9%, 41.9%, and 38.1%, respectively, ($p < 0.05$). All the other land use types showed significant differences ($p < 0.05$), except for the NS and PW.

Differences in earthworm biomass and density of individuals were observed among the different plots (Figure 4) with both these potential indicators varying in a similar way among land use types. Considered together, both the biomass and density of earthworms were the highest in the NW plot (25.37 g m^{-2} and 77 individuals m^{-2}, respectively) and the lowest in the OL plot (9.03

g m^{-2} and 27 individuals m^{-2}, respectively). Earthworm biomass was significantly higher in the NW and NS than in the other plots ($p < 0.05$), whereas the PW, PS, PG, and CL plots showed no significant difference ($p > 0.05$; Figure 4). The density of earthworms was significantly higher in the NW than in the other plots ($p < 0.05$).

3.3 Correlations between earthworm indicators and soil properties

Correlations between earthworm indicators and soil properties are presented in Table 4. Earthworm biomass and density correlated significantly with certain soil physical properties. Both these indicators were strongly negatively correlated with BD but positively correlated with TOP and MWD. These strong correlations suggest that both earthworm biomass and density show the capacity to indicate soil properties. The relationships among earthworm biomass and density, MWD, SOC, and TN showed strong associations which could be used to evaluate the effect of earthworm density on soil quality. The diversity, species richness, and evenness indices were significantly positively correlated with MWD, SOC, and TN ($p < 0.05$), with correlation coefficients of 0.89, 0.93, 0.87 (diversity), 0.91, 0.89, 0.79 (species richness), and 0.75, 0.82 and 0.75 (evenness), respectively. These relationships illustrate the effects of earthworm biodiversity on soil quality and could potentially be used to assess soil degradation. Earthworm biomass and density were positively correlated with MBC, MBN, and SR ($p < 0.01$), and the earthworm diversity and species richness indices were positively correlated with SR and MBC ($p < 0.05$). These findings suggest that these particular earthworm indicators are closely related to and could, therefore, effectively reflect changes in soil biological characteristics.

3.4 Correlation between earthworm indicators and soil degradation index

PCA was used to determine the classification of earthworm community indicators in relation to different degrees of soil degradation; the results are shown in Figure 5. The first two principal components (PCs) explained 93.8% of the variance, with PC1 contributing 91.7% and PC2, 2.1%. On the PC1 axis, the plots with different degrees of soil degradation were clustered into three groups according to the earthworm community characteristics: (1) NW and NS, (2) NG, PW, and PS, and (3) PG, AL, OL, and CL, whereas on the PC2 axis, the plots were clustered into two groups: (1) NW, NS, PG, AL, OL, and CL and (2) NG, PW, and PS. The the angle of the arrow between earthworm community characteristics and the PC1 axis was small, indicating that the PC1 axis mainly related to earthworm community composition. The earthworm community characteristic indicators pointed to the plot with a low degree of soil degradation, indicating that the earthworm community characteristic index was higher in the land use type with the lowest degree of soil degradation. Results of the linear correlation of the SDI and the different earthworm indicators are shown in Figure 6. The R^2 values varied from 0.815 to 0.934, indicating strong linear relationships between these data sets. There was a significant positive correlation between earthworm community indicators and SDI ($p < 0.05$), reflecting that, with an increase in the degree of soil degradation, the values of the earthworm community indicators decreased.

4 DISCUSSION

4.1 Response of earthworm community indicators to land use type

In terrestrial ecosystems, unreasonable management and land use cause soil degradation (Sklenicka et al., 2016; Baude et al., 2019), and actions, including overgrazing, deforestation, and overcultivation, potentially aggravate the degree of soil degradation (Khresat et al., 1998; Tesfahunegn, 2019). At present, many studies have shown that earthworm diversity and biomass are closely related to soil management and land use type (Feijoo et al., 2011; Pelosia et al., 2016). Based on the land use types we studied, we found that the degree of soil degradation associated with human disturbance was higher than that without human disturbance for the same vegetation type. We also found that the biomass, density, and diversity of earthworms in the artificially managed plots were significantly lower than those in the natural plots (Figures 3 and 4). These findings are consistent with those of Butt and Lowe (2004), who suggested that an increase in frequency of human activities will reduce earthworm diversity and biomass. As a consequence of artificial disturbance, new niche openings are destroyed and the ecological balance in natural systems is disrupted; consequently, the number of earthworm species with poor adaptability decreases, thus changing the earthworm abundance and diversity (Brown et al., 2004). Similarly, Schmidt et al. (2003) reported that a higher earthworm diversity and abundance was found in a natural soil without artificial disturbance compared with artificially disturbed soil samples.

