Changes in soil properties in different land use types in a desert-oasis ecotone, Inner Mongolia, China

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This study aims to examine the changes in soil chemical properties (soil organic matter, SOM; available nitrogen, AN; available phosphorus, AP; available potassium, AK; total nitrogen, TN; total phosphorus, TP and pH) in three depths (i.e. 0-5, 5-10, 10-20 cm) from different land use types of the Green Beach Desert-oasis Ecotone, Inner Mongolia, China. Using soil chemical properties data, comprehensive soil quality index (SQI) was calculated based on principal component analysis (PCA) of variables across different soil depths for different land use types. Results showed that soil properties differed significantly according to land use type. The eight land use types all showed decreases in TN and TP meaning values for these variables fell below those measured from the control plot (bare ground or ‘CK’). Farmland and protective forest soils showed higher AK, AN, AP and SOM contents with protective forest soil the higher of the two. This contributed to accumulation of soil nutrients. Soil quality index results showed that the soil quality index of abandoned farmland in 5-10 cm and 10-20 cm soil layer is the highest among the eight types of land, therefore, the 5-10 cm and 10-20 cm soil layers of abandoned farmland could help to optimize soil nutrients. The 0-5 cm layer of the protective forest soil also showed obvious nutrient accumulation. These results provide basic reference data and trends for soil quality assessment in arid, ecologically fragile areas.

1. Introduction

The desert-oasis ecotone is a transitional area that hosts pronounced changes in land cover and is at heightened risk of degradation due to climate change. Small-scale disturbances may cause changes in the dominant species or other aspects of the vegetation community. From the inner oasis to the outer desert, temperature and hydrologic gradients induce comprehensive changes in vegetation, soil and landforms that differentiate the types of land use categories used herein (Zhou et al., 2019; Mu et al., 2013). As the interface between oasis and desert, the desert-oasis ecotone plays an important role in ensuring the ecological security and maintaining the internal stability of the oasis (Liu, 2020). Recent research has shown that increasing population and land reclamation have intensified destruction of the desert-oasis ecotone. The stability of adjacent areas depends on development and maintenance of the transition zone. Unplanned development or utilization can damage the ecosystem and destabilize the environment (Wang et al., 2017). Soil properties vary strongly with land use patterns in desert-oasis ecotones. Different land types in the transition zone also show obvious differences in plant species and soil properties (Tang et al., 2016; Shi et al., 2013). Tripathi et al. (2012) think the nutrient addition can create a strong buffer for soil aggregate formation. Different land use patterns show differential impact of N and P additions on soil organic matter and aggregate structure (Tripathi et al., 2008). Chowlani Manpoong et al. (2020) studied the soil biochemical and microbial community characteristics across different land use systems in mountainous region in Northeast India, think widely practiced shifting cultivation practice created various land uses associated with altered soil biochemical and microbial attributes.

Land use change are considerably affecting organic carbon and biochemical properties of soil (Wapongnungsang and Tripathi, 2018). Academic research has begun to address questions of soil quality among the different land use types in desert-oasis ecotones. In their study of soils impacted by land cover changes in a desert-oasis transition zone of Minqin, Wang (2011) found close relationships between soil organic matter and nutrient content. The correlation between organic matter and
nutrients however differed for different zones. A significant positive correlation occurred between organic matter and total nitrogen, total phosphorus, alkali hydrolyzed nitrogen and available potassium content. This indicated that the loss of organic matter content may also cause the loss of other nutrients. The decrease of soil organic matter content may cause the decrease of soil total nitrogen and total phosphorus content, and the decrease of alkali hydrolyzable nitrogen content may cause the decrease of available phosphorus and potassium content. Available phosphorus correlated negatively with organic matter and other nutrients (Sun et al., 2013; Gong and Wang, 2011; Wang et al., 2018; Liu, 2017). Manpoong et al. (2021) study soil carbon stock in different land-use systems in the hilly terrain of Mizoram, Northeast India, think that the land use change in the mountainous region significantly affected the carbon stock in the soil. Gui et al. (2009, 2010) studied changes in soil quality among different land use types of the Cele Oasis along the southern margin of the Tarim Basin. The four land use types used in artificial cultivation along the edge of the Cele Oasis exerted significant impacts on soil properties and soil quality. Various soil plots showed significant differences in soil organic matter and total nitrogen indicators. Research on soil stoichiometric characteristics showed that certain land use types could increase soil nutrient content in the desert-oasis ecotone along the southern edge of the Taklimakan Desert. Soil nutrient changes may also impart ecological effects (Zhou et al., 2018). Li et al. (2018) studied the effects of sand barriers laid out in a checkerboard pattern and composed of different materials on soil organic carbon, available nitrogen, available phosphorus, available potassium, pH and soil moisture. These workers showed that sand barriers could improve soil quality in sandy areas.

