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Integrated evaluation of soil fertility based on grey correlation analysis at regional scales

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This paper reports on studies of soil samples from the region of Xiaoliang water conservation station, in China, and its naturally restored forest. 32 indices based on the physical, chemical, microbiological and enzyme properties of the soil are studied, from 9 different vegetation patterns at 45 observation points. Grey correlation analysis and integrated evaluation is used for the analysis of soil fertility. From experimental measurements, it is shown that the integrated evaluation of the sample soil fertility by grey correlation analysis provides excellent agreement with the actual soil characteristics. Eucalyptus may be considered as a primary forest choice to recover bare land, however, it is not suitable for long-term planting and cropping since it will eventually result in degradation of soil fertility, and is therefore not favourable for long-term ecological restoration. Nevertheless, if chosen, additional actions can be taken to benefit soil fertility, such as regular changes of breed variety, crop rotation, mixing with broad-leaf forest, protecting undergrowth vegetation and reducing forest litter coverage.

Key words: Grey correlation, integrated evaluation, regional scale, soil fertility, water conservation station.

INTRODUCTION

Soil clearly represents one of the most important constituents of a forest ecological system, and its quality directly affects the health of the whole forest ecosystem, and which influences the sustainable development of the economy of human society (Pamela and John, 2003; Wienhold et al., 2004; Zhong et al., 2005; Dadhwal et al., 2011; Thierfelder and Wall, 2012). Soil affects land productivity and its sustainable use through processes of degradation and protection. It is governed by the interactions of the physical, chemical and biological characteristics of soil, and is also influenced by soil management (Eugène et al., 2010; Pinho et al., 2012). Soil quality assessment is based on the soil function to determine the criteria for quantitative assessment. Quality assessment is the most effective method to determine the dynamic change of soil conditions, reflecting changes of soil management and also the capability of soil to recover from degradation (Huang and Yang, 2009; Bautista-Cruz et al., 2011). The essence of soil quality is soil productivity, and its basis is soil fertility. Soil degradation is a process of decreasing soil productivity, which is affected mainly by mechanical, chemical and biological factors, where the soil characteristics are further affected by artificial interference that is, soil

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management (Huang, 2004; Eni et al. 2010). It is important to give consideration to the selection of soil quality assessment indices and in choosing their relative weightings. According to previously reported research, the indices for soil quality assessment is primarily related to the physical properties, such as unit mass, density and water content, the chemical properties, including pH, cation exchange capacity, and the nutrition content of N, P, K, etc. (Zhang et al., 2002); the biological properties (Hamer et al., 2009), including soil respiration and microbial biomass, and the enzyme activity properties (Kiss et al., 1998).

In this paper, the mechanical, chemical, microbiological and enzyme activity properties are used as a primary methodology for soil quality assessment, and 32 sub-system indices including the water content, unit weight, porosity, etc. are used as a secondary indexing system. The integrated evaluation of soil quality is performed by grey correlation analysis (Liu and Dang, 2008). The aim of the paper is to gain knowledge of the soil quality and its degradation degree in order to provide scientific evidence for ecological restoration, increasing land productivity and promoting the sustainable development of the forest economy.

OVERVIEW OF THE RESEARCH REGION

Xiaoliang water conservation station is on the costal terraced land in the southwest of Xiaoliang town, Dianbai county, Maoming City, Guangdong Province, China, with geographic location of 110°54′18″E, 21°27′49″N. The area of the station is 288.87 m^2. The greatest highest height above sea level is 36 m. It belongs to the northern tropical maritime monsoon climate, and the annual average temperature is 23°C, with the highest temperature 36.5°C, and the lowest 4.7°C. The yearly average precipitation is 1442 mm, and the hyetograph is extremely non-uniform. Patterns of rainfall are normally convectional rain and typhoon rain. Most of the rainfall occurs between June and August. There are obvious divisions between the dry and rainy seasons. The annual average evaporation is 2100 mm. Zonal soils are mostly pebbly clay lateritic, derived from granite parent materials. The top vegetation plant cover is tropical monsoon forest (Liu and Li, 2009).

