

A comparison of soil qualities of different revegetation types in the Loess Plateau, China

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Abstract Serious soil erosion has resulted in widespread land degradation in the Loess Plateau of China. In the past two decades, great efforts have been made to restore degraded soil such as reconvert croplands into forestlands or grasslands. A comparison of soil qualities of different revegetation types has important implications in soil reclamation. Our study investigated the effect of different revegetation types on the physicochemical and microbial soil properties in the Loess Plateau, with the aim of determining which

revegetation type has the best capacity for soil recovery. The vegetation types included two shrublands (*Caragana korshinskii* and *Hippophae rhamnoides*), two grasslands (*Astragalus adsurgens* and *Panicum virgatum*), and two species from croplands that were abandoned for natural recovery (*Artemisia capillaries* and *Heteropappus altaicus*). Among the plants studied, *H. altaicus* and *A. capillaries* had the highest values of soil organic C, total N, total P, available N, available P, moisture content, microbial biomass C (MBC), substrate-induced respiration, saccharase, urease, catalase, and peroxidase. Soil sampled from the *A. adsurgens* plot had the highest bulk density and microbial biomass N, and soil from the *H. rhamnoides* plot had the highest metabolic quotient (basal respiration/MBC). The soil quality index, which was obtained based on the available N, metabolic quotient, MBC, urease, polyphenol oxidase, and bulk density, shows that the abandoned cropland for natural recovery had the highest soil quality, followed by grassland, and then shrubland. Vegetation types affect the physicochemical and microbial properties of soils in arid climatic conditions. Abandoned cropland for natural recovery has the best capacity for improving soil quality in the Loess Plateau among all studied revegetation types. Our study suggests that in the Loess Plateau, natural recovery is the best choice for soil revegetation of sloping croplands.

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Introduction

Land degradation is intensifying in many parts of the world because of poor soil management practices and policies. According to a 2008 estimation of the Food and Agriculture Organization (FAO) of the United Nations, there are approximately 1.5 billion people (quarter of the world's population) who depend directly on land that is being degraded. Land degradation not only induces the deterioration of the ecological function and productivity of land through soil erosion, desertification, and salinization, but also threatens socio-economic and cultural development at regional and global scales (Lal 2001). The Loess Plateau of China has a typical semiarid climate area and has experienced serious soil degradation for the past fifty years. In most parts of the Loess Plateau, many erosion-susceptible slope areas and native grasslands have been converted into farmlands because of the pressures of an increasing population. Severe soil erosion has resulted in the loss of most of the topsoil in many locations, thus exposing parent materials or soils with low nutrient content (Wei et al. 2006; Zhou et al. 2006). The Chinese Government acknowledged the severity of this problem and launched in 1999 a series of nationwide conservation projects focusing on ecological restoration mainly by reconvertng croplands into forestlands and grasslands. These reconversions have improved the soil physical properties (Li and Shao 2006; An et al. 2008; Zhu et al. 2010), nutrient status (Jia et al. 2005; Cao et al. 2008), and microbial properties (Jiang et al. 2009; Fu et al. 2009a, b). Different vegetation types influence soil quality in different magnitudes, so a comparison of the soil qualities of different vegetation types is important for successful soil reclamation in the Loess Plateau.

Physical and chemical properties have been extensively used to evaluate soil quality. These include soil organic matter, available N, and water holding capacity (Parr and Papendick 1997). These properties, however, usually change slowly and thoroughly reflecting soil changes through these properties is impossible. On the other hand, microbial properties rapidly respond to soil changes caused by both natural and anthropogenic factors, and some enzymes are closely related to soil energy flow and nutrient cycles. For instance, soil microbial biomass is considered to be a transformation agent of organic soil materials and a labile pool for plant nutrients (Lin et al. 2004). Urease and polyphenol oxidase play essential roles in catalyzing reactions

necessary for the transformation of N nutrients and decomposition of humus (Benitez et al. 2000; Cullen and Kersten 1996). The metabolic quotient, basal respiration (BR)/microbial biomass C (MBC), has been used to evaluate microbial community in reclamation soils. Soil quality, though, cannot be assessed with one property alone, but with a variety of properties (Nannipieri et al. 1990). Soil quality indicators have been developed because of the complex nature of soils and the exceptionally large number of soil properties that must be determined. The selection of indicators that appropriately reflect the overall change of soil quality is important. Bastida et al. (2006) developed a microbial degradation index based on five properties: dehydrogenase, water-soluble carbohydrates, urease, water-soluble C, and respiration. A rhizosphere soil microbial index (RSMI) employing principal component analysis to assess rhizosphere health has been developed by Sinha et al. (2009). They showed that tree species with higher RSMI values should be used in the revegetation of a degraded coal mining area. Trasar-Cepeda et al. (1998) found that in native soils with climax vegetation, total N can be expressed as a combination of several microbiological and biochemical properties including microbial biomass C, mineralized N, phosphomonoesterase, glucosidase, and urease. However, there is little available information on soil quality evaluation by an integrated index in the Loess Plateau.

The present study investigates the ability of six common **vegetation restoration species** in three land types, namely, shrubland, grassland, and natural fallow, **to regenerate soil quality**. Our objectives are: (1) to study the effects of these six species on the physicochemical and microbial properties of soil in the Loess Plateau, and (2) to establish a soil quality index (SQI) that will determine which vegetation type is most capable of soil quality restoration. We not only provide specific information on the effects of changing land use on physicochemical and microbial soil properties, but also the implications of reasonable utilization of slope cropland in the region.

Materials and methods

Study sites

The present study was conducted in the Dunshan watershed at the Ansai Research Station of Soil and

Water Conservation, Shaanxi Province, in the northern Loess Plateau (109°19'23"E, 36°51'30"N) in China. The area is characterized by a semiarid climate, with a mean annual temperature of 8.8°C and an average annual precipitation of 510 mm, mostly from July to September. The annual evaporation ranges from 1,500 to 1,800 mm and the average frost-free period is approximately 203 day. The soil is mainly Huangmian soil (Calcaric Cambisols, FAO), developed on wind-deposited loessial parent material and characterized by a yellow colour, absence of bedding, silty texture, looseness, macroporousness, and wetness-induced collapsibility. The soil texture is 64% sand, 24% silt, and 12% clay. The study area is representative of soil subjected to both wind and water erosion.

Widespread vegetation restoration has been implemented in the region during the past decade to remedy the soil degradation problem (Fu et al. 2009a, b). The vegetation restoration types are predominately perennial, including shrubs such as *Caragana korshinskii* and *Hippophae rhamnoides*, grasses such as *Astragalus adsurgens* and *Panicum virgatum*, and natural vegetation from abandoned croplands.

