Comparing the soil quality changes of different land uses
determined by two quantitative methods

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Abstract: Soil quality is one of the most important environmental factors in sustaining the global biosphere and developing sustainable agricultural practices. A study was initiated in Wolong Nature Reserve, Sichuan Province, China to elucidate the soil quality changes of natural secondary succession, forest planting and agricultural practices after deforestation in the humid mountainous region. The soil qualities of six land use types (natural forestland, grassland, shrub land, secondary forestland, cultivated land and reforested land) were compared using two quantitative methods: the integrated soil quality index (QI) and soil deterioration index (DI). The QI values of natural forestland, grassland, shrub land, secondary forestland, cultivated land, and reforested land were 0.8030, 0.2727, 0.9127, 0.6881, 0.0285 and 0.3183, respectively. The DI values were 0%, -14%, 12%, 1%, 26% and 18% respectively. Both indexes suggested that shrub land can restore soil properties. To compare the two methods more directly, a deduced index QI2 based on QI value was developed. The results showed that DI and QI2 had a very high linear correlation coefficient (r = 0.9775) despite the values were different. Both methods were efficient in evaluating the soil quality levels and DI was a more simple way in soil quality assessment, while QI could show more ecological meanings.

Keywords: land use; deforestation; soil quality; quantitative methods; comprehensive evaluation; Wolong

Introduction

During the last 50 years, as a result of increasing demand for firewood, timber, pasture, shelter and food crops, natural land covers, particularly forests, are being degraded or converted to cropland at an alarming rate in southwestern China, particularly in Sichuan Province (An, 1997). Land use changes may influence many natural phenomena and ecological processes, including soil nutrients and soil water change (Fu, 1999; 2000). The processes greatly impact the direction and degree of soil quality changes in time and space (Wang, 1998). Soil quality has been defined by many authors in recent years (Pennock, 1997). Soil changes are dynamic over time. Human-induced soil changes and their effects on human lives and ecological environments have received extensive attention (Fu, 2001). But in past studies on land use changes, limited attention has been paid to soil quality and its deterioration following the changes (Jamal, 1998).

Soil nutrients can be changed by the processes that forest is cleared for agricultural cultivation or allowed to revert to natural vegetation or replanted to perennial vegetation. Assessment of soil quality upon conversion of natural forests for varying purposes is of great importance to detect early changes in soil quality. Little study has focused on the soil nutrients and quality changes in post-deforestation processes of succession in the southwestern China (An, 1997). There is a need for research to be conducted under that humid region conditions to determine the effect of land use changes from natural forest to different land use types.

Due to large number of physical and chemical indicators of soil, many methods were proposed to integrate the factors and quantify the soil quality (Adejuwon, 1988). But few studies had the comparison of different methods. Also single soil property evaluations, such as changes in SOM, N, P and K were usually emphasized, and much less attention was paid to a comprehensive assessment of soil quality changes. The results form different researchers are difficult to compare because of the different benchmark soils they used, and therefore, the rate of soil changes can not be accurately assessed and compared (Wang, 1998).

In this study an integrated soil quality index was advanced and the results were compared with soil deterioration index. The objectives of the present study were to (1) analyze the soil quality change of different land uses due to human disturbance and natural succession; (2) compare the two methods in the evaluation of soil quality change.

1 Materials and methods

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1.1 Description of study area

Wolong Nature Reserve (102.52'—103.25'E, 30.45'—31.25'N) was established in 1963 with an original protected area of 200 km² and enlarged to 2000 km² in 1975. The study area was originally covered with original forests and experienced high rates of deforestation and secondary succession. Over the years, people living in the surrounding villages have often encroached upon and cultivated agricultural crops in the clear-felled forestland. These intense human activities have hampered the regeneration of existing residual vegetation on clear-felled lands but there were also artificial forests plantation.

