Received: 11 December 2020 | Revised: 23 February 2021 | Accepted: 28 February 2021

DOI: 10.1002/ldr.3928

RESEARCH ARTICLE

WILEY

Assessment of earthworms as an indicator of soil degradation: A case-study on loess soils

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Funding information
the Strategic Priority Research Program of the Chinese Academy of Sciences, Grant/Award Number: XDA23070202

Abstract

Soil degradation restricts the development of agriculture, and the degree of soil degradation is related to land use type, and efficient evaluation methods are helpful for the timely implementation of remedial measures to ensure soil sustainability. Earthworms are directly affected by the deterioration of soil properties during the degradation process. The feasibility of using earthworms to assess soil degradation, however, still needs to be verified. In our Loess Plateau study, earthworm biomass, density, and diversity (Shannon-Wiener, species richness, and Pielou's evenness) were investigated under nine different land use types (natural woodland, shrubland and grassland; planted woodland, shrubland and grassland; and cropland, orchard, abandoned land) and we analyzed their relationships with soil degradation. Our results showed earthworm biomass, density, and diversity associated with a low degree of degradation were significantly higher than those associated with a high degree of degradation. Earthworms can comprehensively characterize 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 indices, indicating that the latter could be used to effectively evaluate and represent the degree of degradation of soils on the Loess Plateau over a certain degradation range. Nevertheless, this evaluation method requires further validation before wider use.

KEYWORDS
bioindicators, diversity index, earthworms, land use types, soil degradation

1 | INTRODUCTION

Soil degradation is commonly a direct cause of soil quality decline, and its impact on ecosystems cannot be ignored (Zhang, Li, Pan, & Ren, 2006). Unreasonable development and utilization of land and excessive application of chemical fertilizer and organic manure to improve crop yield and quality aggravate the degree of soil degradation (Srinivasrao et al., 2014; Turkelboom, Poesen, & Trébuil, 2008). The aggravation of soil degradation further 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 (Bazhenova & Kobylkin, 2013; Senjobi & Ogunkunle, 2010; Tang, Liu, & Liu, 2013). By selecting suitable soil degradation evaluation indices, evaluating the degree of soil degradation proactively, and implementing corresponding restoration measures, soil quality decline can be accurately assessed and then effectively slowed.

Soil fauna actively promotes the material circulation process in an ecosystem through their activities such as feeding and other behaviours; thus, they significantly affect the soil quality. Moreover, there are many types of soil fauna with activities that are 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 leading to environmental change can be more effectively accomplished in comparison to the use of physical and chemical indicators (Ruf et al., 2003). In addition, biological indicator measurement is cost effective and can be intensively implemented over large areas distances, even in remote places (Cole, Dromph, Boaglio, & Bardgett, 2004; Ouédraogo, Mando, & Brussaard, 2004).

Earthworm species are common members of the soil macrofauna, and have been called 'the soil ecosystem engineer' because they 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 when there is a change in earthworm ecotype (Kherbouche, Bernhard-Reversat, Moali, & Lavelle, 2012). At the same time, many studies have shown that the distribution of earthworm populations changes with alteration in habitat (Carnovale, Baker, Bissett, & Thrall, 2015; Smetak, Johnson-Maynard, & Lloyd, 2007). Xu, Johnson-Maynard, and Prather (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 & 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 earthworms (Jiménez et al., 2011; Perreault & Whalen, 2006). In suitable habitats, the biomass, abundance, and diversity of earthworms increase significantly. Additionally, earthworm communities varied between different land use systems, and earthworm abundance was significantly higher under pastures than maize which was subjected to greater management intensity (Pérès, Bellido, Curmi, Marmonier, & Cluzeau, 2010) Sackett, Smith, and Basiliko (2012), however, suggested forests exposed to human activities that were proximate to agricultural areas have larger earthworm populations.