Experiment design and soil sampling

The experimental area covered a total area of 8800 m². In 2000, six vegetation types were

established on the sloping cropland: two shrubs, *C. korshinskii* and *H. rhamnoides*; two grasses, *A. adsurgens* and *P. virgatum*; and two species from abandoned croplands for natural recovery. The six locations were all similar in terms of the slope aspect, gradient, altitude, and previous farming practices before initiating the experiment, hence the assumption that the differences in soil properties could be attributed to the type of vegetation (Fu et al. 2009a, b; Marzaioli et al. 2010). Three replicate plots (20×20 m) were established for each vegetation type. *C. korshinskii* and *H. rhamnoides* were seeded with a row spacing of 70 and 80 cm, respectively. *A. adsurgens* and *P. virgatum* were both seeded with 45 cm row spacing. In 2008, the predominant species in one of the abandoned croplands for natural recovery was *Artemisia capillaries*, and in another, *Heteropappus altaicus*. All the plants developed under semiarid conditions, without irrigation, fertilization, and disturbance after planting (Zhang et al. 2011). The description of each treatment is shown in Table 1.

In 2008, five subplots were randomly established in each plot for coverage measurement: 2.5 m×2.5 m for *C. korshinskii* and *H. rhamnoides*; and 1×1 m for *A. adsurgens*, *P. virgatum*, *A. capillaries*, and *H. Altaicus*. Soil samples were collected from the top 20 cm of the soil profile with a 5 cm diameter stainless steel corer after litter horizons were removed. Soil was collected along an "S" pattern

Table 1 Sample site description of the Dunshan watershed area. The soil type for all vegetation treatments was loessial soil. Plots were established in 2000. Vegetation coverage measurement and soil sampling was done in 2008

Vegetation Types	Main Vegetation	Slope Aspect	Slope (°)	Altitude (m)	Coverage (%)	Minor Herbaceous Coverage (%)
Shrubland	<i>Caragana korshinskii</i>	N	20	1257	72.48	<i>Artemisia sacrorum</i> (9.80) and <i>C. Chinensis</i> Maxim (7.21)
	<i>Hippophae rhamnoides</i>	N	22	1220	60.62	<i>Artemisia argyi</i> (10.14), <i>Stipa bungeana</i> (4.50), and <i>Artemisia sacrorum</i> (4.50)
Grassland	<i>Astragalus adsurgens</i>	NE 10°	20	1235	68.54	<i>Lespedeza davurica</i> (14.64), <i>Lactuca indic</i> (5.52), <i>Oxytropis bicolor</i> (5.50), and <i>Stipa bungeana</i> (3.64)
	<i>Panicum virgatum</i>	NW 25°	24	1282	75.19	<i>Poa annua</i> (13.32), <i>Heteropappus altaicus</i> (5.53), and <i>Stipa bungeana</i> (3.81)
Abandoned cropland for natural recovery	<i>Heteropappus altaicus</i>	NW 10°	24	1311	70.47	<i>Stipa bungeana</i> (14.55), <i>Artemisia sacrorum</i> (8.73), <i>Cleistogenes squarrosa</i> (3.62), and <i>Artemisia capillaries</i> (2.05)
	<i>Artemisia capillaries</i>	N	22	1298	64.53	<i>Lespedeza davurica</i> (16.45), <i>Potentilla bifurca</i> (10.23), <i>Potentilla bifurca</i> (5.82), and <i>Heteropappus altaicus</i> (2.61)

from six sampling points at each plot. Roots, stones, and debris were removed, and then each sample was divided into two parts. One part was air-dried for analysis of physicochemical soil properties, and the other one was immediately sieved through a 2 mm mesh and then stored at 4°C until soil microbial properties could be analyzed.

Laboratory analysis

Soil organic carbon (SOC) was determined using the Walkley-Black method (Nelson and Sommers 1982), and total nitrogen (TN) by the Kjeldahl method (Bremner and Mulvaney 1982). Total phosphorus (TP) was determined colorimetrically after wet digestion with $\text{H}_2\text{SO}_4 + \text{HClO}_4$, and available phosphorus (AP) was determined by the Olsen method (Olsen and Sommers 1982). Available nitrogen (AN), available potassium (AK), and bulk density were determined according to ISSCAS (1981). AN was determined with a micro-diffusion technique after alkaline hydrolysis. AK was measured in 1 M NH_4OAc extracts by flame photometry. Soil bulk density was determined using a soil core (stainless steel cylinders with a diameter and a height of 5 cm each) at each sampling point. Soil moisture content was determined gravimetrically by drying the samples at 105°C overnight, and the water content was expressed as a percentage of the dry weight. An automatic acid–base titrator (Metrohm 702) was used to determine soil pH in 1:2.5 soil: water suspensions.

MBC and microbial biomass N (MBN) were measured by the fumigation extraction method (Vance et al. 1987). Oven-dry equivalent field-moist soil (25 g) was fumigated for 24 h at 25.8°C with ethanol-free CHCl_3 . Following fumigant removal, the soil was treated with 100 ml of 0.5 M K_2SO_4 by horizontal shaking for 1 h at 200 rpm, and was then filtered. The other non-fumigated 25 g soil sample was extracted simultaneously at the time fumigation commenced. SOC in the extracts was measured using a Liqui TOCII analyzer (Elementar, Germany). TN in the extracts was measured using the Kjeldahl method. MBC was calculated using a k_{EC} factor of 0.38, and MBN using a k_{EN} factor of 0.54 (Vance et al. 1987). All analyses were performed on soil in triplicate at field capacity moisture status, and the extracted volumes took into account the water contained in the moist soil.

Soil BR was estimated via CO_2 evolution at 25.8°C in samples incubated for 14 day, adjusted to 50% of field water holding capacity (Jenkinson and Powlson 1976). The CO_2 respired was trapped in NaOH, and the residual NaOH was titrated with HCl. Soil substrate-induced respiration (SIR) was determined using the same method as BR but with actual addition of glucose to the soil (Zhang et al. 2006). The metabolic quotient BR/MBC was calculated as BR per unit of MBC (Anderson and Domsch 1993). The microbial quotient was calculated by MBC/SOC .

Enzyme activities were assayed as described by Guan et al. (1991). The moisture content was determined after drying at 105.8°C for 48 h. For all enzyme assays, controls were included without substrate and without soil samples. Saccharase activity was measured using 5 g of fresh soil (sieved to <1 mm), 15 ml of 8% glucose solution, 5 ml of 0.2 M phosphate buffer at pH 5.5, and 5 drops of toluene. After incubation for 24 h at 37.8°C, the soil solution was filtered, and a 1 ml aliquot was transferred to a volumetric flask with 3 ml of 3,5-dinitrylsalicylate, and then heated for 5 min. After the solution reached room temperature, the product was quantified colorimetrically in a spectrophotometer (Hitachi, UV2300) at 508 nm. Results were expressed as $\text{mg glucose released} \cdot \text{g}^{-1} \text{ soil} \cdot \text{h}^{-1}$.

Urease activity was determined using 5 g of fresh soil (sieved to <1 mm), 5 ml of citrate solution at pH 6.7, and 5 ml of 10% urea solution. The samples were incubated at 37.8°C for 3 h, and then diluted to 50 ml with distilled water. The suspension was filtered, and then a 1 ml aliquot was treated with 4 ml of sodium phenol solution (100 ml of 6.6 M phenol solution and 100 ml of 6.8 M NaOH) and 3 ml of 0.9% sodium hypochlorite solution. The released ammonium was quantified colorimetrically at 578 nm. Results were expressed as $\text{mg NH}_4^+-\text{N} \cdot \text{g}^{-1} \text{ soil} \cdot \text{h}^{-1}$.