Elevation in the reserve ranges from 1150—6250m above sea level and the research sites were limited to the 1800 to 2500m to avoid the effect of climate and parent material. The soil was classified as humic aerisols. The climate of the study area is interior mountain climate with pronounced wet and cool seasons. The mean annual temperature is 8.5 ± 0.5°C, while the mean annual precipitation is about 890 ± 100 mm. Relative humidity ranges between 75.5 % and 84.8 %.

1.2 Soil sampling methods and processing

In order to assess effects of land use changes on soil properties in the study area, surface soil samples were collected from sites which had the similar landscape properties. The land use types were catalogued into natural forestland, grassland, shrub land, secondary forestland, cultivated land and reforested land. The reason of this selection is that secondary succession after deforestation in Wolong nature reserve generally followed the sequence of grass, shrub, secondary forest and natural forest.

Soil samples (0—30 cm) were collected from different land uses of the adjacent sites and the sample number for natural forestland, grassland, shrub land, secondary forestland, cultivated land and reforested land was 14, 12, 24, 6, 8 and 15, respectively. The examined soil properties included soil bulk density (BD), soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), available nitrogen (AN), available potassium (AK) and available phosphorus (AP). The determinations of them were according to China standard method (Editorial Committee, 1996).

1.3 Calculation of integrated soil quality indices (QI)

Due to the successive property of soil quality change, the continuous membership functions (\( Q(x_i) \)) were used for the evaluation index (Li, 1991). The ascending and descending property of the functions was determined by the positive and negative value of capacity score coefficient of principle component analysis. The values are also in accord with the vegetation effects on their corresponding factors. The ascending function and descending function were listed below:

\[
Q(x_i) = \frac{(x_i - x_{min})}{(x_{max} - x_{min})}, \quad (1)
\]

\[
Q'(x_i) = \frac{(x_{max} - x_i)}{(x_{max} - x_{min})}, \quad (2)
\]

where \( Q(x_i) \) is the membership value of each soil quality factor; \( x_i \) is the values of soil physical and chemical properties which were selected for the soil quality; \( x_{max} \) and \( x_{min} \) are the maximum and minimum value of the i soil property.

The condition or importance to soil quality of each indicator was indicated by a weighting coefficient. In this study, the cumulative percentage of principal soil quality components and values of component capacity score coefficient were calculated by the membership values using SPSS program, and weights of the soil quality factors \( w_i \) were calculated by component capacity score coefficient (Eq. (3)).

\[
w_i = \frac{component \ capacity_i}{\sum_{i=1}^{n} (component \ capacity_i) }, \quad (3)
\]

where component capacity, is component capacity score coefficient of i soil quality factor.

Based on the addition and multiplication principle, the integrated quality index (QI) was calculated by following equations (Zhang, 1999):

\[
QI = \sum_{i=1}^{n} w_i \times Q(x_i), \quad (4)
\]

where \( w_i \) is the weight vector of i soil quality factor.

1.4 Calculation of soil deterioration indices (DI)

The soil deterioration index (DI; Adejuwon, 1988) was computed on the assumption that the status of individual soil property under shrubs, artificial woods, grass, secondary forest and cultivation were once the same as that of adjacent soils under the well-stocked natural forest before conversion. The equation of DI was expressed below:
where $x_i$ is the value of soil physical and chemical properties selected for the soil quality; $x_i'$ is the property under natural forest condition. Negative value of the BD difference was used for that higher BD value usually indicated land deterioration tendency (Lowery, 1995).

2 Results and discussion

2.1 Land use changes in Wolong Nature Reserve

Human disturbance in Wolong Nature Reserve caused heterogeneity mainly around the living area below 3000m. It was generally recognized that the land use change started form the areas near villages and extended to mountainous area. After the land reform in 1981, the plantation forest land increased a little. But landscape pattern still changed a lot especially in the areas where farmers live.

Fig. 1 gave the area changed of different land use types in 1987 and 1997 of the whole nature reserve. The results showed that cultivated land accounted a large proportion, about 16.5%—18.4% of total area. Due to the increasing population pressure the cultivated area increased by 9.7% from 1987 to 1997. Since forest cutting was forbidden since the foundation of the reserve, the natural forest land area increased by over 9.0%. But the area of shrub land and secondary forestland in 1997 decreased compared with 1987, by 13.06% and 15.80% respectively. This is mainly because the increased firewood and timber demand of local inhabitants.