Land use types are associated with soil degradation due to their different soil properties. Silva et al. (2020) reported that earthworm functional diversity and the community-weighted mean of earthworm ecological groups are significantly affected by land use types in the European ecological region. In our study, the PCA results showed that the nine land use types were clustered into three groups according to the earthworm indicators. A comparison of the SDI of each group indicated a close relationship with the degree of soil degradation. This finding supports our hypothesis that earthworm indicators can effectively reflect the degree of soil degradation. Furthermore, in our study, earthworm community characteristics showed negative relationships with the degree of soil degradation: the earthworm density, biomass, and diversity index values were low in the plots with a high degree of soil degradation. Some studies have shown that earthworm diversity and abundance are related to plant diversity and biomass (Cesarz et al., 2007; Carnovale et al., 2015). Wang et al. (2009) reported that, in association with the process of soil degradation, the decrease in earthworm diversity and biomass varied with plant composition. This is an important finding given that artificial land management often results in large-scale planting of single species and uses artificial interventions to destroy natural plant diversity (Amici et al., 2015). Earthworm communities will change with vegetation changes and thus can be used to reflect the degree of soil degradation. Similarly, intensive agricultural methods can greatly reduce earthworm abundance compared with under natural conditions (Edwards and Bohlen, 1996). In the management of farmland and orchards, fertilisers and pesticides are widely used to improve the quality of crops. Frazão et al. (2017) reported that the application of insecticides and herbicides can significantly reduce the diversity of earthworm communities as well as the number of individuals. Pelosi et al. (2013) found that the effect of insecticides on epigeic earthworms was higher than that on other ecotypes which could explain why the lowest diversity and biomass of earthworms in our study occurred in the OL plot which had a high degree of degradation.

4.2 Response of earthworm indicators to soil properties

Soil property changes significantly affect earthworm biomass, density, and diversity (Singh et al., 2016). In the present study, earthworm indicators were significantly correlated with all measured soil properties except TP (Table 4). Food availability in the soil is also an important factor affecting earthworm indicators. Different degrees of soil degradation have different impacts on the food available to earthworms in the soil (Heinze et al., 2010). In our study, the abundance and biomass of earthworms were highest in the plot with the highest SOC content. As SOC is an important source of earthworm food, sufficient SOC would be conducive to earthworm reproduction and diversity (Bartz et al., 2013). Similar results were found by Brown et al. (2000), who reported that SOC is beneficial, as it increases the number of earthworms. As a suitable habitat is conducive to earthworm activities and reproduction, the degradation of soil structure and quality will affect the abundance and diversity of soil fauna (Pestana et al., 2020).

Our results showed that the BD and TOP of highly degraded soils were higher and lower, respectively, than those of the soils with a low degree of degradation (Table 2). Soil BD and TOP effectively represent the air and water exchange between the soil and the atmosphere. Human activities and management may lead to soil compaction, a decrease in total pore space, and a change in pore space distribution (Randrup et al., 1997). After compaction, TOP and the number of macropores are reduced. This results in a reduction in water permeability and oxygen diffusion, which in turn, reduces the abundance of earthworms (Smetak et al., 2007). However, an effective change in soil BD and TOP within a suitable range would lead to an improvement in soil structure (Hou et al., 2012) conducive to earthworm survival. Thus, the abundance and diversity of earthworms would be expected to be higher in the plots with a lower degree of degradation.

The earthworm biomass and diversity index were both positively correlated with soil MWD (Table 4; $p < 0.05$). The higher MWD values reflected good soil structure, as well as indicating the soil macroaggregate content (Six et al., 2000). With an increase in the content of macroaggregates, soil water holding capacity will increase, resulting in preferable soil moisture conditions which can change the population characteristics of earthworms. Findings of our study showed that earthworm diversity and abundance were maximal in the plots with the highest TN and TK. However, these results differ from those of Singh et al. (2020) who found that the biomass and survival rate of earthworms decreased under high N and P conditions. These contrasting results may reflect the existence of a TN threshold in earthworm habitats, where soil N content within a reasonable range is beneficial to the survival of earthworms.

Similarly, some studies have shown that the survival ability of earthworms in acid or alkali environments is lower than that in neutral soils (De Wandeler et al., 2016; McCallum et al., 2016). In this study, the diversity and abundance of earthworms decreased with an increase in pH and CEC. The pH value of the soils varied from 8.11 to 8.71, indicating that the soils were alkaline. The pH values of more highly degraded soils may be too acidic or too alkaline for the survival of earthworms, resulting in a reduction in earthworm diversity and abundance (Mccallum et al., 2016). Soil CEC values can comprehensively reflect soil fertility levels. In our study, the earthworm abundance and diversity were both higher in the plots with good soil fertility and a low degree of degradation (Figures 3 and 4). These findings are consistent with those of Kwak et al. (2019), who observed that the soil fertility and quality improved after restoration, and the survival ability of earthworms increased as a consequence. An improvement in soil fertility and quality of the earthworm living environment would potentially lead to a pH value conducive to earthworm reproduction and sufficient food sources to meet the needs of earthworm feeding behaviour.