Alkaline phosphatase activity was determined using 2 ml of toluene, 10 g of fresh soil (sieved to <1 mm), 10 ml of disodium phenyl phosphate solution, and 10 ml of 0.05 M borate buffer at pH 9.6. The suspensions were incubated for 3 h at 37.8°C. The samples were then filtered and the filtrate was colored with 0.5 ml of 2% 4-aminoantipyrine and 8% potassium ferrocyanide. The phenol released was determined colorimetrically at 510 nm. Results were expressed as $\text{mg phenol} \cdot \text{g}^{-1} \text{ soil} \cdot \text{h}^{-1}$.

Catalase activity was determined using 2 g of fresh soil with 40 ml of distilled water and 5 ml of 0.3% H₂O₂, shaken for 20 min at 150 rpm, and then immediately filtered through Whatman 2 V. The filtrate was titrated with 0.1 M KMnO₄ in the presence of sulfuric acid. The results were expressed as mol KMnO₄ · g⁻¹ soil · h⁻¹.

Polyphenol oxidase activity was determined using 5 g of fresh soil incubated for 2 min in a water bath at 30.8°C, with 10 ml of distilled water, 6 ml of 0.1% ascorbic acid, and 10 ml of 0.02 M catechol. A volume of 3 ml of 10% phosphoric acid was then added to the suspension, and the filtrate was titrated with 0.01 M iodine. Results were expressed as ml 0.01 M I₂ · g⁻¹ soil · h⁻¹. For the measurement of peroxidase, the same method was adopted.

Cellulase activity was determined using 5 g of fresh soil incubated with 1.0% carboxymethyl-cellulose in 5 ml of 0.2 M phosphate buffer (pH 5.5) at 37°C for 24 h. The soil solution filtrate was transferred to a volumetric flask with 3 ml of 3,5-dinitrylsalicylate and was heated for 5 min. After the solution reached room temperature, the product was analyzed colorimetrically at 540 nm. The cellulase activity was expressed as mg glucose · g⁻¹ soil · h⁻¹.

Soil quality index (SQI)

As previously mentioned, soil quality comprises a variety of metabolic processes that cannot be assessed with one property alone, but with a variety of properties (Nannipieri et al. 1990; Bastida et al. 2006). However, because some parameters correlated significantly with each other and usually reflect the same information, thus it is necessary to eliminate the parameters. Based on the method described by Bastida et al. (2006) and Masto et al. (2008), an integrated SQI was established in the present study. The method mainly involves three steps: (1) selecting the appropriate parameters, (2) transforming and weighing the parameters, and (3) combining the scores into an index (Bastida et al. 2006; Sinha et al. 2009). The parameters that differed significantly were chosen for the SQI calculation. The choice of appropriate parameters and their weighing were determined by principal component analysis (PCA). In each principal component (PC), only the parameters loading

higher values were chosen for indexing, and high factor loadings were defined as having absolute values within 10% of the highest factor loading (Andrews et al. 2002). If there were more than one parameter with high loading in a single PC, only the parameters that did not correlate with each other (as determined by Pearson correlation analysis) were considered to be important and were therefore selected. If the parameters were well correlated, the one with higher loading was finally chosen for the determination of the SQI (Sinha et al. 2009). To transform the parameters' values into scores (Y), a sigmoidal type equation was used (Bastida et al. 2006; Masto et al. 2008), with an asymptote tending to 1 and another tending to 0.

$$Y = a / (1 + (x/x_0)^b) \quad (1)$$

In Eq. 1, Y is the score of the proposed parameter after conversion, a is the maximum score (in the present case, $a=1$), x is the value of the parameter, x_0 is the mean value of the parameter, and b is the value of the equation's slope. In the PCA, two kinds of parameters, "+" (meaning "more is better") and "-" (meaning "less is better"), were used to obtain a sigmoidal curve tending to 1 for all the proposed parameters, -2.5 and 2.5 were used as the b values for "+" and "-", respectively.

$$SQI = \sum_{i=1}^n W_i Y_i \quad (2)$$

In Eq. 2, W is the weighing factor of the parameter selected through the PCA. Since the parameters are not equal in their importance in soil quality, each PC explains a certain amount of variance (%) in the total dataset, which provides the weight for the parameters chosen in a PC (Masto et al. 2008; Sinha et al. 2009). The equation was finally normalized to get a maximum SQI of one.

Statistical analysis

Data is expressed as mean ± standard deviation (SD). Differences between mean values were examined by a one-way analysis of variance. Comparison among means was made using the Duncan multiple range test, calculated at $p < 0.05$. All statistical analyses were performed using the software program SPSS 15.0.

Results

Soil physicochemical properties

Table 2 shows the effects of the different vegetation types on SOC, TN, TP, AN, AP, AK, pH, bulk density, and moisture content. The highest SOC, TN, AN, and moisture content were found in the soil of *H. altaicus*, followed by *A. capillaries* and *P. virgatum*, whereas the lowest was in *C. korshinskii*. TP and AP were highest in the soil of *A. capillaries* and *H. altaicus*, followed by *P. virgatum*. AK ranged from 106.55 mg kg⁻¹ in *H. rhamnoides* to 73.86 mg kg⁻¹ in *A. adsurgens*. Bulk density was highest in *A. adsurgens* and lowest in *A. capillaries*. All pH values were above 8.50; the highest was in *P. virgatum* and *A. capillaries*, whereas the lowest was in *H. rhamnoides* and *H. altaicus*.

Soil microbial biomass and respiration

From Fig. 1, the highest MBC value was found in the soil of *H. altaicus* (72.9 mg kg⁻¹). *A. adsurgens*, *C. korshinskii*, and *A. capillaries* came second with 61.2 mg kg⁻¹, and *H. rhamnoides* had the lowest value of 43.9 mg kg⁻¹. MBN was highest in the soil of *A. adsurgens*, followed by *H. altaicus*, and *A. capillaries*, and lowest in *C. korshinskii*. BR was generally highest in *H. altaicus* (52.5 mg CO₂-C kg⁻¹ day⁻¹), followed by *A. capillaries*, *H. rhamnoides*, and *P. virgatum* (42.5 mg CO₂-C kg⁻¹ day⁻¹), and was lowest in *C. korshinskii* (36.3 mg CO₂-C kg⁻¹ day⁻¹). SIR, specifically glucose-amended respiration, behaved similar to BR. MBC/SOC and BR/MBC were within 1.6–3.6% and 24.7–43.4 mg CO₂-C kg⁻¹ day⁻¹, respectively (Fig. 2). *C. korshinskii* soil had the highest MBC/SOC and *H. rhamnoides* soil had the highest BR/MBC.