All the studies mentioned above show 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. To assess the degree of soil degradation using earthworms as indicators, it is necessary to clarify the relationship between earthworm characteristics and different degrees of soil degradation. A clear indicator based on earthworms needs to be established to effectively reflect the degree of soil degradation or remediation in order to improve soil sustainability.

The Loess Plateau suffers from severe soil erosion which leads to widespread land degradation (Zhang, Xue, Liu, & Song, 2011). So far, great efforts have been made to assess the quality of degraded soil in the Loess Plateau area in terms of soil erosion or soil properties (e.g., Fu & Gulinck, 2010; Zhao, Wu, Gao, & Persaud, 2015). A series of afforestation programmes benefits soil fauna, and their quantity and diversity are closely related to soil properties (Yang, Shao, Li, Gan, & Chen, 2021), which offers the possibility of using earthworms as an indicator in land degradation evaluation. Therefore, this study aimed to: (1) explore the relationship between the degree of soil degradation and various earthworm indices (biomass, density, and diversity index) that could be used as indicators; and (2) 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 in the Yeheshan Provincial Nature Forest Reserve (34°31.76′N, 107°54.67′E), Fufeng County, Shaanxi Province, China (Figure 1). 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

The experiment was conducted from August to September 2019. In the study area, nine field plots with different land use types were selected for earthworm sampling: natural woodland (NW), natural shrubbland (NS), natural grassland (NG), planted woodland (PW), planted shrubland (PS), planted grassland (PG), cropland (CL), orchard (OL), and abandoned farmland (AL), in which the AL had been abandoned for 10 years. The basic characteristics and soil properties of all field plots are shown in Tables 1 and 2, respectively. Each land use type covers an area of about 3,400 m^3. A $30 \times 30\ m^2$ 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 hr 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.

Additional soil samples for determination of soil physio-chemical properties were collected from the 0 to 20-cm soil layer with a shovel in each sample plot, after removal of the surface impurities, and