The findings discussed above suggest that earthworm indicators are sensitive to changes in the soil environment, and the soil environment has a significant influence on the abundance and diversity of earthworms. At the same time, suitable earthworm living environments increase the number and species of earthworms and improve the biological characteristics of the soil (Table 2). Groffman et al. (2015) reported that soil microbial biomass and the carrying capacity of soil microbial biomass both increased significantly after addition of earthworms to the soils in northern hardwood forests.

4.3 Applicability of earthworm indicator monitoring

The present study shows that there is a significant relationship between the degree of soil degradation and earthworm community indicators (Figure 6). This suggests that earthworm indicators can effectively reflect the impact of human management practices, land use types, soil physicochemical properties, and other factors on soil quality, thus indirectly responding to the degree of soil degradation. Similar results were obtained by Masin et al. (2020), who reported that the degree of soil disturbance caused by human activities can be estimated by measuring earthworm biomass, diversity, and ecotype distribution in different habitats in Santa Fe, Argentina. Bartz et al. (2013) investigated the range of variation in earthworm density (ind m^{-2}) and species numbers in no-till systems and defined a classification of earthworm indices for different soil qualities as follows: excellent (> 200 ind m^{-2} and > 6 species); good (100–200 ind m^{-2} and 4–5 species); moderate (25–100 ind m^{-2} and 2–3 species); poor (< 25 ind m^{-2} and 1 species). The earthworm biomass in the studies mentioned above was significantly higher than that in our study; however, there is no obvious difference in the number of earthworm species. The main reason for this may be that soil physical and chemical properties and environmental factors significantly affect earthworm biomass. Singh et al. (2020) noted that the diversity index, density, and biomass of earthworms were affected by different sampling areas and soil parent materials.

At present, earthworm biomass, abundance, and richness may enable effective characterisation of the degree of soil degradation in the Yeheshan area. However, with a change in soil type and climate, the earthworm parameter base will change. The variation in earthworm indicators (community characteristics) with the degree of soil degradation determined in this study will enable preliminarily evaluation of the degree of soil degradation in other regions. For further analysis, however, we need to collect basic earthworm indicator data in different regions in order to evaluate the degree of soil degradation over a much larger range of environments.

5. CONCLUSIONS

All seven earthworm species identified in the study were observed in natural woodland, shrubbery, and grassland and in planted woodland and shrubbery. All these land use types were associated with low degrees of soil degradation. In contrast, land use types with higher degrees of soil degradation had lower earthworm diversity, density, and biomass. Earthworm community characteristics were significantly correlated with land use type and soil physicochemical properties and biological characteristics, all of which can effectively characterise soil quality. Compared with the costly and complex procedures required to determine soil properties for soil degradation assessment, earthworm indicators that respond effectively and rapidly to the degree of soil degradation enable convenient and quick assessment of soil degradation, which is conducive to the timeous implementation of remedial measures to slow the rate of soil degradation. The results of the evaluation of earthworm community characteristics in relation to the degree of soil degradation under different land use types reflected consistency with soil physicochemical properties and biological characteristics. The linear correlations also confirmed the significant baseline relationship between the earthworm community characteristics and the soil degradation index. This study shows that earthworm indicators can be effectively used to evaluate soil degradation to a reasonable extent.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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Table 1 Basic status for the sites sampled in the Loess soil.

Sample plot	Slope (°)	Slope position	Slope aspect	Topography	Vegetation
NW	23	upper position	semi-adret	gully slope	Ouercus wutaishanica, Betula platyphylla
NS	25	upper position	semi-udbac	hillside	Rosa xanthina, Sophora davidii
PW	15	middle position	semi-udbac	gully slope	Robinia pseudoacacia
PS	7	middle position	semi-adret	gully slope	Caragana korshinskii
NG	16	middle position	semi-udbac	gully slope	Stipa bungeana, A. giraldii, Leymus secalinus
PG	5	upper position	adret	hillside	Melilotus suaveolens
CL	3	lower position	semi-adret	flood plain	Zea mays*, Triticum aestivum L.*
OL	10	lower position	adret	terrace	Malus domestica
AL	20	upper position	udbac	gully slope	A. Sacrorum, B.ischaemum

Table 2 Soil properties for the sites sampled in the Loess soil.