Having gradually expanded since 1975, the Tengger Desert is the fourth largest desert in China. The expansion of the Tengger threatens certain urban and agricultural developments in the area. Quantitative assessment of soil quality under different land use patterns can provide critical reference information regarding transformational dynamics of land use in the region. It can also inform efforts to protect the environment and prevent oasis desertification. Previous studies aimed at these goals encountered a shortage of soil quality assessment data for the region.

The study area occurs in an area referred to as Green Beach along the eastern edge of the Tengger Desert. A typical desert-oasis ecotone, this area offers representative land use plots that facilitate quantitative evaluation of soil quality. This research used a combination of soil quality index (SQI) and principal component analysis (PCA) to estimate general soil quality of each land use and evaluate variation in soil properties according to land use. The objectives of the study were i) to determine distribution of soil nutrients among different land use types in an ecologically fragile desert-oasis ecotone and ii) to create basic reference data and approaches for oasis soil quality monitoring in arid or desert regions.

Figure 1. Map showing the location of the study area.
2. Site description

The study site occurs in the southeast of Alxa Left Banner (38°43'N, 105°31'E; approx. 1370 m elevation) along the eastern edge of the Tengger Desert, Inner Mongolia, China (Figure 1). The area categorizes as an arid desert climate type with obvious seasonal changes in the temperate zone. The generally dry climate of the area and long term vegetation damage contribute to high evaporation rates. Rainfall is limited. Summer temperatures are high and winter temperatures are low. The area also experiences large diurnal variation in temperature, frequent sandstorms and ongoing long term desertification. The mean annual temperature is 7.7 °C. The average temperature in January is -7.7 °C, and the average temperature in July is 27.4 °C. The frost-free period lasts for 187.5 days. The area receives an average of 180.2 mm annual precipitation, 80% of which comes from May to September. The annual evaporation is 2900 mm. The average wind speed is 3.1 m/s and the maximum sequential wind speed can reach 17.9 m/s (Xie et al., 2019; Ding et al., 2020). The soil consists primarily of grey desert soils and brown calcic soils distributed in a zonal pattern. Of all soil types, aeolian sandy soil covers the largest area. Vegetation tends to consist of a single species including Leguminosae, Caragana Korshinskii Kom, Artemisia ordosica Krasch, Artemisia frigida, pine cone, pine cone and Dendranthema rhombifolium Ling et Shih.

3. Materials and methods

3.1. Sample collection

Following current land use designations of the Green Beach desert-oasis ecotone. Select a profile line to ensure that the profile line covers all land use types in the study area, eight land use types were designated for sampling with system control method is adopted. These included grassland, protective forest, shrub land, farmland, artificial Haloxylon ammodendron woodland, sand barrier, abandoned farmland and a control plot (referred to as ‘CK’), in 2006, the abandoned farmland, which was originally used for farmland, became abandoned because of the limited natural conditions and the arid climate and scarce precipitation in the study area, which were not enough to support the growth of crops. Soil profiles were excavated from each land use type with samples collected at 0–5 cm, 5–10 cm and 10–20 cm. Three lateral replicate samples were collected at each level (Figure 2). The nine sampling points thus gave a total of 72 soil samples collected.

3.2. Soil processing and analysis

The SOM, AK, AN, AP, TN, TP and pH values were measured from soil samples after air drying, impurity removal and screening. SOM was determined using the potassium dichromate external heating method while AK was determined using flame photometric methods. A 0.5 mol L−1 NaHCO3 extraction method was used to determine soil AP while a K’s nitrogen determination method was used to determine AN. TN and TP were measured using an elemental analyzer, and soil pH was measured by conductivity meter.