Soil enzymes

Changes in soil enzymes (saccharase, urease, catalase, peroxidase, alkaline phosphatase, polyphenol oxidase, and cellulase) are shown in Fig. 3. The overall metabolic activity indicated by saccharase was generally grouped into three plant types. The first group (*H. altaicus* and *A. capillaries*) had the highest value (> 2.0 mg glucose g⁻¹ h⁻¹). The second group (*H. rhamnoides*, *A. adsurgens*, and *P.*

Table 2 Physicochemical soil properties of different vegetation types. Results are given as mean ± SD

Plants Species	Organic C (g · kg ⁻¹)	Total N (g · kg ⁻¹)	Total P (g · kg ⁻¹)	Available P (mg · kg ⁻¹)	Available N (mg · kg ⁻¹)	Available K (mg · kg ⁻¹)	pH	Bulk Density (g · cm ⁻³)	Soil Moisture (%)
<i>C. korshinskii</i>	1.87±0.24 D	0.14±0.02 E	0.44±0.01 B	0.27±0.02 E	15.61±2.21 D	76.48±0.52 C	8.61±0.02 C	1.32±0.08AB	6.39±0.42D
<i>H. rhamnoides</i>	2.77±0.20 C	0.33±0.02 BC	0.47±0.01 B	1.95±0.13 C	25.48±3.15 C	106.55±2.40 A	8.56±0.07 CD	1.27±0.02B	7.32±0.72 C
<i>A. adsurgens</i>	2.64±0.11 C	0.27±0.04 D	0.46±0.01 B	0.42±0.04 D	23.28±1.91 C	73.86±1.13 CD	8.75±0.02 B	1.46±0.09A	7.63±0.59 C
<i>P. virgatum</i>	3.09±0.13 B	0.36±0.02 B	0.49±0.01 AB	3.25±0.10 AB	29.48±1.39 B	84.68±0.74 B	8.85±0.01 A	1.21±0.03BC	8.97±0.77B
<i>H. altaicus</i>	3.83±0.09 A	0.48±0.01 A	0.53±0.02 A	3.33±0.02 A	37.53±1.22 A	82.66±0.55 B	8.56±0.01 CD	1.21±0.06BC	11.27±0.75A
<i>A. capillaries</i>	3.16±0.06 B	0.38±0.02 B	0.52±0.02 A	3.34±0.05 A	32.17±1.55 B	78.36±2.05 C	8.87±0.02 A	1.14±0.03D	9.54±0.81B

Values with the same letter are not significantly different at the $p < 0.05$ level

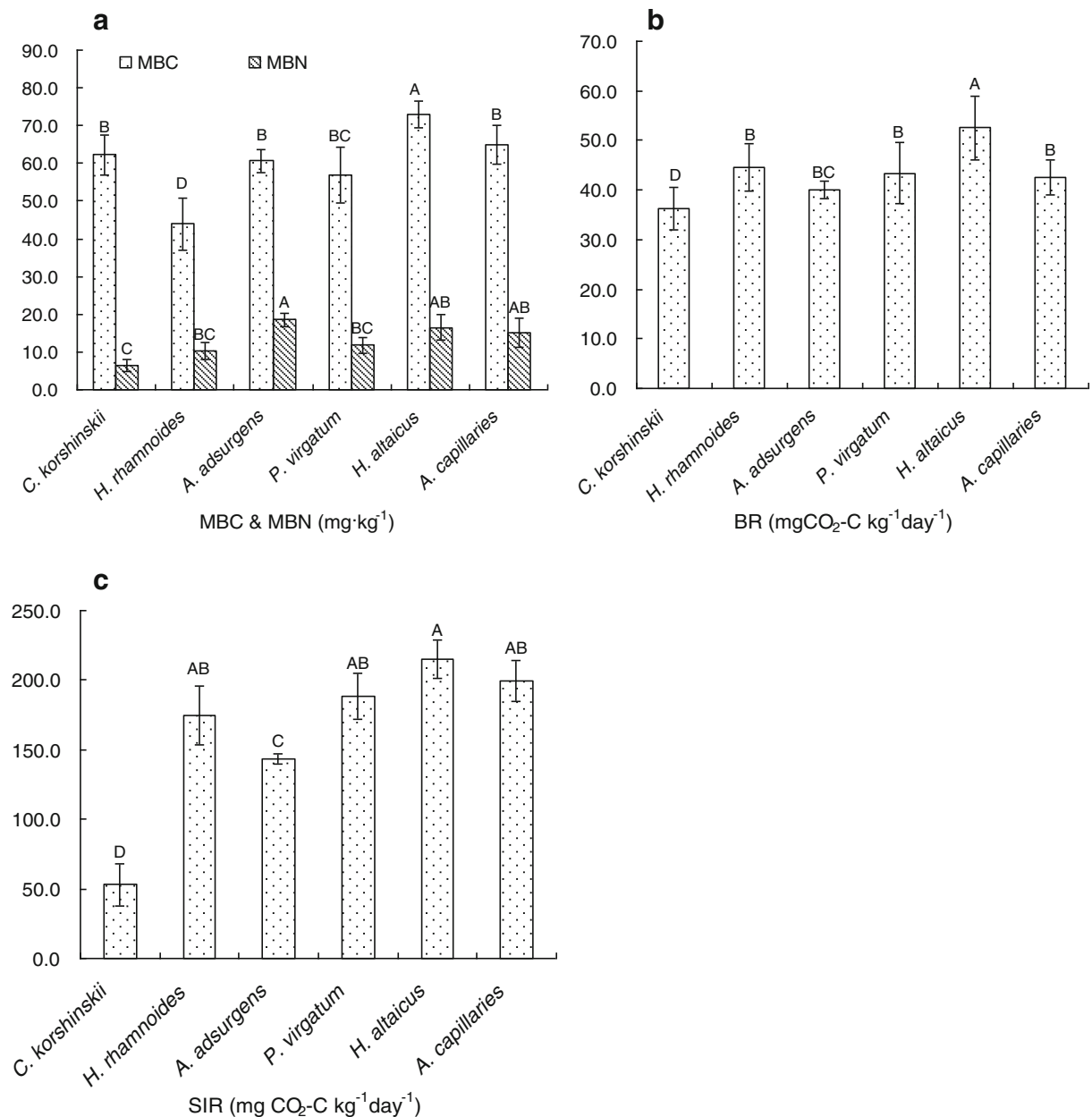


Fig. 1 Soil MBC and MBN (**a**), BR (**b**), and SIR (**c**) among revegetation types. Results are given as mean \pm SD. MBC is microbial biomass C; MBN is microbial biomass N; BR is

basal respiration; and SIR is substrate-induced respiration. Values with the same letter are not significantly different at the $p < 0.05$ level

virgatum) had intermediate values (1.0–2.0 mg glucose g⁻¹ h⁻¹). The third group (*C. korshinskii*) had the lowest value (0.7 mg glucose g⁻¹ h⁻¹). The highest urease activity was found in the soil of *H. altaicus*, followed by *A. capillaries*, and the lowest was in *C. korshinskii* and *H. rhamnoides*. Soil catalase and peroxidase were highest in *H. altaicus*

and *A. capillaries*. Alkaline phosphatase was highest in *H. altaicus* (4.0 mg phenol g⁻¹ h⁻¹) and lowest in *P. virgatum* (2.5 mg phenol g⁻¹ h⁻¹). Polyphenol oxidase was highest in *P. virgatum*, followed by *C. korshinskii* and *A. adsurgens*. No significant difference was observed on cellulase activity for the different soils.

