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Full Length Research Paper

Effects of 22 years of re-vegetation on soil quality in the semi-arid area of the Loess Plateau

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Re-vegetation is an important practice for eco-environmental rebuilding of degraded environments. Accordingly, re-vegetation has been widely used to reduce erosion and protect soils against degradation in the Loess Plateau. However, little research has been conducted to study the effects of long-term re-vegetation on soil properties, which is essential to reveal corresponding changes in soil quality. Therefore, this study was conducted to evaluate the influence of 22 years of re-vegetation on soil quality in a semi-arid area. Soil samples were collected from a bare slope, a re-vegetated northern slope and a re-vegetated southern slope. The soil properties were then determined and the soil quality indices were calculated. The results showed that long-term re-vegetation significantly improved soil properties in the Loess Plateau, but that the effects of re-vegetation varied with slope aspect, slope position and soil depth. The greatest improvement in soil properties was observed in topsoil, on northern slopes and in lower positions of the slopes. Significant correlations were observed among soil chemical properties (including organic matter and total N contents) and soil enzymatic activities. Total nitrogen and organic matter content, activities of urease, invertase and alkaline-phosphatase could all be combined into one factor to indicate soil quality and characterize the distribution of soil properties along slopes. The resulting soil quality index (SQI) can effectively reflect the changes in soil quality in response to 22 years of re-vegetation in the Loess Plateau.

Key words: Re-vegetation, soil properties, soil quality index, the Loess Plateau.

INTRODUCTION

Soil quality is defined as the capacity of a soil to sustain biological production within ecosystem boundaries, to maintain environmental quality and to promote plant and animal health (Doran and Parkin, 1994). Conventionally, the evaluation of soil quality or the calculation of SQI (soil quality index) has been described on the basis of soil fertility conditions. Therefore, soil nutrients are the main components of soil quality. Accordingly, many studies have been conducted to evaluate the relationship between soil quality and the SQI (Carter et al., 1997; Karlen et al., 1997; Rezaei et al., 2006) and a formula for the expression of SQI based on soil physicochemical and nutritional properties has been formulated.

It has been proposed that the microbiological and biochemical status of a soil can be used as an early and sensitive indicator of soil ecological stress or restoration processes in both natural and agro-ecosystems (Doran, 1980; Bolton et al., 1985; Dick and Tabatabai, 1993; Dick, 1994; Ruf et al., 2003; Wu et al., 2004). Among these microbiological and biochemical factors, soil enzymes have been suggested as potential indicators of soil quality due to their biological nature, simple measurement and rapid response to changes in soil management when compared to other biological properties (Dick, 1994; Dick et al., 1996). Numerous studies have been conducted to evaluate the potential use of enzymatic activity as an index of soil productivity or soil fertility (Weaver et al., 1994; Alef and Nannipieri, 1995; Dick et al., 1996). Li et al. (2006) found that urease activity was closely related to soil nutrient conditions and recommended that urease be

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considered when calculating the SQI. Frankenberger and Dick (1983) observed that the activities of alkaline phosphatase and catalase were correlated with biological factors in soils. Kandeler et al. (1999) found a close relationship between enzymatic activities and particle-size fractions, with xylanase and invertase being associated with the coarse sand and the silt fraction, respectively. However, few studies have been conducted to evaluate soil quality using a combination of physico-chemical and enzymatic properties.

Re-vegetation is the most widely accepted and useful practice for reduction of erosion and protection against soil degradation. Many countries have adopted re-vegetation as an important measure to restore and reconstruct natural ecosystems. Re-vegetation not only can increase the land cover and improve plant diversity, but can also strengthen the soil capacity by conserving water and increasing the soil fertility level. Various studies have demonstrated that re-vegetation has a great effect on soil nutrients and enzymatic activities (Hu et al., 2002; Izquierdo et al., 2005; Peng et al., 2005; Du et al., 2007). Furthermore, the effects of re-vegetation on soil nutrient and biological properties are reflected in deeper soil layers as the re-vegetation time increases. As reported by Wang et al. (2001), after more than 20 years of restoration with artificial vegetation coupled with the cessation of grazing in the Zhifanggou Watershed, the plant communities had obvious effects on soil nutrient accumulation. Furthermore, they found that the soil nutrient content was higher in the 0 - 20 cm than in 20 - 40 cm layer. Zhang and Chen (1997) pointed out that the contents of soil organic matter, total nitrogen, available N and P, sucrase, urease and neutral phosphatase in an abandoned pasture of a loessial hilly region all decreased as the soil depth increased, but that all of these values increased with time.

Arid and semi-arid areas currently cover more than one-third of the Earth's total land surface (Reynolds, 2001) and such areas may increase in response to climate change (Schlesinger et al., 1990). China has one of the largest arid and semi-arid areas in the world. Indeed, the arid area comprises 30% of the total territory of China. One-fifth of this area is occupied by semi-arid are as, which are primarily located around the Loess Plateau (62.4×10^4 km^2). The Loess Plateau is located in the north and the middle portion of China, which has a typical continental climate. The annual precipitation in the region is 400 mm, most of which occurs in summer. The special natural conditions, which include concentrated precipitation, dry climate, intensive evaporation, short frost-free period and frequent natural disasters, have led to poor growing environments for vegetation. In addition, improper land use and soil management have caused severe soil and water erosion on the Loess Plateau. As a result, approximately 16×10^8 t of mud and sand are lost from the Loess Plateau into the Yellow River annually (Su, 1996). In 1999, a program designed to transform farmland into forests or grasslands known as the grain for green program was launched. Afforestation is already known as a crucial way to utilize and rehabilitate mountain areas, highlands, abandoned and degraded cultivated lands and arid and semi-arid areas in which trees are planted to prevent further deterioration of the environment.

Recently, many studies have been conducted to evaluate changes in soil nutrition and quality in degraded and re-vegetated ecosystems subjected to different climate conditions. However, few studies have been conducted to evaluate changes in soil quality with soil enzymes, especially in restored ecosystems in arid areas. Therefore, this study was conducted to evaluate the effects of re-vegetation on soil quality in arid areas. In addition, we attempted to develop a method of evaluating soil quality by combining data regarding soil nutrient contents and enzymatic activities, which may be especially useful for the comprehensive assessment of soil quality in restored ecosystems.

MATERIALS AND METHODS

Research sites

This study was conducted in the Yunwushan natural grassland protection zone (106°24′ ~ 106°28′E; 36°13′ ~ 36°19′N) in Guyuan City, Ningxia Hui Autonomous Region, which is located in the middle part of the Loess Plateau. The grassland protection zone was initiated in 1984 and consists of 4000 km^2 with an elevation that ranges from 1800 to 2148 m. The weather in the study area is characterized by a continental monsoon climate. The mean temperature is 6.9℃ and the highest and lowest temperatures are observed in July (24℃) and January (-14℃), respectively. The frost-free period is 124 d, which normally begins in mid-April and ends in late September. The annual mean precipitation is 425 mm. The soil in the study area is a mountain grey-cinnamon soil according to the Chinese classification system, which corresponds to Mollisols according to American Soil Taxonomy.