3.3. Data analysis

Statistical and principal component analysis were conducted using the statistical software SPSS (Windows v. 26.0) and Excel 2010. Graphics were constructed in OriginPro 9.1. Statistical analysis of soil fertility included calculation of mean, minimum and maximum values along with skewness, standard deviations and other metrics. Principle Component Analysis (PCA) identified arrays of variables that covaried with land type to give the most explanatory estimates of soil quality. Arrays derived from standardized data matrices containing eigenvalues greater than 1. These were used to select variables that explained the largest proportions of variation. Pearson correlation coefficients were calculated and compared to assess relationships between different soil variables and indexes. Statistical analysis allowed for construction of a comprehensive SQI representing soil quality. “More is better” and “less is better” scoring curves were used to evaluate index values that best conform to the non-linear equation. A sigmoidal type equation was used to perform non-linear scoring of variables (Askari and Holden, 2015) as follows:

$$S = \frac{a}{1 + (x/x_0)^b}$$

where S is the non-linear score of the soil indicator, a is the maximum score (=1), x is the soil property value, xo is the mean value of the soil property in the study and b is the slope of the equation for the “more is better” (−2.5) and “less is better” (2.5) curves (Zhang et al., 2011).

$$SQI = \sum_{i=1}^{n} W_i S_i$$

In the SQI equation above, Si represents the soil indicator score, n represents the number of properties integrated in the index and Wi is the weighing value for indicators as determined by PCA.

4. Results and discussion

4.1. Distribution of soil nutrients under different land use conditions

4.1.1. Distribution of soil organic matter (SOM)

Measured SOM content varied significantly with different land use types and gave a standard deviation of 3.37 (Table 1). Among all land use types, farmland soils exhibited the highest average SOM value (9.26 g/kg) followed by protective forest (3.98 g/kg). The 0–20 cm soils from
sand barriers exhibited the lowest average SOM values of 0.65 g/kg. These fell below even those measure from the control plot (CK). SOM values measured from the 0–20 cm layer increased according to land use type in the following order: sand barrier < CK < grassland < shrub land < artificial Haloxylon ammodendron woodland < abandoned farmland < protective forest < farmland (Figure 3a). SOM derived primarily from the decomposition of vegetation litter, which appears to accumulate as SOM. Vegetation also blocks eolian stress and transport of vegetation thereby reducing SOM loss. Data showed relations between SOM and the density of surface vegetation with high density areas placing greater demands on SOM. Generally speaking, vegetation coverage strongly influenced soil SOM values for all land use types relative to relations and values observed for the control plot (CK).

4.1.2. Distribution of soil available potassium

In the 0–20 cm soil layers (Figure 3b), AK content varied significantly among different land use types to give a standard deviation of 12.09. Average AK values for the 0–20 cm soil layer ranked as follows: sand barrier < CK < abandoned farmland < grassland < shrub land < farmland < artificial Haloxylon ammodendron woodland < protective forest < farmland (Figure 3a). AK still varied clearly with different land use types. In the 20 cm soil layer (Figure 3d), AK content varied significantly with land use type in the following order: sand barrier < CK < artificial Haloxylon ammodendron woodland < abandoned farmland < protective forest < farmland (Figure 3a). SOM derived primarily from the decomposition of vegetation litter, which appears to accumulate as SOM. Vegetation also blocks eolian stress and transport of vegetation thereby reducing SOM loss. Data showed relations between SOM and the density of surface vegetation with high density areas placing greater demands on SOM. Generally speaking, vegetation coverage strongly influenced soil SOM values for all land use types relative to relations and values observed for the control plot (CK).

4.1.4. Distribution of soil available nitrogen

Soil AN content differed markedly with different land use types and gave a standard deviation of 9.16. Farmland soils gave much higher AN values than those measured from the control plot. Farmland soils gave the highest average AN value (28.35 mg/kg), which exceeded that of control plots by a factor of about 2.6. Shrubland soils gave the lowest average AN value (8.02 mg/kg). The 0–20 cm AN values for the different land use types ranked as follows: shrubland < artificial Haloxylon ammodendron woodland < abandoned farmland < control plots < grassland < sand barrier < protective forest < farmland. Farmland thus appears to accumulate the most AN among other land use types.