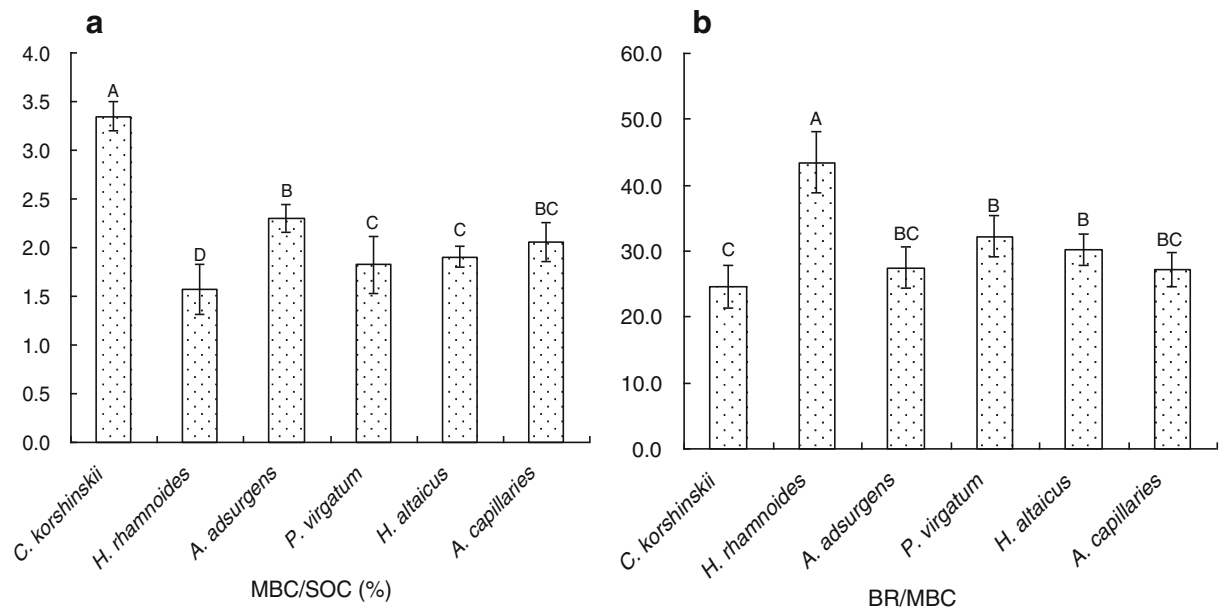


Fig. 2 Soil microbial quotient MBC/SOC (**a**) and metabolic quotient BR/MBC (**b**) among revegetation types. Results are given as mean \pm SD. MBC is microbial biomass C; BR is basal

respiration; and SOC is soil organic C. Values with the same letter are not significantly different at the $p < 0.05$ level

Soil quality index (SQI)

All studied soil parameters were chosen through the PCA for calculating the SQI, with the exception of cellulase because its content did not significantly differ among the vegetation types. As shown in Table 4, eigenvalues of the first four PCs were above 1, and the highly weighted parameters in PC-1 were SOC, TN, AN, SM, BR/MBC, and saccharase. AN had the highest loading and highly correlated with SOC, TN, SM, and saccharase ($r > 0.85$; Table 3); thus, SOC, TN, and saccharase were eliminated from the SQI. No significant correlation was found between AN and BR/MBC ($r = 0.02$); therefore, both AN and BR/MBC were selected for the SQI determination. In PC-2, the highly loaded parameters included MBC and urease, and they were retained for indexing because both of them did not correlate significantly ($r = 0.45$). Likewise, polyphenol oxidase and BD were chosen for calculating the SQI due to their higher loading in PC-3 and PC-4. In summary, the most critical parameters as determined from the PCA for the SQI determination were AN, BR/MBC, MBC, urease, polyphenol oxidase, and BD (Table 4). The

final polynomial for the SQI was calculated using Eq. 2, as follows:

$$\begin{aligned} \text{SQI} = & 0.31Y_{\text{AvailableN}} + 0.31Y_{\text{BR/MBC}} + 0.13Y_{\text{MBC}} \\ & + 0.13Y_{\text{Urease}} + 0.08Y_{\text{Polyphenoloxidase}} \\ & + 0.05Y_{\text{Bulk density}} \end{aligned}$$

where Y are the scores of the critical parameters and were determined based on Eq. 1. Table 5 shows the mean value of these parameters and their curve type. As shown in Fig. 4, the SQI differed significantly among the different plants. *H. altaicus* (0.63) and *A. capillaries* (0.61) had the highest values, followed by *P. virgatum* (0.50) and *A. adsurgens* (0.47), and the lowest was found in the soil of *H. rhamnoides* (0.36).

Discussion

Soil physicochemical properties

Vegetative cover has fundamental effects on soil properties (Rutigliano et al. 2004), mainly due to its