METHODOLOGIES

Collection of soil samples

The collection of forest soil samples are at the same time period and under similar site conditions. The soil samples are collected from the different vegetation patterns: mixed forest, pure eucalyptus forest and bare land, separately. According to the vegetation patterns and the planting time, 9 sample areas are chosen in, and around, Xiaoliang water conservation station for investigation. 5 sample plots are chosen in each sample area, in an ‘X’ formation. A profile is dug in each sample plot. The soil profile is at the concentrated distribution area of the forest root growth, ~ 1 m from the tree trunk, avoiding the fertilization spot and the manual farmland soil. The soil samples are gathered evenly from bottom to top on the 0 ~ 60 cm soil profile in 3 layers. The mass of the soil sample from every profile layer is 0.2 kg, which is further mixed to form one soil sample with a mass of 1 kg. The soil samples are subsequently taken to the laboratory for physical, chemical, microbiological and enzyme activity testing (Carter, 1993; Sparks, 1996; Sarkar, 2005).

Pre-processing of soil samples

Soil samples gathered from the field are pre-processed in the laboratory prior to subsequent testing and analysis. The purpose of sample pre-processing is, (1) to prolong the service of the samples and reduce deterioration due to microbial activity, (2) to assure the results of analysis represent the original composition of the soil by removing non-soil particles from the samples, (3) to make the analysis samples more representative and to reduce the errors on sample mass by adequate grinding and full blending of the field samples, (4) to maintain consistency of the reactions of the testing soil solutions by increasing the surface area of the soil particles through grinding of the field samples.

Conventional pre-processing of soil samples

Conventional processing of soil samples use air-drying, grinding, screening, blending, separating, weighing and storage. The field forest soil samples are air-dried immediately to avoid the samples becoming moldy and affecting their quality. The processing method is to break the soil sample into small pieces and spread them flat onto a thin layer on clean paper in a cool, well-ventilated environment, turning them regularly to accelerate the drying. Direct sunlight is avoided. The soil samples are then grinded, screened, blended and separated into suitable analysis samples.

Processing for special soil samples

To analyse the physical properties of soil, 100 ~ 200 g of air-dried samples are used, and any large organic materials and stone blocks are picked out, grinded, screened by sieve No. 6 ~ 7 (3 mm) and sieve No. 8 (1 mm). The fine gravels of the scale of 1 ~ 3 mm, are weighed. Meanwhile the soil samples after sieve size of 1 mm are weighed, and the percentage of 1 ~ 3 mm fine gravels, is calculated. Finally, after blending, the soil samples are placed into a wide-mouthed container for an analysis of particles and testing of other physical properties. If iron manganese concretions or calcareous concretions exist, they are carefully removed and weighed for further analysis and testing.

Testing methods for the soil samples

The soil samples, after pre-processing, are used for tests of their physical, chemical, biological and enzyme activity properties. The measurement results are given in Appendix Table 1. The following list provides the testing method of each property:

(i) Water content in soil – oven-drying method;
(ii) Specific weight – pycnometer;
(iii) Physical composition of soil – densimeter;
(iv) pH of soil – potentiometric method;
(v) Organic content in soil – potassium dichromate oxidation-reduction titration method;
(vi) Nitrogen content in soil – Kjeldahl nitrogen determination method;

Table 1. Average testing values of the physical properties of soil in sample areas.

Sample areas	Naturally restored forest	Broad-leaved forest	Eucalyptus pine mixed forest	Bare land	W5.41	W5.44	W5.34	W5.31	U6.31
Unit weight (g cm^{-3})	1.383	1.660	1.673	1.677	1.683	1.717	1.720	1.720	1.770
Specific weight (g cm^{-3})	2.543	2.593	2.540	2.577	2.637	2.660	2.653	2.607	2.607
Rock content (%)	21.233	25.640	21.727	21.213	20.580	20.967	20.573	20.563	20.570
Clay content(%)	35.160	30.340	34.480	38.250	32.397	32.253	40.430	32.153	32.387
Gross porosity (%)	37.743	35.090	37.403	31.953	36.283	36.213	34.293	36.957	37.597
Capillary porosity (%)	28.383	27.410	31.797	26.447	30.070	27.830	28.077	32.807	32.880
Noncapillary porosity (%)	9.360	7.683	5.607	5.507	6.213	8.383	6.250	4.150	4.720
Natural water content (%)	16.910	16.500	12.523	9.090	7.113	7.150	11.373	6.197	6.167
Soil hygroscopic water (%)	1.207	1.003	0.633	0.590	0.853	0.863	1.063	0.867	0.853
Field water capacity (%)	17.927	16.283	19.997	15.083	17.900	16.403	16.107	19.963	20.213

(vii) Variation of alkaline hydrolysis nitrogen – alkali -hydrolyzed diffusing method;
(viii) Total phosphorus in soil – NaOH fusion–Mo-Sb anti spectrophotometric method;
(ix) Available phosphorus in soil – 0.05 mol L^{-1} HCl - 0.025 mol L^{-1} (1/2) H_2SO_4 bleaching solution – anti-spectrophotometric method;
(x) Total potassium in soil – NaOH fusion flame photometry;
(xi) Available potassium in soil – 2 mol L^{-1} HNO_3 bleaching solution-flame photometry;
(xii) Microbial biomass in soil – beef extract plate method to determine the biomass of bacteria, fungus and actinomyces;
(xiii) Soil respiration and induced respiration – isolation tank-alkaline solution absorption method;
(xiv) Urease activity in soil – indophenol blue colorimetric method;
(xv) Soil phosphatase activity – disodium phenyl phosphate colorimetry;
(xvi) Saccharase activity – 3, 5-dinitrosalicylic acid colorimetry.