4.1.5. Distribution of soil total nitrogen

Total nitrogen (TN) is a critical component of soil nutrients. Figure 3e shows TN variation among different land use types. Overall TN values gave a standard deviation of 1.34. For different land use types, TN values ranked as follows: protective forest < abandoned farmland < artificial Haloxylon ammodendron woodland < farmland < grassland < sand barrier < shrub land < control plots. Soils from different land use types did not show significant differences in TN values, but all fell below that measured from the control plot, which gave an average TN value of 7.19 g/kg. Shrubland soils gave an average TN value of 6.75 g/kg while protective forest soils gave the lowest average TN value of 4.00 g/kg. The 0–20 cm soil layers gave TP values with a standard deviation of 0.51. Figure 3f shows that farmland soils gave the highest average TP value (3.00 g/kg) The control plot soils gave the next highest value (average 2.94 g/kg), and the protective forest gave the lowest average TP value (1.88 g/kg). Land use types ranked as follows in terms of soil TP content: protective forest < abandoned farmland < artificial Haloxylon ammodendron woodland < farmland < grassland < sand barrier < shrub land < control plots. Soils from different land use types did not show significant differences in TN values, but all fell below that measured from the control plot, which gave an average TN value of 7.19 g/kg. Shrubland soils gave an average TN value of 6.75 g/kg while protective forest soils gave the lowest average TN value of 4.00 g/kg.

4.1.6. Distribution of soil total phosphorus

Soil pH values depend on cycling of ions in soil. As shown in Figure 3g, soils gave alkaline pH values with a standard deviation of 0.28. The artificial Haloxylon ammodendron woodland soils gave the highest pH value (8.87) followed by shrub land (8.74), grassland (8.73) and the control plot (8.71). Values for other land use types fell below that of the control plot. Farmland soils gave the lowest value (8.22). The 0–20 cm soil layers for the different land use types gave pH values that ranked as follows: farmland < protective forest < abandoned farmland < sand barrier < control plot < grassland < shrub land < artificial Haloxylon ammodendron woodland. Artificial Haloxylon ammodendron woodland soil pH values exceeded those of the control plot only slightly, by a factor of 1.02. The pH value of soils facilitates release of trace elements. While plants can release organic acids from their root systems to help neutralize the soil environment, pH values too alkaline or acidic can inhibit biological processes in soil.

Table 1. Descriptive statistics for soil nutrients from plots protected by different land use types as measured over 0–20 cm profile.

| Soil nutrient | Unit       | Minimum | Maximum | Mean   | Standard Deviation | Skewness | N  |
|--------------|------------|---------|---------|--------|--------------------|----------|----|
| SOM          | (g/kg)     | 0.01    | 13.98   | 2.66   | 3.37               | 1.95     | 54 |
| AK           | (mg/kg)    | 18.69   | 67.16   | 30.38  | 12.09              | 1.53     | 54 |
| AP           | (mg/kg)    | 4.79    | 17.94   | 6.38   | 2.36               | 3.00     | 54 |
| AN           | (mg/kg)    | 5.64    | 59.54   | 14.15  | 9.16               | 3.13     | 54 |
| TN           | (g/kg)     | 1.67    | 8.37    | 6.26   | 1.34               | -1.3     | 54 |
| TP           | (g/kg)     | 0.89    | 3.51    | 2.74   | 0.51               | -1.28    | 54 |
| pH           | —          | 7.80    | 9.60    | 8.60   | 0.28               | -0.13    | 54 |

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Figure 3. Soil properties measured from different land use types. Notes: a, b, c, d, e, f and g represent grassland, protective forest, shrub land, farmland, artificial Haloxylon ammodendron woodland, sand barrier, and abandoned farmland use types (respectively).
4.2. Soil quality index (SQI)

A soil quality index (SQI) was generated to interpret soil data and specifically detect changes in soil quality associated with different land use types. PCA was performed on the standardized data matrix to identify the best combinations of variables for assessing soil quality. The results formed SQIs for individual 0–5, 5–10 and 10–20 cm layers as well as the complete 0–20 cm profile.