Experimental design and soil sampling

To test the effects of re-vegetation on soil quality, a bare slope, a re-vegetated northern slope and a re-vegetated southern slope were selected for study in April 2005. There is very little vegetation on the bare land slope, which has suffered serious soil erosion and nutrient loss. The re-vegetated northern and southern slopes have been covered by long silk grass (*Bungeana Trin L.*)-thyme (*Thymus mongolicus Ronn L.*) + asteriated cinquefoil (*Potentilla acaulis L.*) and long silk grass (*Bungeana Trin L.*) + sea starwort (*Sacrorum Ledeb.var.incana Mattf L.*)-wormwood sage (*Frigida Willd L.*) + asteriated cinquefoil (*Potentilla acaulis L.*), respectively, for 22 years. The average coverage of vegetation for the northern and southern slopes were 82 and 52%, respectively. The lengths of the 3 slopes were 150, 140 and 150 m, respectively.

For each slope, three profile sampling sections were set along the upper, middle and lower positions. At each sampling section, three soil pits were dug to collect a composite sample. Each soil pit was 100 cm wide, 200 cm long, and 105 cm deep. After the soil profile was described, 1 kg soil samples were collected at intervals of 15 cm from the bottom to the topsoil to avoid sample contamination. In addition, 3, 6 and 7 surface soil sampling sections were selected along the bare land slope, southern slope and northern slope at intervals of 50, 25 and 20 m, respectively. In each sampling section, five 0-15 cm soil samples were collected to make a composite sample. The soil moisture was measured in the field using the drying method. All fresh soil samples were placed in plastic bags and sealed, after which they were transported to the laboratory where plant litter, coarse root materials and stones were removed by hand. The moist field soil was air-dried and ground to pass through 1.00 and 0.25 mm nylon screens for laboratory analysis.

Laboratory analysis

Soil organic C was determined using the Walkley–Black method (Nelson and Sommers, 1982). Total N was measured using the Kjeldahl method (Bremner and Mulvaney, 1982). Total P was determined colorimetrically after wet digestion with sulfuric acid and perchloric acid (Olsen and Sommers, 1982). To improve the precision of determination, each sample was measured 3 times and the average value was calculated.

The urease, alkaline phosphatase and invertase activities were measured using the procedure described by Zhou and Zhang (1980). Catalase activity was measured using the 0.1 mol L^{-1} potassium permanganate titration method (Johnson and Temple, 1964). Soil urease activity was determined using 10% urea as a substrate. After sterilization with 1 ml of toluene, 20 ml of citrate buffer (pH 6.7) and 10 ml of substrate were added to 5 g of soil and the samples were then incubated at 37℃ for 2 h. Urease activity was determined as the NH_4^+ released during the hydrolysis reaction and expressed as NH_3-N μg (g h) $^{-1}$. Invertase activity was determined using 8% sucrose as a substrate. Briefly, 5 ml of phosphoric acid buffer (pH 5.5) and 15 ml of substrate were added to 5 g of soil and then incubated at 37℃ for 2 h. Next, 3 ml of 3,5-dinitrosalicylic acid were added to 1 ml of the soil filtrate and the mixture was then heated for 5 min in a water bath at 95℃. The amount of 3-amino-5-nitrosalicylic acid formed was determined based on the absorbance at 508 nm using a spectrophotometer and the activity was expressed as glu. μg (g h) $^{-1}$. Alkaline-phosphatase was determined using 0.5% disodium phenyl phosphate as a substrate. After sterilization with 0.25 ml toluene, a 20 ml mixture of disodium phenyl phosphate and borate buffer (pH 9.4) was added to 5 g of soil and the sample was then incubated at 37℃ for 2 h. Next, 0.25 ml of ammonia water buffer (pH 9.8), 0.5 ml of 2% 4-amino-antipyrine and 0.5 ml of 8% $K_3Fe(CN)_6$ were added to the soil filtrate. The amount of phenol formed was determined based on the absorbance at 510 nm using a spectrophotometer and the activity was expressed as ph (OH). μg (g h) $^{-1}$. The catalase activity was measured by potassium permanganate titrimetry. Briefly, a mixture of 40 ml of distilled water and 5 ml of 0.3% H_2O_2 was put in an oscillator for 20 min, after which 5 ml of 3 mol L^{-1} H_2SO_4 were added to the soil filtrate. Finally, the filtrate was titrated with 0.1 mol·L^{-1} potassium permanganate. The catalase activity was then expressed as $KMnO_4$ ml (g h) $^{-1}$.

Statistical analysis

Correlation analysis and principal component analysis were conducted using the SAS software (SAS Inst, 1989). Principal component analysis is a coordinate transformation typically associated with multiband imagery. Principal component analysis reduces the redundancy contained within a dataset by creating a new series of components in which the axes of the new coordinate systems point in the direction of decreasing variance. The resulting components are often more interpretable than the original images. In this study, principal component analysis was conducted to simplify the interpretation of the entire dataset.

RESULTS AND DISCUSSION

Soil moisture

The soil moisture distribution in 0-105 cm soils varied greatly with slope directions and positions (Figure 1). Soil moisture in the upper, middle and lower slope positions decreased in the order of northern slope > southern slope > bare land slope. The profile distribution in which soil moisture increased with soil depth was similar at different positions on the bare land slope. However, the profile distribution of moisture in the northern slope soil was opposite to that of the southern slope and decreased with soil depth, except at the upper slope position, in which the greatest moisture content was observed in the 30 - 50 cm soil layer. The distribution pattern of soil moisture in the southern slope was increased slightly and then decreased as the soil depth increased (Figure 1).

The profile distribution of soil moisture is influenced by factors such as the absorption of soil water by plants, reservation of rainfall by vegetation, soil evaporation and plant transpiration and the position on the slope and surface relief (Francis et al., 1986; Famiglietti et al., 1998; Qiu et al., 2001). In bare land, soil moisture is subject to loss by evaporation due to the absence of cover. In addition, part of the precipitation that occurs in bare land is lost as slope runoff. Conversely, precipitation that infiltrates into deeper soil layers will not be lost to evaporation or plant absorption. Therefore, the moisture content increased with soil depth in bare land slope. Although both southern and northern slopes were covered by vegetation, the moisture level was higher in the northern slope soil, presumably because there was stronger soil evaporation and plant transpiration in the southern slope soil. The growth of plants on the northern slope, which conserves more precipitation, was better than on southern slope. Additionally, moisture in the northern slope soil was higher at 0-60 cm than at 60-100 cm because there are more soil pores, which allows the infiltrated precipitation to accumulate more in the 0-60 cm layer than the 60-100 cm layer soils. However, extensive soil evaporation in the upper position of the northern slope results in its moisture content being lower at 0-30 cm than in the corresponding soil layer in the middle and lower positions. These results further suggest that revegetation exerts positive effects on water conservation in slope soils.