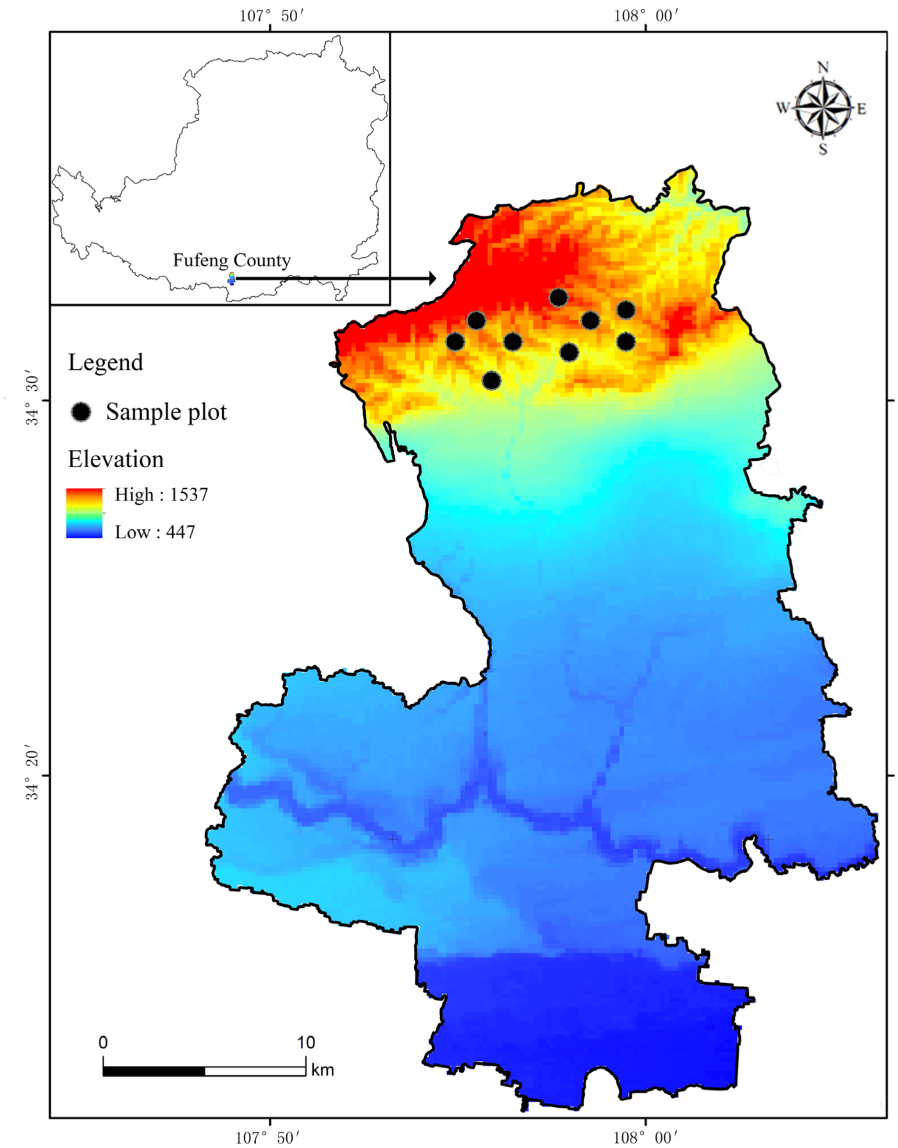

FIGURE 1 Location of the study site and the distribution of the sampling sites [Colour figure can be viewed at wileyonlinelibrary.com]

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*, *Artemisia 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	*Artemisia sacrorum*, *Betula ischaemum*

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), microbial biomass carbon (MBC), and nitrogen (MBN) content were determined using the external heating potassium dichromate, ammonium acetate exchange, and chloroform

TABLE 2 Soil properties for the sampling sites in the loess soil

	BD ($g{\cdot}cm^{-3}$)	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

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

fumigation extraction methods, respectively. Total nitrogen (TN), total phosphorus (TP), and total potassium (TK) were measured using a continuous flow analyzer (F-410; UK). 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:

$$\mathrm{MWD} = \sum_{i=1}^{n} (\overline{xi}wi), \tag{1}$$

Where: $\overline{xi}$ 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:

$$\text{Shannon-Wienerindex}: H' = -\sum_{i=1}^{s} P_i ln P_i \tag{2}$$

$$\text{Species richness index}: S = 1 - \sum_{i=1}^{s} P_i^2, \tag{3}$$

$$\text{Pielou's evenness index}: E = H'/lns, \tag{4}$$

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 & Weil, 2000):

$$\mathrm{SDI} = [(\mathrm{P}_1 - P'_1)/P'1 + (\mathrm{P}_2 - P'_2)/P'_2 + \cdots + (P_n - P'_n)/P'_n] \times 100\%/n, \tag{5}$$

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. Generally, the baseline values of soil properties were obtained from the most well-stocked land. In this study, the NW with highest vegetation coverage and least human disturbance 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 2.

One-way analysis of variance (ANOVA) was used to determine the effects of soil degradation on earthworm abundance and diversity. Differences were considered significant at $p < .05$. Shapiro–Wilk test and Levene's test were used to test the normality and heterogeneity of variance for each data set before one-way ANOVA. Nonnormal data were transformed using a natural log-transformation prior to the analysis. The relationships between soil properties and earthworm biomass, density, and diversity indices were determined using Pearson's correlation analysis. To determine the classification of earthworm indices in relation to different degrees of soil degradation, principal component analysis (PCA) was conducted based on the earthworm indices (biomass, density, H′, S and E) under different degrees of soil degradation using CANOCO v. 5.0 (Biometris, Wageningen, The Netherlands). Firstly, the adequacy of the earthworm indices matrix was measured by two tests: Kaiser-Meyer-Olkin (KMO) and Bartlett's test of sphericity. The KMO measure yielded a value of 0.862, and Bartlett's test of sphericity was highly significant ($p < .001$), determining the suitability of the data set for PCA. Then, PCA extracted the factors with eigenvalues greater than 1.0. 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 v. 20.0 software (SPSS Inc., Chicago, IL). GRAPHPAD PRISM v. 8 for Windows (GraphPad Software, La Jolla, CA) 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*, *Drawida japonica*, *Amynthas 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 3). 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