4.2.1. SQI values for the 0–5 cm layer

A PCA matrix returns correlation coefficients as principal components or arrays of variables that show the highest amounts of co-variation with dependent variables. PCA identified three components with values exceeding 1 explained 98.41% of the variation in soil mass of the 0–5 cm surface layer (Table 2). The highest ranked component explained 60.27% of the variance and included the highest variable weightings of the three variables, SOM (0.70) and AP (0.72). This component strongly and positively correlated with each other (r = 0.957; Table 3). The pH variable was retained in the SQI given its larger absolute weighting according to PC1. The second principal component (PC2) accounted for 23.70% of the variance and included TP (0.72). This variable was included in the SQI. The third principal component (PC3) accounted for 14.44% of the variance and included AK (0.70) and AN (−0.72) (Table 4). No correlation appeared between AK and AN (r = 0.086) so both were retained in the SQI. Table 4 lists normalization equations of the scoring curves for the 0–5 cm soil layer. The final SQI calculation equation for the 0–5 cm layer of soils was thus defined as follows:

\[
SQI = 0.58S_{\text{pH}} + 0.13S_{\text{TP}} + 0.61S_{\text{AK}} + 0.31S_{\text{AN}}
\]

Normalized SQI = 0.36S_{\text{sP}} + 0.08S_{\text{TP}} + 0.37S_{\text{sAK}} + 0.19S_{\text{sAN}}

Single sample T test analysis results found significant differences in soil quality values in the upper 0–5 cm layer. Except for grassland, other land use types showed improved the soil quality values in the upper 0–5 cm layer.

4.2.2. SQI values for the 5–10 cm layer

PCA of the 5–10 cm soil layer data detected two components which explained about 83.61% of the variation in the 5–10 cm soil layer (Table 5). SOM (0.74), AP (0.71) and AN (0.70) were closely related to PC1, accounting for 45.86% of the variance (Table 6). SOM and AN (r = 0.903) shared a high correlation, as did TP and SOM (r = 0.956). Because SOM exhibited the maximum weighting of the three variables, this variable was retained in SQI. PC2 accounted for 37.76% of the variance and included TP (0.71). Table 7 gives normalization equations of the scoring curves for the 5–10 cm soil layer. The SQI model for the 5–10 cm soil layer was defined as follows:

\[
SQI = 0.40S_{\text{SOM}} + 0.32S_{\text{TP}}
\]

Normalized SQI = 0.56S_{\text{SOM}} + 0.44S_{\text{TP}}

A sample T test found significant differences in the SQI values for the eight land use types (t = 6.076, p < 0.05). The SQI value of the control plot was 0.28. Farmland soils gave the highest SQI value (0.83) while sand barrier soils gave the lowest SQI value (0.25). Except for grassland and sand barrier soils, SQI values for other land types exceeded those estimated for the control plot soils (Figure 4b).

4.2.3. SQI values for the 10–20 cm layer

PCA performed on data from the 10–20 cm soil layer returned two components which explained 85.51% of the variance (Table 8). The highest ranking component accounted for 46.37% of the variance and included SOM (0.71) and AP (0.70) as variables. This component strongly and positively correlated with PC1 (r = 0.959) (Table 9). PC2 included TN (0.73) and TP (0.71), which correlated strongly with each other (r = 0.906). The variable with the larger weighting, TN, was retained in the SQI. Table 10 shows normalization equations of the scoring curves for the 10–20 cm soil layer. The SQI calculation equation for the 10–20 cm soil layer was defined as follows:

\[
SQI = 0.37S_{\text{SOM}} + 0.21S_{\text{TN}}
\]

Normalized SQI = 0.64S_{\text{SOM}} + 0.36S_{\text{TN}}

Results of a single sample T test found significant differences in SQI values of the 10–20 cm soil layer for different land use types (T = 6.273, P < 0.05). Grassland and sand barrier types gave the lowest SQI values (both 0.22). These fell below that estimated for the control plot (0.30). Farmland gave the highest SQI values (0.79; Figure 4c).

4.2.4. SQI values for the 0–20 cm layer

Table 11 lists the PCA results including the two highest ranked components that explained about 88.54% of the variance for the composite 0–20 cm soil profile. PC1 accounted for 56.22% of the variance.
and included the SOM (0.78), AP (0.72) and pH (−0.74) variables. The pH variable correlated negatively with PC1, while the other two variables correlated positively with PC1. As listed in Table 12, SOM showed strong correlation with AP ($r = 0.958$) and with pH ($r = -0.792$). Since SOM exhibited the largest relative coefficient, this variable was included in the SQI. PC2 accounted for 33.32% of the variance and included TP, which was also retained in the SQI. Table 13 lists normalization equations of the scoring curves for the complete 0–20 cm soil profile. The final SQI equation for the 0–20 cm profiles was defined as:

$$SQI = 0.57S_{\text{SOM}} + 0.08S_{\text{TP}}$$

(9)