Soil nutrients

Soil nutrient distribution along slopes

The distribution of nutrients in surface layer soils on different slopes is shown in Figure 2. Soil organic matter and total nitrogen were distributed similarly along slopes and generally decreased from the upper to lower slope posi-

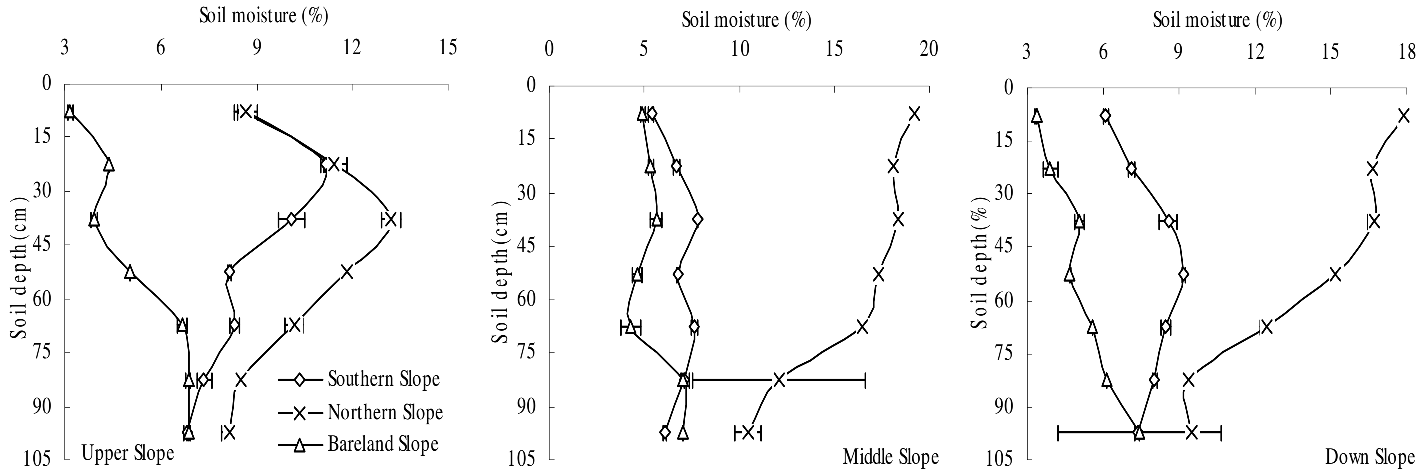

Figure 1. Profile distribution of soil moisture at different slope positions.

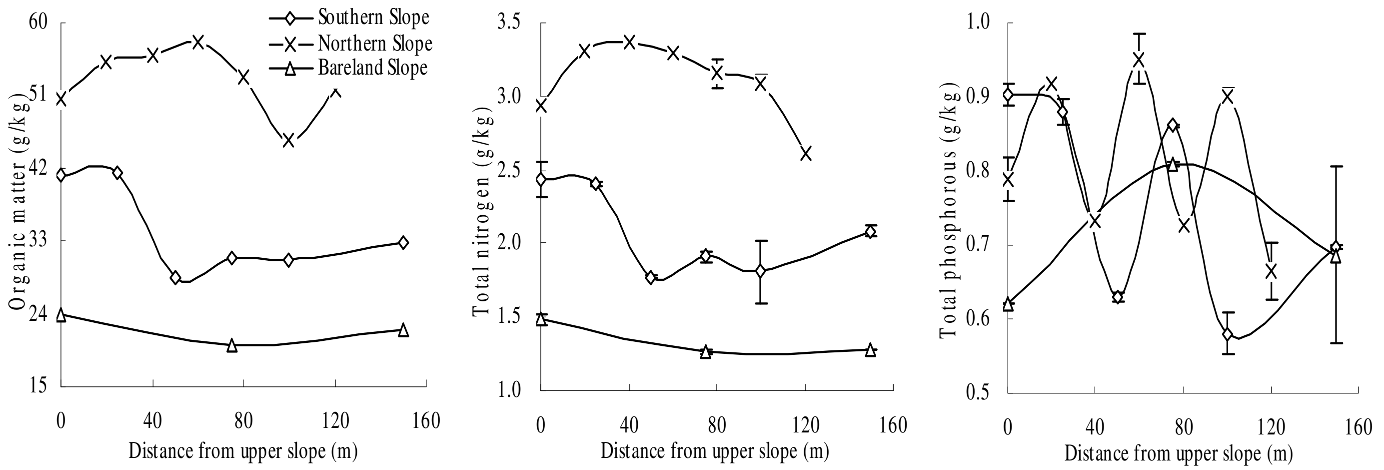

Figure 2. Distribution of nutrients in surface soils along slopes.

tion. In contrast, the total phosphorus content varied greatly along the slopes. The results shown in Figure 2 further indicated that organic matter and total nitrogen increased markedly after 22 years of re-vegetation (no initial control) and the increase varied with slope types.

Soil nutrient distribution in soil profiles

After 22 years of re-vegetation, the soil quality was improved in surface soil and deeper soil (Figure 3). The improvement of soil quality in deeper layers may have more important eco-environmental significance than the improvement in surface soil. Organic matter and total nitrogen were distributed similarly in the soil profile, with the content decreasing with depth. In the upper position, the northern slope soil had the lowest organic matter and total nitrogen content, with values of 50.49 and 2.94 g kg^{-1} being observed in topsoil and 7.44 and 0.48 g kg^{-1} being found in deep layers, respectively. Additionally, the organic matter and total nitrogen content in bare land slopes decreased the least, with 23.97 and 1.48 g kg^{-1} being observed in topsoil and 18.11 and 1.10 g kg^{-1} being observed in deep layers, respectively. When compared with bare land, the organic matter and total nitrogen contents were higher in re-vegetated soils, with significant differences being observed in the 0-35 cm and 0-50 cm layers in upper positions, in the 0-60 cm and 0-100 cm layers in middle positions and the 0-105 cm and 0 -80cm layers in lower positions. These results suggest that the distribution of soil quality in sites that were undergoing re-vegetation varied with slope position, the influencing depth of re-vegetation on soil quality increased with decreasing of slope position. In addition, these findings indicate that the response of organic material to changes in soil quality may be more sensitive than that of total nitrogen.