	BD (g·cm-3)	TOP (%)	MWD (mm)	SOC (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	MBC (mg kg^{-1})	MBN (mg kg^{-1})	SR (mg kg^{-1} d^{-1})	CEC (cmol kg^{-1})	pH
NW	0.87±0.01	66.81±2.33	3.28±0.25	24.57±0.83	2.12±0.11	0.68±0.11	12.17±0.23	148.3±3.2	88.5±2.7	38.5±1.1	12.36±0.45	8.11±0.01
NS	0.91±0.01	62.33±1.74	3.71±0.23	18.12±0.66	1.33±0.09	0.63±0.08	12.33±0.16	135.2±3.9	78.3±2.4	33.4±0.8	11.02±0.38	8.48±0.02
PW	1.11±0.02	54.15±2.10	2.23±0.26	10.13±0.57	0.51±0.05	0.50±0.03	16.62±0.13	128.7±4.6	71.2±3.1	28.7±0.7	5.16±0.13	8.65±0.03
PS	1.13±0.01	54.63±2.06	2.88±0.18	9.58±0.48	0.48±0.04	0.52±0.06	16.37±0.09	124.6±3.9	66.5±2.1	26.2±0.6	4.43±0.11	8.68±0.02
NG	1.21±0.03	53.72±1.88	3.03±0.19	13.37±0.52	0.64±0.06	0.61±0.05	16.11±0.11	131.8±2.7	75.2±1.9	30.6±1.2	5.49±0.17	8.54±0.03
PG	1.12±0.02	55.33±1.75	1.25±0.07	6.94±0.27	0.35±0.03	0.58±0.09	18.48±0.09	117.5±2.5	59.8±1.6	24.3±0.5	4.88±0.09	8.51±0.05
CL	1.19±0.02	53.36±1.84	0.87±0.02	6.35±0.23	0.38±0.04	0.62±0.07	18.62±0.22	92.4±1.6	30.7±1.4	22.6±0.5	4.91±0.15	8.66±0.06
OL	1.16±0.02	54.27±1.66	1.57±0.06	6.05±0.21	0.25±0.02	0.59±0.06	15.75±0.25	89.7±1.5	48.6±1.1	20.7±0.6	5.25±0.14	8.71±0.03
AL	1.12±0.01	53.92±1.38	1.74±0.08	6.58±0.26	0.34±0.03	0.56±0.04	16.83±0.17	113.4±2.1	54.2±1.5	23.1±0.4	5.06±0.08	8.70±0.04

BD: bulk density; TOP: total porosity; MWD: mean weight diameter; SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; TK: total potassium; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; SR: soil respiration; CEC: cation exchange capacity.

Table 3. The details of earthworm species.

Earthworm species	Family	Genera	Ecological category
Drawida gisti gisti (Michaelsen, 1931)	Moniligastridae	Drawida	Epigeic
Drawida japonica japonica (Michaelsen, 1982)	Moniligastridae	Drawida	Epigeic
A mynthas pingi pingi (Stephenson, 1925)	Megascolecidae	A mynthas	Epigeic
Metaphire guillelmi (Michaelsen, 1895)	Megascolecidae	Metaphire	Endogeic
Eisenia foetida (Savigny, 1826)	Lumbricidae	Eisenia	Epigeic
Lumbricus rubellus (Hoffmeister, 1843)	Lumbricidae	Lumbricus	Epi-endogeic
Allolobophora longa (Ude, 1885)	Lumbricidae	Allolobophora	Endogeic

Table 4. Correlation between earthworm indicators and soil properties.

	BD	TOP	MWD	SOC	TN	TP	TK	MBC	MBN	SR	CEC	pH
biomass	-0.89**	0.95**	0.77*	0.98**	0.98**	0.68	-0.86*	0.92**	0.89**	0.81**	0.96**	-0.89*
density	-0.67*	0.73*	0.90**	0.92**	0.84**	0.42	-0.75*	0.97**	0.83**	0.76**	0.74*	-0.72*
H’	-0.71*	0.76*	0.89**	0.93**	0.87**	0.43	-0.78*	0.83*	0.91*	0.85*	0.78*	-0.73*
S	-0.63*	0.68*	0.91**	0.89**	0.79**	0.34	-0.74*	0.81*	0.77*	0.80*	0.70*	-0.66*
E	-0.57	0.63	0.75*	0.82*	0.75*	0.38	-0.56	0.42	0.69*	0.66	0.64	-0.69*

H’: Shannon-Wiener index; S: Species richness index; E: Pielou’s evenness index; BD: bulk density; TOP: total porosity; MWD: mean weight diameter; SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; TK: total potassium; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; SR: soil respiration; CEC: cation exchange capacity.