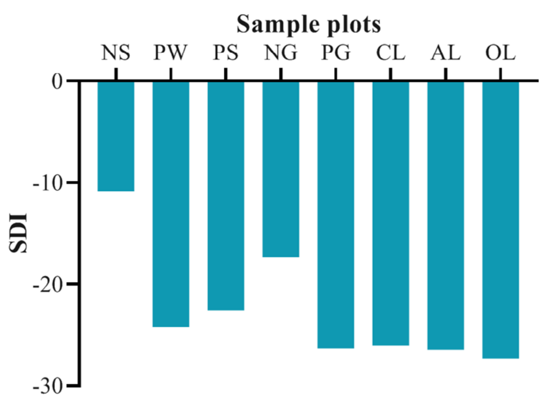

FIGURE 2 Soil degradation index (SDI) in different plots [Colour figure can be viewed at wileyonlinelibrary.com]

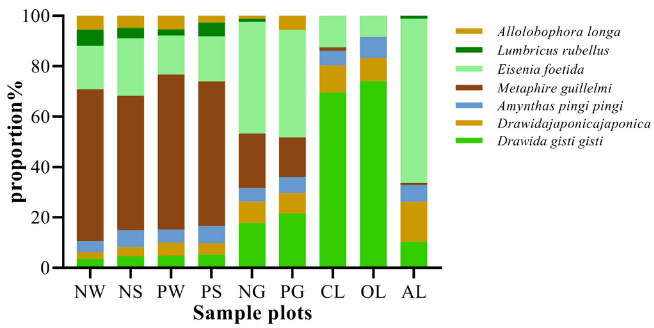

FIGURE 3 Earthworm community structure of different plots [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 The details of earthworm species

Earthworm species	Family	Genera	Ecological category
Drawida gisti (Michaelsen, 1931)	Moniligastridae	Drawida	Epigeic
Drawida japonica (Michaelsen, 1892)	Moniligastridae	Drawida	Epigeic
Amynthas pingi (Stephenson, 1925)	Megascolecidae	Amynthas	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

plots, respectively. *Drawida 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. Combined with the SDI values of the plots, more species and ecotype of earthworms were observed in the plots with lower degradation degree than those with higher degradation degree.

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 4. All three indices varied consistently among the different plots in the following order: NW > NS > NG > PS > PW > CL > PG > AL > OL. Meanwhile, they decreased with the aggravation of soil degradation, indicating less earthworm abundance and diversity in more severely degraded soil. There were significant differences in the Shannon index among the different plots ($p < .05$), 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 ($p < .05$). 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, ($p < .05$). All the other land use types showed significant differences ($p < .05$), except for the NS and PW.

Differences in earthworm biomass and density of individuals were observed among the different plots (Figure 5) with both these potential indices 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), which indicated that the biomass and abundance of earthworm would decrease with the increase of soil degradation. Earthworm biomass was significantly higher in the NW and NS than in the other plots ($p < .05$), whereas the PW, PS, PG, and CL plots showed no significant difference ($p > .05$; Figure 5). The density of earthworms was significantly higher in the NW than in the other plots ($p < .05$).