The distribution pattern of soil total phosphorus in the

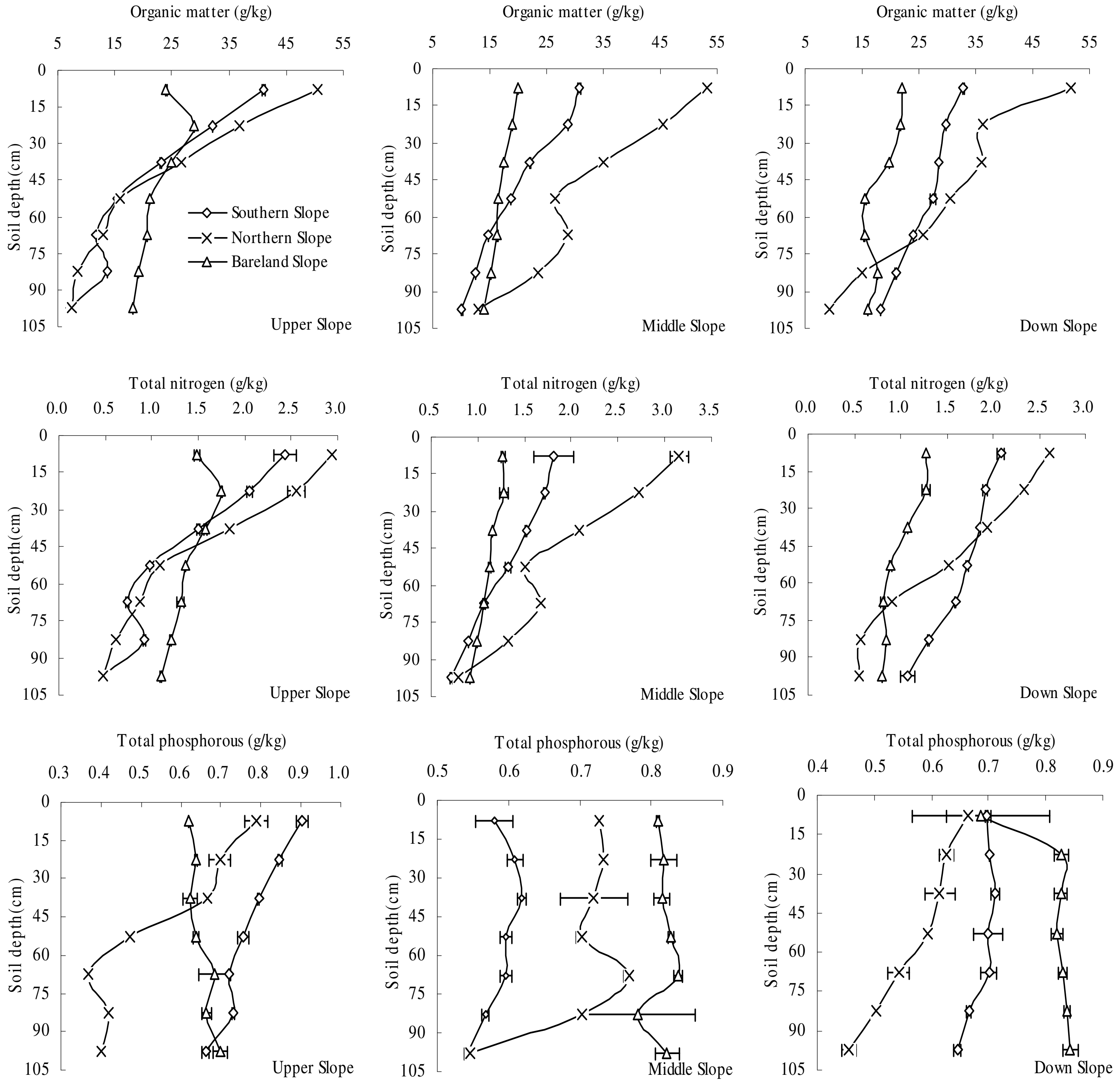

Figure 3. Profile distribution of soil nutrients at different slope positions.

soil profile varied greatly with slope position and direction (Figure 2). The total phosphorus content of re-vegetated slopes decreased with soil depth, especially on the northern slope. In contrast, the total phosphorus in the bare land slope increased slightly with soil depth. Moreover, the total soil phosphorus content in the middle and lower positions of re-vegetated slopes was significantly lower than that of bare land slopes. The distribution of total phosphorus may be caused by plant growth and the absorption intensity, which is related to slope position and direction. Because bare land slopes have little vegetation, soil and water losses should be higher in upper positions. As a result, soil nutrients accumulate in the lower position. These ecological processes presumably caused the profile distribution pattern of the soil organic matter and total nitrogen that was observed in the bare land slope, which were higher in the lower positions than in the middle slope positions. The vegetation grown on the southern slope may have partially prevented soil, water and nutrient loss from the middle position and weakened