Normalized $SQI = 0.88S_{\text{SOM}} + 0.12S_{\text{TP}}$  

(10)

The 0–20 cm SQI values differed significantly for different land use types according to a sample $T$ test ($t = 3.469$, $P < 0.05$). The sand barrier

| Parameter | SOM (g/kg) | AK (mg/kg) | AP (mg/kg) | AN (mg/kg) | TN (g/kg) | TP (g/kg) | pH |
|-----------|------------|------------|------------|------------|-----------|-----------|----|
| Average ($x_0$) | 3.49 | 34.16 | 6.63 | 17.04 | 5.50 | 2.47 | 8.45 |
| Curve types | More is better | More is better | More is better | More is better | More is better | More is better | Less is better |
| Normalization equation | $S = \frac{1}{1 + (x/x_0)^2}$ | $S = \frac{1}{1 + (x/x_0)^2}$ | $S = \frac{1}{1 + (x/x_0)^2}$ | $S = \frac{1}{1 + (x/x_0)^2}$ | $S = \frac{1}{1 + (x/x_0)^2}$ | $S = \frac{1}{1 + (x/x_0)^2}$ |

Table 4. Average values and normalization equations of the scoring curves (0–5 cm).

Table 5. PCA results for soil properties of different land use types (5–10 cm).

| Principal components | PC1 | PC2 |
|----------------------|-----|-----|
| Eigen value          | 1.70 | 1.84 |
| Variance (%)         | 45.86 | 37.76 |
| Cumulative (%)       | 45.86 | 83.61 |
| Indicators           | Eigenvectors |
| SOM                  | 0.74 | 0.13 |
| AK                   | 0.43 | -0.56 |
| AP                   | 0.71 | 0.15 |
| AN                   | 0.70 | 0.27 |
| TN                   | -0.27 | 0.67 |
| TP                   | -0.05 | 0.71 |
| pH                   | -0.31 | -0.19 |

Figure 4. Effects of different land use types on soil quality index (SQI). Notes: a, b, c, d, e, f and g present grassland, protective forest, shrub land, farmland, artificial Haloxylon ammodendron woodland, sand barrier and abandoned farmland use types (respectively).
Table 6. Pearson Correlation matrix for different properties as measured from the 5–10 cm soil layer.

| Parameters | SOM  | AK  | AP   | AN  | TN  | TP  | pH  |
|------------|------|-----|------|-----|-----|-----|-----|
| SOM        | 1    | .434| .956 | .903| -0.157| 0.160| -0.326|
| AK         | .434| 1   | .388 | 0.203| -.835 | -0.722 | 0.097 |
| AP         | .956|     | 1    | .889| -.105 | 0.195 | -0.154|
| AN         | .903| .203| 1    | .939| -0.005| 1.012 | 0.262 |
| TN         | -0.157|   | 1    | .012| 0.262 | .939  | -0.059|
| TP         | -0.326| | 0.097| -0.154| -0.559| -0.005| -0.059|

* Correlation is significant at the P < 0.05 level (two tailed).
** Correlation is significant at the P < 0.01 level (two tailed).

Table 7. Average values and normalization equations of the scoring curves (5–10 cm).

| Parameter | SOM (g/kg) | AK (mg/kg) | AP (mg/kg) | AN (mg/kg) | TN (g/kg) | TP (g/kg) | pH  |
|-----------|------------|------------|------------|------------|-----------|-----------|-----|
| Average   | 2.47       | 33.92      | 6.10       | 12.09      | 5.92      | 2.63      | 8.75|
| Curve types | More is better | More is better | More is better | More is better | More is better | More is better | Less is better |

Normalization equation

\[ S = \frac{1}{1 + \left(\frac{x}{x_0}\right)^2} \]

Table 8. PCA results for soil properties of different land use types (10–20 cm).