RESULTS AND ANALYSIS

The physical properties of soil provide a comprehensive reflection of its basic features, and are an amalgamation of many factors. They also affect the soil productivity. The analysis is typically complex with many inter-related factors influencing quality (Wang et al., 2007; Yusuf and Yusuf, 2008; Adesanwo et al., 2009; Belachew and Abera, 2010). The grey system theory is based on an analysis and determination of the interactions between many inter-related factors and their contributions to the principal characteristics, according to relative similarities and differences. It is a quantitative assessment method, providing a magnitude, direction and speed of the factors in the system process. If the relative change between two factors is consistent, they are considered to have high correlation. The grey correlation degree is the index for the uncertainties between the factors, or those between a factor and the principal characteristic. From the sample areas chosen here, the physical properties of soil can be analyzed with respect to correlations between factors such as soil unit mass, specific weight, content of rock fragments, content of clay, porosity, water content, among others.

From a random factor sequence, the correlation can be calculated to determine their contribution to the soil fertility through a quantitative analysis of the physical properties. The method is proved to be effective, efficient and intuitive. The procedure for grey correlation analysis for the 9 sample plots is as follows:

(1) Determine the reference sequence of the factors:

$X_0=\{X_{01}, X_{02}, X_{03}, \ldots, X_{0n}\}$ (K=1, 2,… , n);
$X_0=\{1.383, 2.540, 20.563, 40.430, 37.743, 32.880, 9.360, 16.910, 1.207, 20.213\}$;

(2) Determine the comparative sequence of the factors:

$X_i=\{X_{i1}, X_{i2}, X_{i3}, X_{in}\}$ (i=1,2,3,… , m; K=1,2,… , n;)

Where X_1={naturally restored forest}; X_2={broad-leaved forest}; X_3={eucalyptus pine mixed forest }; X_4={bareland}; X_5={W5.41}; X_6={W5.44}; X_7={W5.34};

Table 2. The physical properties of soil after nondimensionalization.

Sample areas	Naturally restored forest	Broad-leaved forest	Eucalyptus pine mixed forest	Bare land	W5.41	W5.44	W5.34	W5.31	U6.31
Unit weight	1.000	1.200	1.210	1.213	1.217	1.242	1.244	1.244	1.280
Specific weight	1.001	1.021	1.000	1.015	1.038	1.047	1.044	1.026	1.026
Rock content	1.033	1.247	1.057	1.032	1.001	1.020	1.000	1.000	1.000
Clay content	0.870	0.750	0.853	0.946	0.801	0.798	1.000	0.795	0.801
Gross porosity	1.000	0.930	0.991	0.847	0.961	0.959	0.909	0.979	0.996
Capillary porosity	0.863	0.834	0.967	0.804	0.915	0.846	0.854	0.998	1.000
Noncapillary porosity	1.000	0.821	0.599	0.588	0.664	0.896	0.668	0.443	0.504
Natural water content	1.000	0.976	0.741	0.538	0.421	0.423	0.673	0.366	0.365
Soil hygroscopic water	1.000	0.831	0.524	0.489	0.707	0.715	0.881	0.718	0.707
Field water capacity	0.887	0.806	0.989	0.746	0.886	0.812	0.797	0.988	1.000

X_8={W5.31}; X_9={U6.31}*. The average testing values of the mechanical properties of soil are listed in Table 1.

(3) Nondimensionalization of the data: Because the units of the collected data and the physical significance of the factors are different, to make sure the equivalence of each factor, the original collected data is nondimensionalized, by $X_i' = X_i/X_0$. The data, after nondimensionalization is listed in Table 2.

(4) Calculate the absolute difference sequence – Define $\Delta 1=|A_0(K)-A_1(K)|$; $\Delta 2=|A_0(K)-A_2(K)|$; and so on. The absolute differences are listed in Table 3.