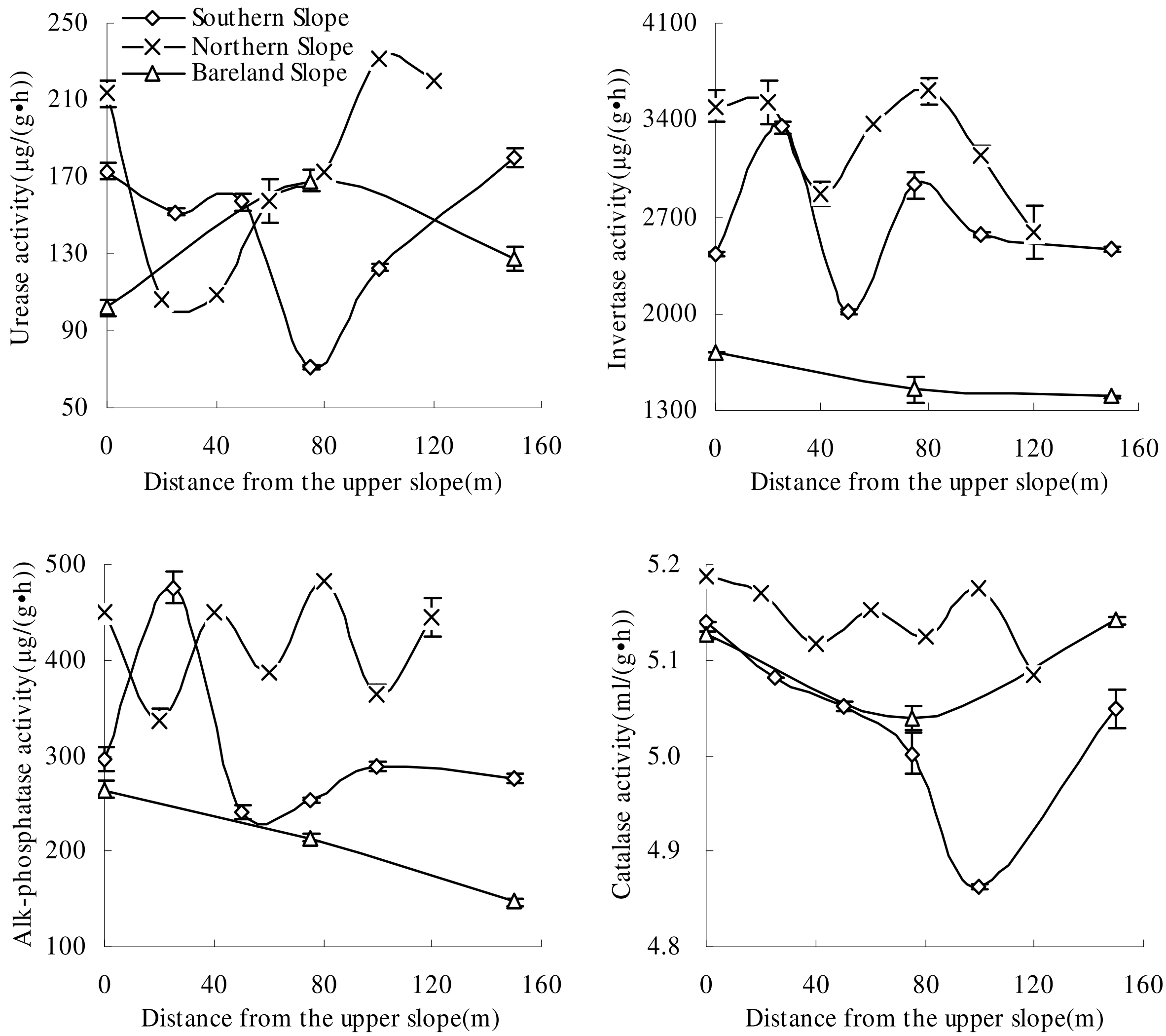

Figure 4. Distribution of enzyme activities in surface soils along slopes.

their enrichment in the lower slope position. On the northern slope, the high amount of vegetation may have nearly completely prevented soil, water and nutrient losses and the effects of enrichment in the down slope were no longer observed. These findings may be characteristic of the profile distribution of nutrients in sloped land. The results shown in Figure 2 indicate that long-term re-vegetation led to significant conservation of soil nutrients and that the effect was greater on northern slopes than southern slopes.

Soil enzymatic activities

Distribution of soil enzymatic activities along slopes

The distribution of soil enzymatic activities varied markedly with slope types and positions (Figure 4). Among the 4 enzymes, the greatest variation was observed in urease activity, which decreased in the order of southern slope>bare land slope>northern slope at a distance of 30 - 50 m from the upper positions, but followed the order of northern slope>bare land slope>southern slope at 60 - 120 m from the upper positions. However, the distribution of invertase and alkaline-phosphatase along the 3 slopes followed the pattern of northern slope>southern slope> bare land slope. The catalase activity showed less variation with slope types and positions and followed the pattern of northern slope>bare land slope>southern slope. Unlike the soil nutrient content, which was often lower in the upper slope than lower slope positions, the distribution of soil enzymatic activities in slope land did not present such a trend (Figure 4). These findings may have reflected the soil enzyme sources, soil biological properties and micro-relief of the slope land.

The results presented above also indicate that long-term re-vegetation has led to marked improvement of the soil biological properties. The improvement of such pro-

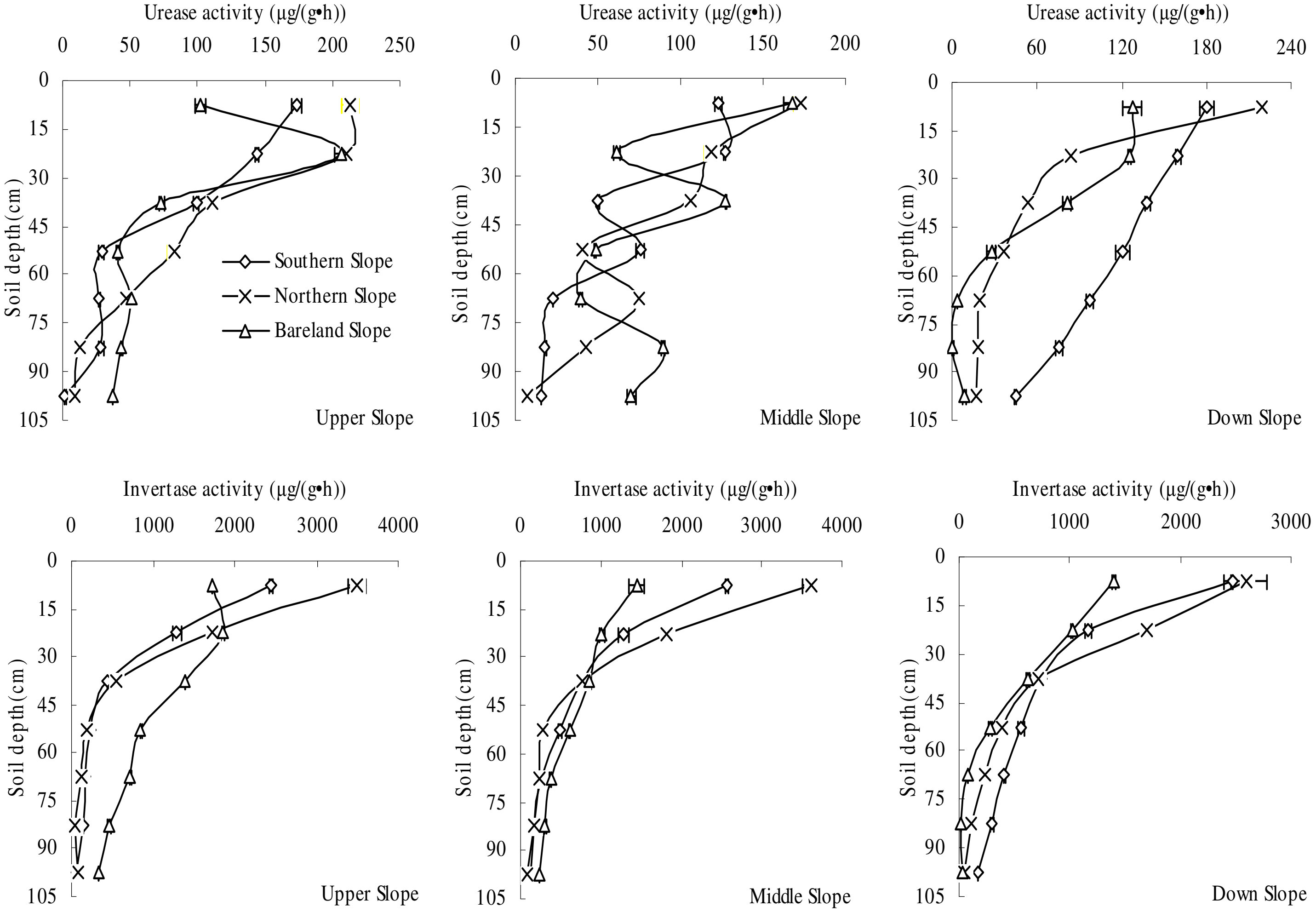

Figure 5. Profile distribution of enzyme activities in different slope positions.