3.3 | Correlations between earthworm indices and soil properties

Correlations between earthworm indices 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,

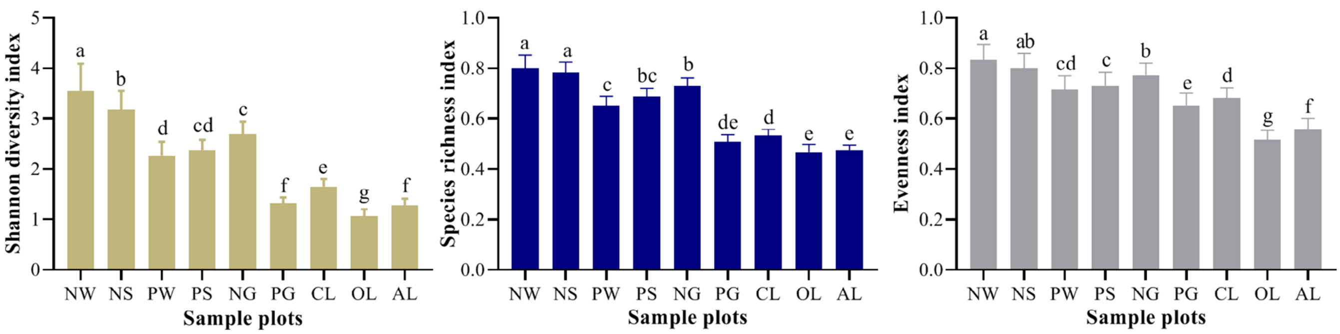

FIGURE 4 Earthworm diversity, richness, and evenness index in different plots [Colour figure can be viewed at wileyonlinelibrary.com]

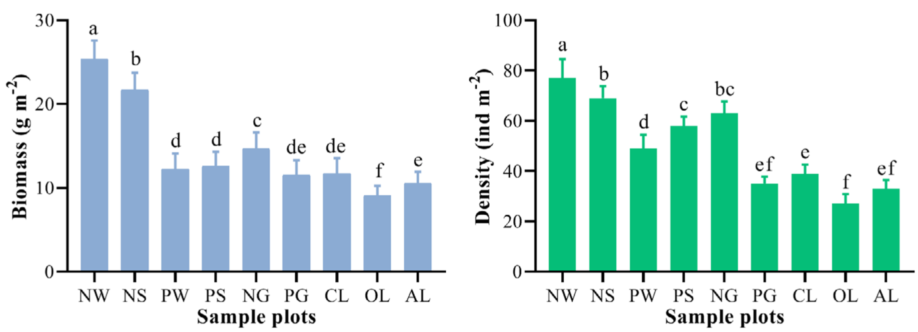

FIGURE 5 Earthworm biomass and density in different plots. ind, individual [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Correlation between earthworm indices 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*

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

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 ($p < .05$), with correlation coefficients of 0.89, 0.93, and 0.87 (diversity), 0.91, 0.89, and 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 ($p < .01$), and the earthworm diversity and species richness indices were positively correlated with SR and MBC ($p < .05$). These findings suggest that these particular earthworm indices are closely related to and could, therefore, effectively reflect changes in soil biological characteristics.

3.4 | Correlation between earthworm indices and soil degradation index

Results from PCA analysis showed the first two principal components (PCs) with eigenvalues values greater than 1.0 (8.92 and 1.87) explained 93.8% of the variance, with PC1 contributing 91.7% and PC2, 2.1% (Figure 6). The contribution of earthworm biomass, density, H′, S, and E to PC1 and PC2 was all greater than 0.5, in which earthworm biomass contributed most to PC1 (94.3%) and H′ contributed most to PC2 (91.2%). On the PC1 axis, the plots with different degrees of soil degradation were clustered into three groups according to the earthworm 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 angles of the arrow between the PC1 axis and earthworm biomass, density, and diversity indices were all small, indicating that the PC1 axis mainly related to earthworm population characteristics. The above indices pointed to the plot with a low degree of soil degradation, indicating that the land use type with lower degree of soil degradation was more beneficial for earthworm activity. Results of the linear correlation of the SDI and the different earthworm indices are shown in Figure 7. The R^2 values varied from 0.815 to 0.934, indicating a significant positive correlation between SDI and earthworm biomass, density, and Shannon-Wiener index ($p <$ .05), reflecting that, with an increase in the degree of soil degradation, the earthworm abundance and diversity decreased. Compared to density and Shannon diversity index, SDI was more correlated to earthworm biomass.