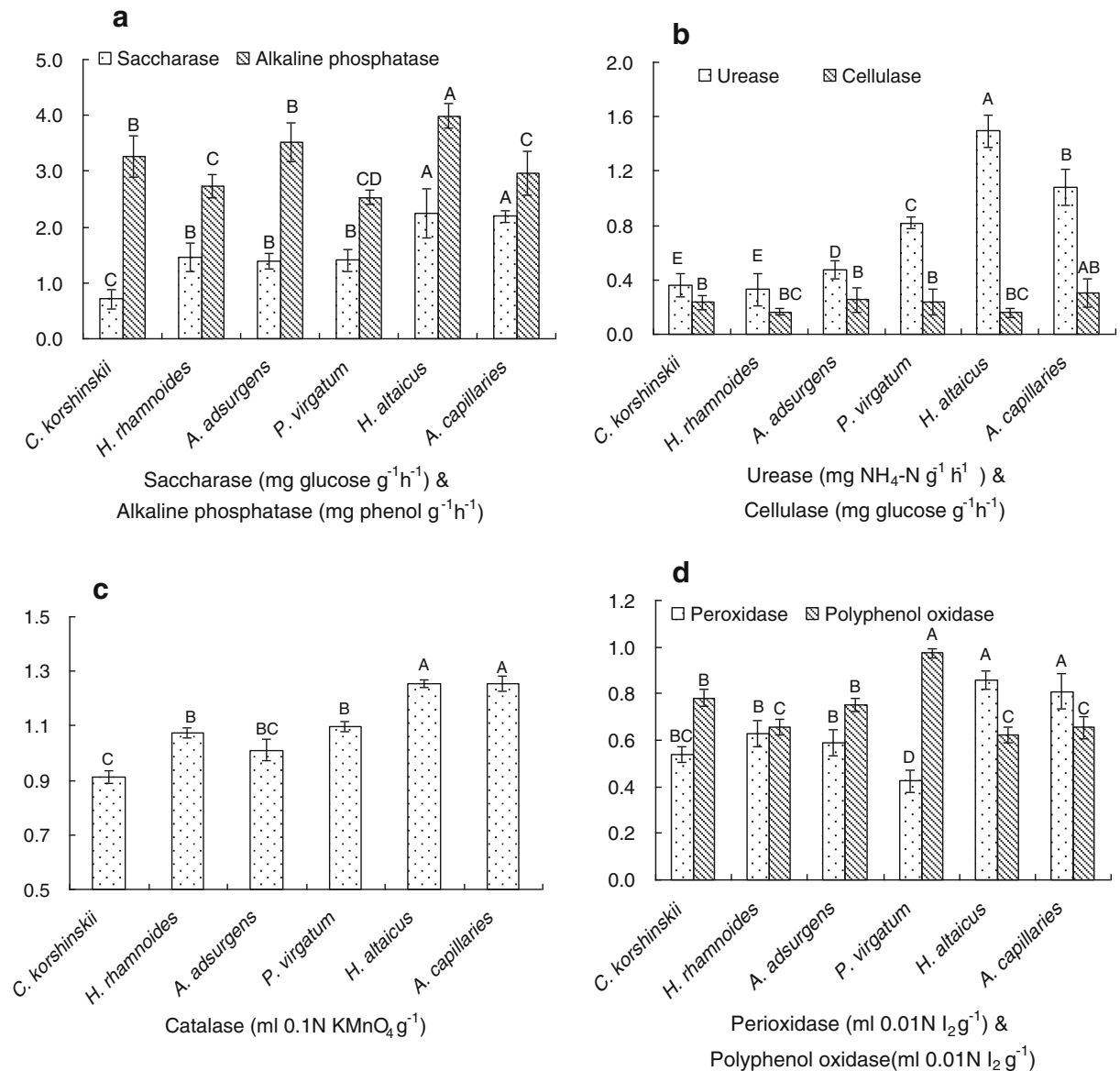


Fig. 3 Soil enzymes (**a**, **b**, **c**, **d**) among revegetation types. Results are given as mean \pm SD. Values with the same letter are not significantly different at the $p < 0.05$ level

contribution of organic matter to the soil. In the present study, all the physicochemical soil properties differed significantly among the vegetation types. This is probably related to changes in the amounts and forms of organic materials added to the soils of the different vegetation types (Condon and Newman 1998). *H. altaicus* and *A. capillaries* showed the highest SOC, TN, AN, TP, AP, and moisture content, suggesting that naturally grown vegetation could more significantly improve the soil C, N, P compo-

nents and the water content. This is in accordance with the report of Li et al. (2010), who found that the contents of SOC and TN in natural grasslands was 3.0 times higher than that in artificial grasslands, and 3.3 times higher than artificial shrublands in the Loess Plateau. Albaladejo et al. (1994) reported that the increase in SOC and nitrogen could be accompanied by improvement in the soil structure and diminution of bulk density, consistent with our results. These effects could be attributed to the extensive fine root

Table 3 Correlation matrix among the different properties determined. Sample size=18

Parameters ^a	SOC	TN	TP	AP	AN	AK	pH	BD	SM	MBC	MBN	BR	SIR	MBC/SOC	BR/MBC	SAC	URE	ALP	CEL	CAT	POX	PPO
SOC	1																					
TN	0.96**	1.00																				
TP	0.77**	0.79**	1.00																			
AP	0.83**	0.86**	0.90**	1.00																		
AN	0.92**	0.87**	0.77**	0.79**	1.00																	
AK	0.08	0.21	0.39	0.20	0.03	1.00																
PH	-0.24	-0.17	-0.17	0.07	-0.21	-0.39	1.00															
BD	-0.18	-0.19	-0.52	-0.40	-0.27	-0.26	0.05	1.00														
SM	0.92**	0.85**	0.74**	0.77**	0.89**	0.32	-0.41	-0.22	1.00													
MBC	0.37	0.19	0.12	0.17	0.42	-0.62**	-0.14	-0.01	0.25	1.00												
MBN	0.64**	0.53*	0.15	0.26	0.63**	-0.33	-0.11	0.10	0.68**	0.46	1.00											
BR	0.62**	0.58*	0.50*	0.48*	0.56*	0.22	-0.47	-0.09	0.58*	0.38	0.39	1.00										
SIR	0.90**	0.93**	0.75**	0.84**	0.85**	0.25	-0.01	-0.19	0.84**	0.10	0.59**	0.55*	1.00									
MBC/SOC	-0.68**	-0.78*	-0.62**	-0.65**	-0.57*	-0.56*	0.09	0.15	-0.58*	0.41	-0.35	-0.28	-0.83**	1.00								
BR/MBC	0.10	0.28	0.29	0.20	0.02	0.84**	-0.20	-0.08	0.34	-0.74**	-0.21	0.32	0.35	-0.65**	1.00							
SAC	0.84**	0.82**	0.74**	0.74**	0.93**	-0.01	-0.07	-0.37	0.89**	0.32	0.62**	0.38	0.81**	-0.58	0.00	1.00						
URE	0.83**	0.79**	0.67**	0.75**	0.83**	-0.29	-0.07	-0.16	0.86**	0.45	0.47*	0.54*	0.66**	-0.34	-0.13	0.77**	1.00					
ALP	0.22	0.13	-0.11	-0.17	0.22	-0.45	-0.44	0.02	0.24	0.44	0.38	0.22	-0.09	0.23	-0.34	0.21	0.42	1.00				
CEL	-0.12	-0.13	-0.07	0.07	0.07	-0.34	0.42	0.02	-0.14	-0.10	0.02	-0.42	-0.08	0.05	-0.30	0.19	0.07	-0.11	1.00			
CAT	0.74**	0.78**	0.77**	0.78**	0.86**	0.29	-0.07	-0.20	0.75**	0.04	0.39	0.52*	0.86**	-0.68**	0.37	0.81**	0.63**	-0.12	0.14	1.00		
POX	0.55*	0.51*	0.47*	0.39	0.74**	-0.09	-0.42	-0.25	0.66**	0.35	0.44	0.39	0.43	-0.23	-0.05	0.73**	0.67**	0.55*	0.24	0.61**	1.00	
PPO	-0.25	-0.25	-0.27	-0.06	-0.47*	-0.16	0.52*	0.25	-0.31	-0.09	-0.25	-0.27	-0.22	0.16	-0.17	-0.50*	-0.29	-0.48*	-0.01	-0.44	0.86**	1.00

SOC Soil organic C; TN Total N; TP Total P; AP Available P; AN Available N; AK Available K; BD Bulk density; SM Soil moisture; MBC Microbial biomass C; MBN Microbial biomass N; BR Basal respiration; SIR Substrate-induced respiration; SAC Saccharase; URE Urease; ALP Alkaline phosphatase; CEL Cellulase; CAT Catalase; POX Peroxidase; PPO Polyphenol oxidase