perties was more obvious on the northern slope than the southern slope. Additionally, the effect of re-vegetation on soil biological properties was primarily dependant on plant growth. On the northern slope, the plant growth and soil-water conservation effects were greater than on the southern slope, which ultimately favors the resistance of soil degradation and the improvement of soil quality.

Distribution of soil enzymatic activities in soil profiles

As shown in Figure 5, the activities of urease followed the pattern of lower > upper > middle slope positions. These results suggest that lower slope positions serve as a sink of mass loss from the slope. As a result, soils in this position are rich in nutrients, which accelerate soil biological processes and increase the soil urease activity. Another reason for the distribution of enzymatic activities may be differences in the soil water conditions. Specifically, the soil water content down slope is always higher than that of other slope positions, which leads to the leaching of bioactive compounds from the surface to deeper soil layers and increases the urease activity throughout the soil profile.

Soil invertase and alkaline-phosphatase activities had a similar distribution in the soil profiles and decreased with soil depth. Among the 3 slope positions, the effect of re-vegetation on invertase was more obvious than the effects on alkaline-phosphatase (Figure 5). The results shown in Figure 5 implied that the depth to which re-vegetation impacted the soil invertase and alkaline-phosphatase content varied with slope positions. In re-vegetated slopes, invertase and alkaline-phosphatase activeties were higher than those in bare land in the 0 - 20 cm layer in the upper position, but in the 0 - 40 cm layer in the middle position and throughout the soil profile at the lower position. The different depth of soil affected by re-vegetation at different slope positions may be related to the loss of mass that occurs at the upper position, the

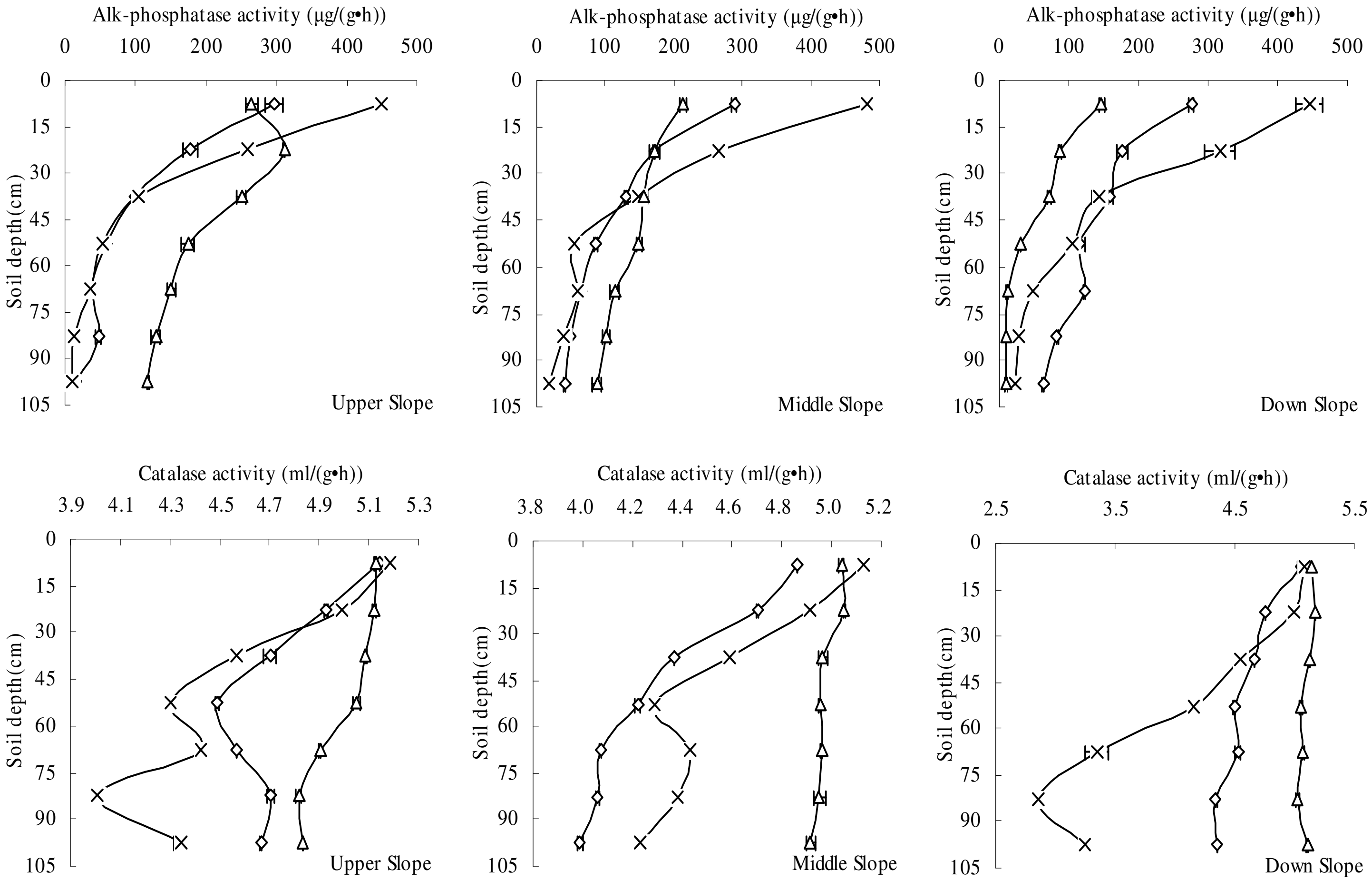

Figure 5. Contd.

deposition and release that occurs at the middle position and enrichment that occurs at the lower position in response to water erosion and mass transport. The long-term impacts of re-vegetation on the soil nutrient distribution may be explained by the plant-soil interactions.