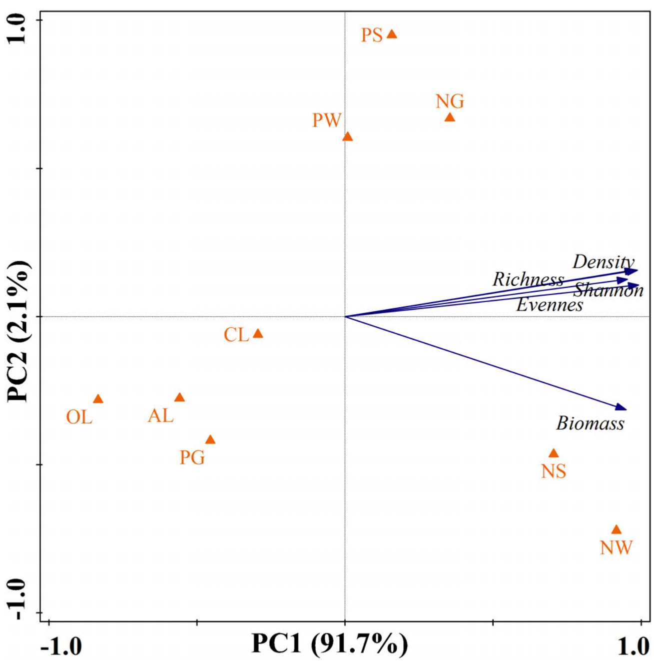

FIGURE 6 Principal component analysis on the earthworm indices under different soil plots [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

4.1 | Responses of earthworm indices to land use type

In terrestrial ecosystems, unreasonable management and land use cause soil degradation (Baude, Meyer, & Schindewolf, 2019; Sklenicka, 2016), and actions, including overgrazing, deforestation, and overcultivation, potentially aggravate the degree of soil degradation (Khresat, Rawajfih, & Rusan, 1998; Tesfahunegn, 2019). At

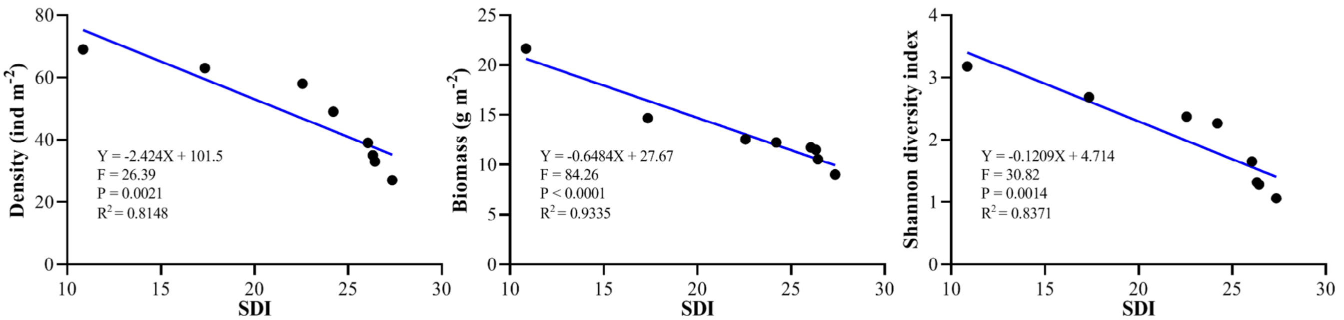

FIGURE 7 The relationship between SDI and earthworm density, biomass, and Shannon diversity index. ind, individual [Colour figure can be viewed at wileyonlinelibrary.com]