^a. *Correlation is significant at the $p < 0.05$ level (2-tailed); **Correlation is significant at the $p < 0.01$ level (2-tailed)

Table 4 Principal component analysis of soil properties of different vegetation types

Principal component	1	2	3	4
Eigenvalue	9.169	3.787	2.182	1.351
Variance (%)	48.224	19.897	11.520	7.091
Cumulative (%)	48.224	68.121	79.641	86.732
Eigenvectors ^a				
Soil organic C (SOC)	0.923	0.075	0.118	0.144
Total N (TN)	0.910	-0.103	0.109	0.135
Total P (TP)	0.825	-0.258	0.051	-0.382
Available P (AP)	0.844	-0.208	0.326	-0.261
Available N (AN)	0.947	0.255	0.031	-0.009
Available K (AK)	0.154	-0.683	-0.412	-0.033
pH	-0.227	-0.070	0.758	-0.121
Bulk density (BD)	0.301	0.132	0.130	-0.796
Soil moisture (SM)	0.912	0.120	0.303	-0.119
Microbial biomass C (MBC)	0.255	0.817	0.139	-0.160
Microbial biomass N (MBN)	0.548	0.429	0.102	0.477
Basal respiration (BR)	0.816	-0.203	0.207	0.159
Substrate-induced respiration	-0.714	0.544	-0.049	-0.312
BR/MBC	-0.867	0.201	-0.322	0.211
MBC/SOC	0.346	0.599	-0.434	0.247
Saccharase	0.901	0.155	0.040	-0.075
Urease	0.338	0.811	0.149	-0.070
Alkaline phosphatase	0.131	0.689	-0.460	0.119
Catalase	0.839	-0.227	0.017	0.020
Peroxidase	0.665	0.365	-0.443	-0.090
Polyphenol oxidase	-0.473	-0.205	0.780	0.048

^a Bold-faced and underlined parameters are considered as critical ones and were included in the SQI calculation.

$$SQI = 0.48_{\text{Available N}} + 0.48_{\text{BR/MBC}} + 0.20_{\text{MBC}} + 0.20_{\text{Urease}} + 0.12_{\text{Polyphenol oxidase}} + 0.07_{\text{Bulk density}}$$

$$\text{Normalized SQI} = SQI/1.55 = 0.31_{\text{Available N}} + 0.31_{\text{BR/MBC}} + 0.13_{\text{MBC}} + 0.13_{\text{Urease}} + 0.08_{\text{Polyphenol oxidase}} + 0.05_{\text{Bulk density}}$$

systems in grasslands that also enhance the soil porosity (Wei et al. 2009). The various acid exudates released from roots could be responsible for the small differences in the pH values (Garcia et al. 2005).

Soil microbial biomass and respiration

Microbial biomass has been considered as an indicator of changes in organic matter content (Powlson and Jenkinson 1981). In the present study, MBC and

Table 5 Average values, normalization equations, and R^2 coefficients of the scoring curves

Parameter	Available N	MBC	Metabolic Quotient (BR/MBC)	Urease	Polyphenol Oxidase	Bulk Density
Average (\bar{x}_0)	26.90	60.22	30.88	0.76	0.74	1.27
Curve Type*	+	+	-	+	+	-
Normalization Equation	$Y = 1 / \left(1 + (x/26.90)^{-2.5} \right)$	$Y = 1 / \left(1 + (x/60.22)^{-2.5} \right)$	$Y = 1 / \left(1 + (x/30.88)^{2.5} \right)$	$Y = 1 / \left(1 + (x/0.76)^{-2.5} \right)$	$Y = 1 / \left(1 + (x/0.74)^{-2.5} \right)$	$Y = 1 / \left(1 + (x/1.27)^{2.5} \right)$
R^2	0.988	0.979	0.992	0.991	0.994	0.988

*(+) means "more is better", (-) means "less is better"

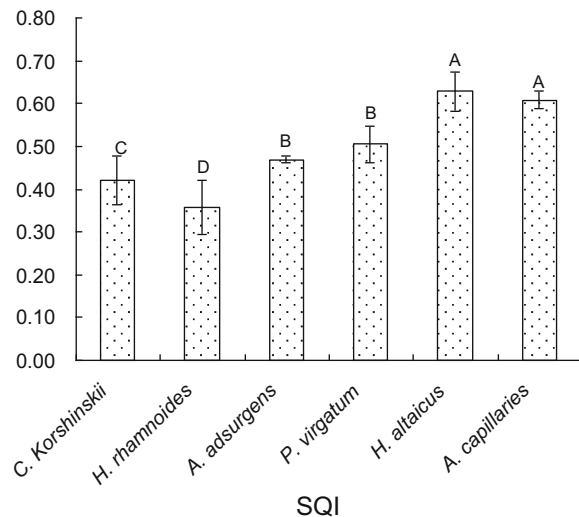


Fig. 4 Soil quality index (SQI) among vegetation types. Results are given as mean \pm SD. Values with the same letter are not significantly different at the $p < 0.05$ level

MBN differed significantly among all six soils, indicating that microbial biomass seems to be strongly influenced by the nature of the plants, in agreement with the results of Garcia et al. (2005) and Sinha et al. (2009). Differences in MBC in the studied soils were higher than the differences in SOC, confirming that MBC is a more sensitive index of changes of the SOC (Powlson et al. 1987). A positive correlation between SOC and MBC is usually found (Jia et al. 2005; Arunachalam and Pandey 2003), but this correlation was not observed in the present study. Garcia et al. (2005) reported that a positive correlation between SOC and MBC is usually found in soils where C is a limiting factor and the soils have reached equilibrium. In our case, either C availability was not a limiting factor or the soils had not yet reached equilibrium.

MBC reflects the size of microbial populations and includes both metabolically active and resting-state microorganisms, whereas parameters such as BR and SIR reflect the actual and potential microbial activities in the soil. Bastida et al. (2006) reported that there is a highly positive correlation coefficient between SOC and BR, i.e., the soils with greater SOC content also showed greater BR. Indeed, in the present study, the correlation coefficient between SOC and BR was high, as well as the coefficient between SOC and SIR. This suggests that a large part of the SOC is dedicated to sustaining microbial respiration. The zones with the

highest SOC values (*H. altaicus*) are also the zones with the highest respiration. Microbial quotient MBC/SOC, which can be interpreted as the available substrate and the portion of total soil carbon immobilized in microbial cells, is a sensitive parameter for monitoring organic carbon or microbial biomass (Garcia et al. 2002). In the present study, *C. korshinskii* presented the highest microbial quotient. Similarly, Zhang et al. (2010) found that microbial quotient in the soil of *C. korshinskii* was significantly higher compared with that in natural grassland, although the soil microbial biomass was slightly lower than in natural grassland. Jia et al. (2005) reported that microbial quotient had a positive correlation with MBC and SOC; however, in the present study, microbial quotient was negatively correlated with SOC and not at all correlated with MBC, in agreement with the results of Schipper et al. (2001). This can be explained by the fact that changes in the microbial quotient depend not only on the soil microbial biomass, but also on the SOC. This can be clearly seen from Table 2 and Fig. 1, where *H. altaicus* soil has the highest SOC and MBC, whereas *C. korshinskii* soil has the lowest SOC but has a high MBC. Consequently, microbial quotient in *C. korshinskii* soil was higher than in *H. altaicus* soil. This implies that microbial quotient is affected not only by the quantity, but also by the quality of the carbon input (Singh et al. 1991). The metabolic quotient BR/MBC has been used as an ecophysiological index to reflect the bioenergetic status of microbial community in reclamation studies (Insam and Domsch 1988). Tirol-Padre et al. (2007) found that metabolic quotient in a disturbed soil ecosystem was higher than that in a stable one. This is because the stress is severe and soil microbial activity is low in disturbed soil, and an increased energy is needed by soil microorganisms to repair the damages caused by the stress (Odum 1985). This implies that the higher metabolic quotient of *H. rhamnoides* soil is indicative of its poor quality.