The catalase activity decreased with soil depth in the re-vegetated slopes, with the greatest decrease occurring on the northern slope. When the surface soil in the upper, middle and lower positions was compared, the catalase activity in deep soil on the northern slope decreased by 0.841 ml (g h)$^{-1}$, 0.893 ml (g h)$^{-1}$ and 1.844 ml (g h)$^{-1}$, respectively. In contrast, the catalase activity decreased only slightly with soil depth on the bare land slope, with the greatest difference between surface and deep layers being 0.31 ml (g h)$^{-1}$. Because catalase is an oxidation-reduction enzyme, its activity is closely related to the soil redox regime, which is primarily determined by soil water conditions and organic matter content. The higher moisture and organic matter contents lead to increased reduction conditions. The major function of catalase is to catalyze the decomposition of H_2O_2; therefore, its activity is low under reduced conditions. The soil moisture and organic matter contents were greater in northern slope soil than southern slope soil and higher in southern slope soil than in bare land slope soil. Consequently, the redox potential was lowest on the northern slope and highest on the bare land slope, resulting in a catalase activity pattern of bare land slope>southern slope>northern slope.

Effects on soil quality

Significant positive correlations were observed between the soil organic matter and total nitrogen contents and soil enzymatic activities (Table 1). These results were supported by the results of previous studies (Guo et al., 1997; Masciandaro and Ceccanti, 1999). The significant relationships between soil nutritional properties and enzymatic activities may be explained by increased nutrient release from plants into the soil, available resources for micro-organisms and soil enzymatic activities. Soil enzymes are primarily derived from microbial cells (Ladd, 1978), but they can also originate from plant and animal residues (Bahl and Agrawal, 1972; Tabatabai, 1994). Enzymes accumulating in soils are free enzymes released from living or disintegrated cells and enzymes

Table 1. Correlation coefficients between soil properties.

Property	Soil Moisture	Organic matter	Total nitrogen	Total phosphorous	Urease	Invertase	Alkaline-phosphatase	Catalase
Soil moisture	1.000	0.562**	0.500**	-0.154	0.134	0.148	0.211	-0.233
Organic matter		1.000	0.967**	0.245	0.757**	0.825**	0.844**	0.369**
Total nitrogen			1.000	0.258*	0.807**	0.840**	0.867**	0.436**
Total phosphorous				1.000	0.284*	0.207	0.199	0.661**
Urease					1.000	0.824**	0.817**	0.496**
Invertase						1.000	0.959**	0.524**
Alkaline phosphatase							1.000	0.527**
Catalase								1.000

*Significant at $p < 0.05$, **significant at $p < 0.01$.

bound to cell constituents (Kiss et al., 1975). Soil enzymes are directly responsible for the initial processing of detrital carbon and organic-bound nutrients (Collins et al., 1996). Therefore, the strong correlation between soil enzymatic activities and soil fertility properties and the significant difference among re-vegetation practices suggests that enzymatic activity may be used as a valuable biological indicator of soil ecological stress or of the effectiveness of restoration processes.

Due to the large number of soil properties evaluated and the close relationships between these properties, principal component analysis was conducted to simplify the interpretation of the entire dataset (Table 2). The results revealed the eigenvectors of 3 final principal components. The first principal component was composed of total nitrogen, organic matter, urease, invertase and alkaline-phospharase. The second principal component included total phosphorous and catalase. The third principal component reflected soil moisture and total phosphorous. The three principal components together explained 92.37% (>85%) of the total covariance. The first and second principal components accounted for 82.4 % of total covariance, indicating that they can illustrate the relationships among soil properties and enzymatic activities (Figure 6). These results showed that total nitrogen and organic matter contents, as well as urease, invertase and alkaline-phosphatase activities can be classified into a factor to indicate soil quality and characterize the distribution of soil properties along slopes. Conversely, soil organic matter and nitrogen play an important role in improving soil physical, chemical and biological properties and soil quality is primarily reflected in the soil carbon and nitrogen balance. Furthermore, soil enzymatic activity has long been considered a sensitive indicator of soil quality (Nannipieri, 1994) and a valid biomarker to indicate changes in the total microbial activity induced by changes in soil management (Ceccanti et al., 1993). Moreover, many studies have indicated that enzymatic activities could be used as an index of soil productivity or microbial activity (Dick, 1994; Gregorich et al., 1994; Jordan et al., 1995; Badiane et al., 2001) and there is considerable evidence that these activities can be used to evaluate the influence of management and land-use on soil quality (Saggar et al., 1999). Therefore, we concluded that it was reasonable to assess soil environmental conditions on the basis of soil organic matter, total nitrogen contents and soil enzymatic activities. Accordingly, the soil quality index was expressed on the basis of 5 soil properties using the following formula (Adejuwon and Ekanade, 1988):

$$SQI=[(P_1-P'_1)/P'_1+(P_2-P'_2)/P'_2+\ldots+(P_n-P'_n)/P'_n]\times 100\%/n$$

where P'_1, P'_2, and…P'_n are the values of different properties in bareland slope soils; P_1, P_2 and … P_n are the values of corresponding properties in southern or northern slope soils and n is the number of selected soil properties.

The calculated soil quality index reflects the relative differences in soil properties with respect to their values under a bare land slope (Figure 7). The SQI in re-vegetation slopes varied with slope positions and soil layers. Generally, re-vegetation led to significantly improved soil quality in the middle and lower slope positions. In contrast, the improvement of soil quality at the upper position was only observed in the topsoil layer. The soil quality index on the northern slope was significantly higher than on the southern slope, indicating that re-vegetation had a greater impact on soil quality.

Conclusions

In the Yunwushan natural grassland protection zone of the Loess Plateau, 22 years of re-vegetation have led to significantly improved soil properties in surface soils and deep soils. However, the improvement in soil properties in response to re-vegetation varied greatly with slope directions and positions. The greatest improvement in soil properties was observed at the lower position on the northern slope. The soil enzyme activities were found to be important for the assessment of soil quality. Speci-