present, many studies have shown that earthworm diversity and biomass are closely related to soil management and land use type (Feijoo, Carvajal, Zúñiga, Quintero, & Fragoso, 2011; Pelosi 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 4 and 5). 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, Clements, and Donaldson (2003) reported that a higher earthworm diversity and abundance were 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. The effects of land-use change on soil degradation have been well known based on many case- studies (Zhao, Xiao, Liu, & Li, 2005; Zucca, Canu, & Previtali, 2010). For example, Zhao et al. (2005) reported that cultivation of grassland is accompanied by coarsening in soil texture and the losses in organic C and nutrients and leading to a significant soil degradation, while vegetation restored after fields were abandoned. Zucca et al. (2010) compared the physical, chemical, biological, and micromorphological properties of paired forest and pasture soil samples and a significant degradation after the conversion of forest to pasture land in Sardinia. Different soil properties inevitably results in changes in earthworms. 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 indices. 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 indices can effectively reflect the degree of soil degradation. Furthermore, in our study, earthworm indices 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 (Carnovale et al., 2015; Cesarz, Fahrenholz, Migge-Kleian, Platner, & Schäfer, 2007). Wang, Long, Wang, Jing, and Shi (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 & Bohlen, 1996). In the management of farmland and orchards, fertilizers 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 the highest degree of degradation.

4.2 | Response of earthworm indices to soil properties

Soil property changes significantly affect earthworm biomass, density, and diversity (Singh, Singh, & Vig, 2016). In the present study, earthworm indices were significantly correlated with all measured soil properties except TP (Table 4). Food availability in the soil is also an important factor affecting earthworm indices. Different degrees of soil degradation have different impacts on the food available to earthworms in the soil (Heinze, Raupp, & Joergensen, 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, Pasini, & Brown, 2013). Similar results were found by Brown, Barois, and Lavelle (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 (de Abreu Pestana, de Souza, Tanaka, Labarque, & Soares, 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, 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; $p < .05$). The higher MWD values reflected good soil structure, as well as indicating the soil macroaggregate content (Six, Paustian, Elliott, & Combrink, 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 Kahlon, Sharma, Khajuria, Singh, and Vig (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 4 and 5). 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 indices 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 indices monitoring

The present study shows that there is a significant relationship between the degree of soil degradation and earthworm indices (Figure 7). This suggests that earthworm indices 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, Rodriguez, Zalazar, and Godoy (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); and 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 Kahlon 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 diversity may enable effective characterization of the degree of soil degradation in the Yeheshan area. Earthworm biomass performed best in assessing soil degradation among all the indices concerning earthworms in our study. However, with a change in soil type and climate, the earthworm parameter base will change. The variation in earthworm indices with the degree of soil degradation determined in this study will enable preliminarily evaluation of the degree of soil degradation in other regions. Bartz et al. (2013) used earthworm density and species richness to classify soil quality and found different results were obtained based on different index. Therefore, a preliminary investigation is needed to determine the specific optimal indices based on earthworms before the assessment of soil degradation using earthworms as indicator for other studies. For further analysis, however, we need to collect basic earthworm data in different regions in order to evaluate the degree of soil degradation over a much larger range of environments.

5 | CONCLUSIONS

The biomass, density, and diversity of earthworms tended to decrease in more degraded soils and were significantly correlated with land use type, soil physicochemical properties, and biological characteristics. The results of the evaluation of earthworms in relation to the degree of soil degradation under different land use types reflected consistency with soil properties. This study shows that earthworms that respond effectively and rapidly to the degree of soil degradation enable convenient and quick assessment of soil degradation.

ACKNOWLEDGMENTS

This study was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA23070202).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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How to cite this article: Li Y, Wang J, Shao M. Assessment of earthworms as an indicator of soil degradation: A case-study on loess soils. *Land Degrad Dev*. 2021;32:2606–2617. https://doi.org/10.1002/ldr.3928