2.2 Effects of different land uses on soil properties after deforestation

Table 1 shows the effect of land use type on selected physical and chemical properties for soil quality of adjacent areas in Wolong area. Statistically significant differences were found in SOC, TN, BD, AP and AK among the six land use types. SOC and TN of cultivated land were dramatically lower than of other land uses, but BD was higher. Shrub land had the highest SOC and TN values. Close observation of Table 1 showed that TP, TK, AN, AP, AK showed the lowest or lower values in cultivated land.

<table>
<thead>
<tr>
<th>Land-use types</th>
<th>Natural forestland</th>
<th>Secondary forestland</th>
<th>Shrub land</th>
<th>Reforested land</th>
<th>Cultivated land</th>
<th>Grassland</th>
<th>$F$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size</td>
<td>14</td>
<td>6</td>
<td>24</td>
<td>15</td>
<td>8</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>BD, g/cm³</td>
<td>0.72 (0.08)</td>
<td>0.88 (0.18)</td>
<td>0.84 (0.19)</td>
<td>0.99 (0.17)</td>
<td>1.17 (0.15)</td>
<td>1.03 (0.21)</td>
<td>5.71**</td>
</tr>
<tr>
<td>SOC, g/kg</td>
<td>17.76 (8.77)</td>
<td>58.18 (8.77)</td>
<td>81.33 (12.12)</td>
<td>44.51 (18.98)</td>
<td>33.12 (7.42)</td>
<td>60.24 (7.20)</td>
<td>5.99**</td>
</tr>
<tr>
<td>TN, g/kg</td>
<td>4.45 (2.04)</td>
<td>5.49 (3.09)</td>
<td>6.16 (2.22)</td>
<td>3.82 (0.71)</td>
<td>3.18 (0.95)</td>
<td>4.24 (2.70)</td>
<td>2.58**</td>
</tr>
<tr>
<td>TP, g/kg</td>
<td>1.01 (0.22)</td>
<td>1.07 (0.18)</td>
<td>1.04 (0.22)</td>
<td>0.97 (0.07)</td>
<td>1.00 (0.17)</td>
<td>0.98 (0.17)</td>
<td>0.58**</td>
</tr>
<tr>
<td>TK, g/kg</td>
<td>21.85 (7.73)</td>
<td>21.38 (3.95)</td>
<td>22.02 (6.00)</td>
<td>21.27 (6.00)</td>
<td>17.90 (4.61)</td>
<td>21.61 (4.06)</td>
<td>0.30**</td>
</tr>
<tr>
<td>AN, mg/kg</td>
<td>1098.26 (218.96)</td>
<td>1073.57 (395.13)</td>
<td>1247.86 (256.08)</td>
<td>998.24 (75.60)</td>
<td>978.56 (277.99)</td>
<td>982.93 (277.99)</td>
<td>1.05**</td>
</tr>
<tr>
<td>AP, mg/kg</td>
<td>16.00 (4.34)</td>
<td>15.96 (4.65)</td>
<td>14.88 (5.91)</td>
<td>12.87 (5.45)</td>
<td>8.07 (4.03)</td>
<td>8.07 (4.51)</td>
<td>1.97**</td>
</tr>
<tr>
<td>AK, mg/kg</td>
<td>362.43 (195.50)</td>
<td>199.77 (54.33)</td>
<td>286.50 (164.71)</td>
<td>148.21 (48.85)</td>
<td>123.00 (23.33)</td>
<td>153.46 (46.82)</td>
<td>3.11**</td>
</tr>
</tbody>
</table>

Notes: BD = bulk density, SOC = soil organic carbon, TN = total nitrogen, TP = total phosphorus, TK = total potassium, AN = available nitrogen, AP = available phosphorus, AK = available potassium; numbers in the brackets are standard deviations; * . significant; ** . very significant; n.s. not significant
Soil organic carbon, as a major attribute of soil quality, is responsive to agricultural land use practice including tillage. The result indicated that land use changes influence soil nutrient process and human disturbance could cause soil nutrient loss (Fu, 2000; 2001). The results showed that cultivation decreased soil nutrient levels (Davidson, 1993). Conditions under the shrubs are suitable for the SOC accumulation due to their largest layer coverage, species number, richness and lower light penetration. The vegetation coverage, richness of different ecosystems during secondary succession varied a lot, and so altered the ecosystem biomass and the micro-environmental conditions such as light, water and soil microorganism.