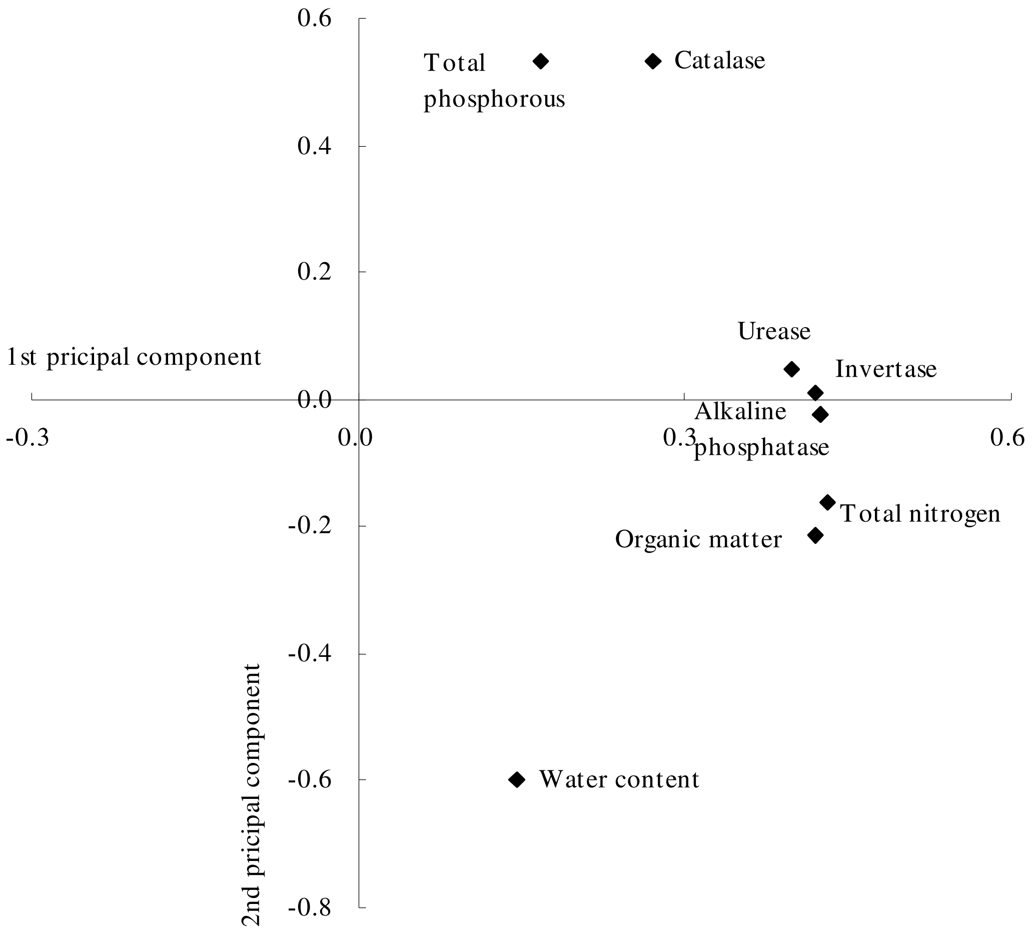

Figure 6. Eigenvector plot for the 1st component versus 2nd component of the 8 soil properties.

Table 2. Principal component analysis of soil properties.

Property	1st component	2nd component	3rd component
Soil moisture	0.145	-0.599	0.569
Organic matter	0.420	-0.213	0.162
Total nitrogen	0.430	-0.163	0.109
Total phosphorous	0.167	0.534	0.635
Urease	0.399	0.047	-0.220
Invertase	0.420	0.008	-0.318
Alkaline-phosphatase	0.425	-0.022	-0.268
Catalase	0.271	0.531	0.115
Cumulative proportion of covariance (%)	61.41	82.35	92.37

fically, total nitrogen, organic matter, urease, invertase and alkaline-phospharase could be used to evaluate changes in the soil properties after 22 years of re-vegetation in the study area. Additionally, a soil quality index based on total nitrogen, organic matter, urease, invertase and alkaline-phospharase could effectively reflect changes in soil quality in response to re-vegetation in the Loess Plateau.

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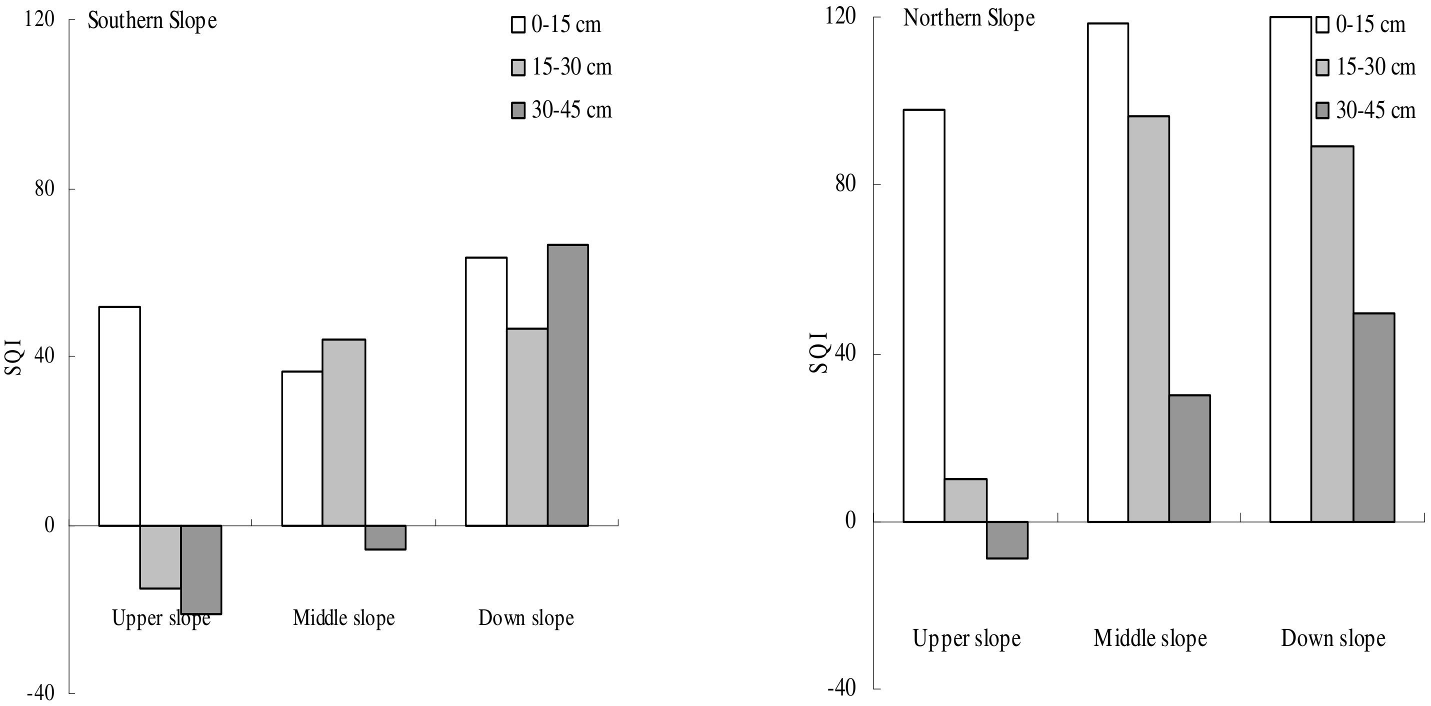

Figure 7. Soil quality index of the southern slope and northern slope after 22 years of re-vegetation.

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