| Principal components | PC1  | PC2  |
|----------------------|------|------|
| Eigen value          | 1.85 | 1.70 |
| Variance (%)         | 46.37| 37.14|
| Cumulative (%)       | 46.37| 83.51|
| Indicators           | Eigenvectors |
| SOM                  | 0.71 | 0.12 |
| AK                   | 0.30 | -0.41|
| AP                   | 0.70 | 0.21 |
| AN                   | 0.64 | 0.15 |
| TN                   | -0.11| 0.73 |
| TP                   | 0.16 | 0.71 |
| pH                   | -0.48| 0.49 |

Table 9. Pearson Correlation matrix for different properties as measured from the 10–20 cm soil layer.

| Parameters | SOM  | AK  | AP   | AN  | TN  | TP  | pH  |
|------------|------|-----|------|-----|-----|-----|-----|
| SOM        | 1    | .305| .959 | .789| -0.018| 0.382| -0.545|
| AK         | .305| 1   | 0.221| 0.078| -.421 | -0.279 | -0.515|
| AP         | .959| 0.221| 1    | .900| 0.099 | 0.441 | -0.405|
| AN         | .789| 0.078| 1    | .900| 1    | -0.004| 0.299 |
| TN         | -0.018| -0.421| 0.999| -0.004| 1    | .906  | 0.686 |
| TP         | 0.382| -0.279| 0.441| 0.239| .906  | 1    | 0.377 |
| pH         | -0.545| -0.515| -0.405| -0.373| 0.686 | 0.377 | 1    |

* Correlation is significant at the P < 0.05 level (two tailed).
** Correlation is significant at the P < 0.01 level (two tailed).

Table 10. Average values and normalization equations of the scoring curves (10–20 cm).

| Parameter | SOM (g/kg) | AK (mg/kg) | AP (mg/kg) | AN (mg/kg) | TN (g/kg) | TP (g/kg) | pH  |
|-----------|------------|------------|------------|------------|-----------|-----------|-----|
| Average   | 2.11       | 32.36      | 6.31       | 11.32      | 6.25      | 2.63      | 8.55|
| Curve types | More is better | More is better | More is better | More is better | More is better | More is better | Less is better |

Normalization equation

\[ S = \frac{1}{1 + \left(\frac{x}{x_0}\right)^2} \]

Table 11. PCA results for soil properties of different land use types (0–20 cm).

| Principal components | PC1  | PC2  |
|----------------------|------|------|
| Eigen value          | 1.44 | 1.36 |
| Variance (%)         | 56.22| 32.32|
| Cumulative (%)       | 56.22| 88.54|
| Indicators           | Eigenvectors |
| SOM                  | 0.78 | 0.28 |
| AK                   | 0.52 | -0.46|
| AP                   | 0.72 | 0.36 |
| AN                   | 0.68 | 0.44 |
| TN                   | -0.53| 0.63 |
| TP                   | -0.23| 0.81 |
| pH                   | -0.74| 0.03 |

Table 12. Average values and normalization equations of the scoring curves (0–20 cm).

| Parameter | SOM (g/kg) | AK (mg/kg) | AP (mg/kg) | AN (mg/kg) | TN (g/kg) | TP (g/kg) | pH  |
|-----------|------------|------------|------------|------------|-----------|-----------|-----|
| Average   | 2.11       | 32.36      | 6.31       | 11.32      | 6.25      | 2.63      | 8.55|
| Curve types | More is better | More is better | More is better | More is better | More is better | More is better | Less is better |

Normalization equation

\[ S = \frac{1}{1 + \left(\frac{x}{x_0}\right)^2} \]
and control plot soils exhibited the lowest SQI values of 0.09. Grassland SQI resembled that of the control plot (0.10). Shrubland SQI equaled that of artificial *Haloxylon ammodendron* woodland (0.32). Farmland soils gave the highest SQI value (0.91) followed by protective forest soils (0.68) (Figure 4d). Given the uniform geomorphology and climatic conditions of the study area, SQI values are interpreted as arising from different land use impacts throughout the 0–20 cm soil profile. Farmland exhibited the most intensive impacts.

Vector loading plots were constructed to analyze effects of barriers on soil properties for different soil depths (0–5, 5–10 and 10–20 cm).