2.3 The QI value of different land use types

The calculated integrated soil quality index (QI) reflects the relative soil quality degree of different land use types. Using Eq. (1) and Eq. (2), the membership value \( Q(x_i) \) of each soil quality factor was calculated (Table 2). Table 3 shows the results of the cumulative percentage of principal soil quality components, values of component capacity score coefficient and weights of the soil quality factors (\( W_i \)) using Eq. (3). \( W_i \) was calculated by the first component capacity score due to its cumulative percentage had reached 72.55%. The integrated quality index (QI) was further derived from Eq. (4).

<table>
<thead>
<tr>
<th>Soil quality factors</th>
<th>Natural forestland</th>
<th>Secondary forestland</th>
<th>Shrubs land</th>
<th>Reforested land</th>
<th>Cultivated land</th>
<th>Grassland</th>
</tr>
</thead>
<tbody>
<tr>
<td>BD</td>
<td>1</td>
<td>0.3184</td>
<td>0.7374</td>
<td>0.6378</td>
<td>0</td>
<td>0.3982</td>
</tr>
<tr>
<td>SOC</td>
<td>0.6658</td>
<td>0.5625</td>
<td>1</td>
<td>0.5197</td>
<td>0</td>
<td>0.2362</td>
</tr>
<tr>
<td>TN</td>
<td>0.429</td>
<td>0.3573</td>
<td>1</td>
<td>0.7767</td>
<td>0</td>
<td>0.2169</td>
</tr>
<tr>
<td>TP</td>
<td>0.4074</td>
<td>0.6014</td>
<td>0.6532</td>
<td>0.8459</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TK</td>
<td>0.9592</td>
<td>0.9011</td>
<td>1</td>
<td>0.3528</td>
<td>0</td>
<td>0.0731</td>
</tr>
<tr>
<td>AN</td>
<td>0.4458</td>
<td>0.0162</td>
<td>0.8581</td>
<td>0.9954</td>
<td>0</td>
<td>0.6056</td>
</tr>
<tr>
<td>AP</td>
<td>1</td>
<td>0.3184</td>
<td>0.7374</td>
<td>0.6378</td>
<td>0</td>
<td>0.3982</td>
</tr>
</tbody>
</table>

Table 2 Membership function values of soil quality factor of different land use types

<table>
<thead>
<tr>
<th>Component number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of variance</td>
<td>72.55</td>
<td>12.55</td>
<td>7.73</td>
<td>5.66</td>
<td>1.51</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative percentage</td>
<td>72.55</td>
<td>85.10</td>
<td>92.83</td>
<td>98.49</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Component capacity score</td>
<td>0.159</td>
<td>0.157</td>
<td>0.155</td>
<td>0.111</td>
<td>0.116</td>
<td>0.152</td>
<td>0.154</td>
<td>0.145</td>
</tr>
<tr>
<td>Weight</td>
<td>0.136</td>
<td>0.134</td>
<td>0.133</td>
<td>0.095</td>
<td>0.116</td>
<td>0.130</td>
<td>0.132</td>
<td>0.124</td>
</tr>
</tbody>
</table>

Table 3 Cumulative percentage of principal soil quality components, values of component capacity score coefficient and weights of the soil quality factors