Soil enzymes

Enzyme activity plays an important role in soil nutrient cycling and in the degradation of organic inputs, and can thus be useful for indicating the degree of change in soil fertility and microbial activity (Badiane et al. 2001; Bandick and Dick 1999). Research has shown that soil enzyme activity is

closely related with the SOC because the transformations of important organic elements are facilitated by microorganisms (An et al. 2008; Jiang et al. 2009). Our results agree with this view based on the observations that saccharase, urease, catalase, and peroxidase significantly correlated with the SOC ($p < 0.01$ or $p < 0.05$; Table 3). This suggests that a large part of the SOC could contain substrates that stimulate the synthesis of these enzymes. The high amount of these enzymes in *H. altaicus* and *A. capillaries* soils could be due to the sufficient amount of C input by their root exudates. *H. altaicus* soil had the highest alkaline phosphatase content, probably caused by the greater adsorption of inorganic P or depletion of AP. Polyphenol oxidase, an important enzyme closely related to soil humus decomposition, did not significantly correlate with SOC. This may be related to the different components of the litter and the pathway of humus decomposition in the soils of the different species.

Many researchers have reported a significant correlation between soil enzyme activity and MBC (Sinha et al. 2009; Jiang et al. 2009; Taylor et al. 2002), but this correlation was not observed in the present study. This is probably due to soil enzymes that have significant abiotic activity (Nannipieri et al. 1990).

Soil quality index (SQI)

Many studies have analyzed soil quality using different parameters, ranging from a purely agricultural point of view to a more environmental perspective. However, the large number of studied sites and the high variability of the studied physical, chemical, and biological indicators make it difficult to clearly interpret results. The synthetic approach derived from the use of an SQI, as well as multivariate analyses (PCA), allowed us to point out a clear separation of the sites into three classes of different soil qualities. We finally chose six soil parameters for the SQI calculation, which we considered the most important indicators of soil quality: AN, BR/MBC, MBC, urease, polyphenol oxidase, and bulk density. Almost all of these indicators were also suggested by Bastida et al. (2006), Armas et al. (2007), Erkossa et al. (2007), and Sinha et al. (2009). The species from croplands abandoned for natural recovery (*H. altaicus* and *A. capillaries*) had the highest SQI, followed by those from grasslands (*A. adsurgens* and *P. virgatum*),

and then by shrublands (*C. korshinskii* and *H. rhamnoides*).

The process of reconverting slope croplands into forestlands and grasslands has been implemented to avoid the soil degradation problem of the past two decades in the Loess Plateau. Shrubs grown on slope croplands such as *C. korshinskii* and *H. rhamnoides*, as well as grasses such as *A. Adsurgens* and *P. virgatum*, are predominately revegetation measures. Many studies have demonstrated that this reversion can significantly improve the physical, chemical, and biological soil properties (An et al. 2008; Zhu et al. 2010). The improvement in shrubland and grassland soil qualities can be attributed to the increased plant cover and reduced decomposition rate as a consequence of tillage, which increases input of organic matter and physical protection of soil from erosion (Moscatelli et al. 2007). In the present study, the grassland species generally showed higher SQI than shrubland species, suggesting a better soil recovery capacity in grasslands than shrubland. This higher grassland soil quality is probably due to the larger herbaceous coverage (Table 1), because plant coverage plays an important role in both soil protection from erosion and contribution to soil organic matter content (Marzaioli et al. 2010). Indeed, high soil quality often occurred in the soils where the herbaceous coverage was high. Similar to our results, Caravaca et al. (2003) found that perennial grass species improved soil quality in an abandoned agroecosystem in Spain by increasing organic matter and nitrogen content, as well as by favoring the formation of stable aggregates and the development of mycorrhizal propagules. Furthermore, extensive fine root systems in grasslands can be another contributing factor to the high grassland soil quality, because abundant exudates released from roots and widely distributed in the soil improve chemical and physical soil properties (Wei et al. 2009; Zhang et al. 2010).

In the Loess Plateau, natural vegetation from abandoned croplands can both protect the soil from erosion and improve soil properties, such as organic matter content, soil structure, and infiltration rate. In the present study, abandoned cropland for natural recovery had the best soil quality on the basis of the considered parameters, indicating that it has the best capacity for soil recovery. This agrees with Li et al. (2010) who observed that soil carbon and nitrogen

components was higher in natural grasslands compared with artificial shrublands and grasslands (human-planted) in the Loess Plateau. Aside from the presence of a dense herbaceous layer due to recolonization by spontaneous plants (Rutigliano et al. 2006), the excellent soil quality of abandoned croplands could be related to the nature of the plants therein. Compared with artificial vegetation, where the species are selected by humans, natural vegetation occurs through spontaneous natural succession without any anthropogenic influence whatsoever (Zhang et al. 2011). Natural vegetation depends on the natural factors of the broader ecosystem development context of plant associations, soil, animals, and particularly soil organisms (Whisenant 1995). This results in a stronger adaptability of natural vegetation to natural environment conditions. Natural vegetation can allow more species to colonize due to the creation of high habitat diversity, which are difficult or impossible to achieve through planting (Florgard 2004).

Conclusions

Different vegetation types significantly affected in different magnitudes the physical, chemical, and microbial properties of arid climatic soils. Compared with the soils of shrubs (*C. korshinskii* and *H. rhamnoides*) and grasses (*A. adsurgens* and *P. virgatum*), the soil of natural species from abandoned cropland species (*H. altaicus* and *A. capillaries*) had the highest SOC, TN, TP, AN, AP, MBC, SIR, saccharase, urease, catalase, and peroxidase. The SQI, which was calculated by integrating all critical parameters, indicated that in the Loess Plateau, abandoned croplands for natural recovery have the best capacity for soil restoration. Thus, the present study suggests that in the Loess Plateau, natural recovery is the best choice for soil revegetation of sloping croplands. However, our suggestion was based on the natural recovery that normally takes place, if there are dangerous invasive weeds capitalizing on the bare ground, more research should be conducted.

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