![Vector loading plots](image)

**Figure 5. Vector loading plots.**

### Table 12. Pearson Correlation matrix for different properties as measured from the 0–20 cm soil layer.

| Parameters | SOM  | AK   | AP   | AN   | TN   | TP   | pH   |
|------------|------|------|------|------|------|------|------|
| SOM        | 1    | 0.423| 0.958*| .887**| -0.367| 0.077| -0.792|
| AK         | 0.423| 1    | 0.388| 0.175| -0.675| -0.602| -0.402|
| AP         | 0.958*| 0.388| 1    | .899**| -0.24 | 0.181| -0.628|
| AN         | 0.887**| 0.175| 0.999**| 1    | -0.144| 0.216| -0.745*|
| TN         | -0.367| -0.675| -0.24| -0.144| 1    | 0.881**| 0.608|
| TP         | 0.077| -0.602| 0.181| 0.216| 0.881**| 1    | 0.304|
| pH         | -0.792*| -0.402| -0.628| -0.745*| 0.608| 0.304| 1    |

* Correlation is significant at the *P* < 0.05 level (two tailed).
** Correlation is significant at the *P* < 0.01 level (two tailed).

### Table 13. Average values and normalization equations of the scoring curves (0–20 cm).

| Parameter | SOM (g/kg) | AK (mg/kg) | AP (mg/kg) | AN (mg/kg) | TN (g/kg) | TP (g/kg) | pH |
|-----------|------------|------------|------------|------------|-----------|-----------|----|
| Average (x0) | 2.68       | 33.48      | 6.35       | 13.48      | 5.89      | 2.62      | 8.58|
| Curve types | More is better | More is better | More is better | More is better | More is better | More is better | Less is better |
| Normalization equation | \[ S = \frac{1}{1 + (x/x_0)^2} \] | \[ S = \frac{1}{1 + (x/x_0)^2} \] | \[ S = \frac{1}{1 + (x/x_0)^2} \] | \[ S = \frac{1}{1 + (x/x_0)^2} \] | \[ S = \frac{1}{1 + (x/x_0)^2} \] | \[ S = \frac{1}{1 + (x/x_0)^2} \] | \[ S = \frac{1}{1 + (x/x_0)^2} \] |
Figure 5 shows vector loading plots from this analysis. PCA axes are represented by the length and angle of the vectors. PC1 and PC2 account for 84% of the variance observed from the 0–5 cm soil layer (Figure 5a), for 84% of the variance observed from the 5–10 cm soil layer (Figure 5b), for 84% of the variance observed in the 10–20 cm soil layer (Figure 5c) and for 89% of the variance observed in the complete 0–20 cm soil profile (Figure 5d). These components demonstrate that different land use types influence soil properties at all soil depths. For the upper 0–5 cm layer, all land use types exhibited elevated PC1 values consisting of AN, AK, SOM and AP variables and elevated PC2 values consisting of TN and TP variables. The pH variable in PC1 declines under the influence of different land use types (Figure 5a). For the 5–10 cm layer, different land use types caused increases in AN, AP and SOM variables (PC1), as well as TN and TP variables (PC2), but a decrease in the pH (PC1) and AK (PC2) variables (Figure 5b). For the 10–20 cm layer, different land use types caused an increase in the AP, AN and SOM variables (PC1), as well as in the pH, TN and TP variables (PC2), but a decrease in the AK (PC2) variable (Figure 5c). For the 0–20 cm profile, different land use types caused an increase in AN, AP, SOM and AK (PC1) variables, as well as in TN and TP (PC2) variables but a decrease in the pH (PC1) variable (Figure 5d). The vector loading plots thus demonstrate that different land use types caused variation in soil properties between different soil layers.

5. Conclusions

Across a complete 0–20 cm soil profile, most land use types showed accumulation of SOM, AK, AN and AP, with decreasing TN, TP and pH values. Of all the land use types, farmland exhibited the largest increases in SOM, AP and AN in the soil. The sand barrier land use did not strongly impact soil properties. The SQI specifically indicated that relative to other land use types, protective forest exerted the strongest positive effects on nutrients in the 0–5 cm soil layer. Farmland exerted positive impacts in the 5–10 cm, 10–20 cm and 0–20 cm soil layers. These were significant and appeared throughout the soil profile. The impacts of different land use types generally differed among different soil depths. Only grassland and sand barrier land usage did not appear to impart beneficial effects on soil properties.

Declarations

Author contribution statement

Yunhu Xie: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Ting Yu: Performed the experiments.
Zihui Hou; Li Zhu: Contributed reagents, materials, analysis tools or data.
Zhanhong Li: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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