Fig. 2 shows the QI values of different land use types. The results clearly showed that the drastic land use changes had resulted in very different soil quality levels. The QI values for natural forestland, grassland, shrub land, secondary forestland, cultivated land and reforested land were 0.8039, 0.3277, 0.9127, 0.6881, 0.0285 and 0.3183 respectively. Shrub land had the highest value while cultivated land exhibited the lowest value. The results validated again that cultivation could lower soil quality levels. The reforested land and grassland showed lower QI than natural forestland mainly because of the human disturbance and the animals grazing activity. In contrast, QI of shrub land and secondary forestland were higher, indicating they can restore soil nutrients. The more complex community of shrub and secondary forest might be a reason for this change. Thus shrub maybe is an optional choice to restore the soil properties as they can decrease soil erosion and improve soil conditions at the ecosystems scale (Wang, 2000). For some area, it is better to
change cultivated land or grassland to shrubs due to the finance or labor shortage.

2.4 The DI value of different land use types

Soil deterioration index (DI) can be regarded as an indication of soil deterioration (improvement) degree. The calculated DI reflects the percent changes in soil properties from their values under natural forest (Fig. 3). In our study soils under cultivation had a significantly lower (i.e., negative) DI (−26%) than soils under the other land use types. The reforested lands also had a low DI (−18%) because some reforested lands were formerly cultivated for agricultural use. DI of natural secondary succession after deforestation (grass, shrubs and secondary forest) changed dramatically. DI for soils under shrubs and secondary forest were actually positive (12% and 1%), but the grassland had a negative DI value (−14%).

Compared with other studies, the DI value in cultivated land and the change between different ecosystems were far less (Islam, 2000; Wang, 2000). The cool, humid climate of Wolong maybe is also a factor to the mild soil change of different land uses for the easy soil organic matter accumulation in the native state (Davidson, 1993).

2.5 Comparison of the two quantitative methods

The QI and DI values of different land use types exhibits the same tendency, but the values have different ecological meanings. To make a clearer and more direct comparison, a deduced index (QI′) was cited as Eq. (6).

\[
QI' = \left(\frac{QI - QI_{nf}}{QI_{nf}}\right) \times 100\% , \quad (6)
\]

where the QI, is the integrated quality index of different land use types; QI_{nf} is the integrated quality index of natural forestland. The treatment method was somewhat similar to DI. Fig. 4 gave the comparison of QI′ and DI of six different land use types. The results showed that though the two indices have different values (QI′ values range from −96% to 14%, while DI values range from −26% to 12%). The positive linear relationship between QI′ and DI had a high correlation coefficient (r = 0.9775).

The comparison results showed that both the quantitative methods were efficient in evaluating the soil quality levels. Soil deterioration index (DI) method is a more simple and direct way to determine the changes of soil nutrients. Due to the larger variation range of QI′, integrated soil quality index (QI) method maybe is a better way to discern the small change of land use change such as continuous succession. Also the calculation process of QI contains more ecological meanings.

3 Conclusions

Subsequent secondary succession after forest cutting and human disturbance caused ecosystem heterogeneity in Wolong Nature Reserve. The cultivated land area increased 9.7% from 1987 to 1997 due to the increasing population pressure. In this
study, soil quality of six typical land use types were compared with two different quantitative methods. ANOVA showed that there were significant differences for soil properties among land uses. Soil nutrients in the cultivated land had lower levels than other land uses but the BD had higher values. Both the integrated soil quality index (QI) and soil deterioration index (DI) showed the same tendency of soil quality levels of different land use types, i.e., shrub land > natural forestland > secondary forestland > grassland > reforested land > cultivated land. This means shrub land maybe is an optional choice to restore the soil properties for the areas where the conditions are suitable for shrubs secondary succession.

A deduced index (QI') calculated from the QI value was proposed to make a clearer and more direct comparison of the two quantitative methods. The results exhibited the QI' and DI had a high positive linear relationship correlation coefficient (r = 0.9775), thus both the quantitative methods were efficient in evaluating the soil quality levels.

References:


Fu B J, Chen L D, Ma K M et al., 2000. The relationships between land use and soil conditions in the hilly area of the loess plateau in northern Shaanxi, China[J]. Catena, 39:69—78.