(5) Find the maximum and minimum differences: The maximum difference is: $M=\max_i.\max_k \Delta_i(K)$, M=0.635; and the minimum difference is: $m=\min_i.\min_k \Delta_i(K)$, m=0.000.

*U6.31: Eucalyptus urophylla asexual plantation, the third crop annual eucalyptus; W5.31: Eucalyptus ABL12 asexual plantation, the third crop annual eucalyptus; W5.34: Eucalyptus ABL12 asexual plantation, the third crop four yearly eucalyptus; W5.41: Eucalyptus ABL12 asexual plantation, the fourth crop annual eucalyptus; W5.44: Eucalyptus ABL12 asexual plantation, the fourth crop four yearly eucalyptus.

(6) Calculate the correlation coefficients, as listed in Table 4: p=0.5

$$\eta_{0i}(\kappa)=\frac{P\min.\min\left|\chi_0(\kappa)-\chi_i(\kappa)\right|+P\max.\max\left|\chi_0(\kappa)-\chi_i(\kappa)\right|}{\left|\chi_0(\kappa)-\chi_i(\kappa)\right|+P\max.\max\left|\chi_0(\kappa)-\chi_i(\kappa)\right|}$$

(7) The correlation degrees (Table 5) are calculated from

$$\tau_i=\frac{1}{n}\sum_{k=1}^{n}\eta_i(k)$$

(8) Analysis of the results: The results show that, r1 > r3 > r9 > r8 = r7 > r2 > r5 > r6 > r4, where ri > rj, showing that the grey correlation degree of X_i with respect to reference X_0 is higher than X_j. The higher the correlation degree, the stronger the relationship exists between it and the reference factor. Here, it is shown that the naturally restored forest provides the best physical properties, and bare land yields the poorest. The relative order of the 9 sample areas, with respect of the physical properties of soil, in descending order is: naturally restored forest > eucalyptus pine mixed forest > U6.31 > W5.31 = W5.34 > broad-leaved forest > W5.41 > W5.44 > bare land.

Using the same procedure as above, the grey correlation degrees for the chemical properties of soil are listed in Table 6, for microbiological properties in Table 7, and for enzyme activities in Table 8. The results of the grey correlation degrees for the chemical properties of soil in Table 6 show that, r1 > r2 > r9 > r6 > r3 > r8 > r5 > r7 > r4. The results of the grey correlation degrees for the microbiological properties of soil in Table 7 show that, r1 > r2 > r3 > r7 > r9 > r8 > r5 > r6 > r4. It is shown from the results of the grey correlation degrees for the enzyme activity in soil in Table 8 that, r1 > r2 > r3 > r9 > r5 > r8 > r7 > r6 > r4.

Integrated evaluation of the soil fertility

The degradation of soil productivity is a process of decreasing soil fertility, which is a comprehensive reflection of the degradation of its physical, chemical, microbiological and enzyme activity properties. Based on the results from the grey correlation analysis, a comprehensive index of soil

Table 3. The physical properties of soil in order of absolute difference.

S/No	∆1	∆2	∆3	∆4	∆5	∆6	∆7	∆8	∆9
1	0.000	0.200	0.210	0.213	0.217	0.242	0.244	0.244	0.280
2	0.001	0.021	0.000	0.015	0.038	0.047	0.044	0.026	0.026
3	0.033	0.247	0.057	0.032	0.001	0.020	0.000	0.000	0.000
4	0.130	0.250	0.147	0.054	0.199	0.202	0.000	0.205	0.199
5	0.000	0.070	0.009	0.153	0.039	0.041	0.091	0.021	0.004
6	0.137	0.166	0.033	0.196	0.085	0.154	0.146	0.002	0.000
7	0.000	0.179	0.401	0.412	0.336	0.104	0.332	0.557	0.496
8	0.000	0.024	0.259	0.462	0.579	0.577	0.327	0.634	0.635
9	0.000	0.169	0.476	0.511	0.293	0.285	0.119	0.282	0.293
10	0.113	0.194	0.011	0.254	0.114	0.188	0.203	0.012	0.000
min	0.000	0.021	0.000	0.015	0.001	0.020	0.000	0.000	0.000
max	0.137	0.25	0.476	0.511	0.579	0.577	0.332	0.634	0.635

Table 4. The correlation coefficients of the physical properties of soil.

S/No	n01	n02	n03	n04	n05	n06	n07	n08	n09
1	1.000	0.613	0.602	0.599	0.594	0.568	0.566	0.566	0.532
2	0.996	0.938	1.000	0.956	0.893	0.870	0.877	0.923	0.923
3	0.907	0.563	0.849	0.909	0.997	0.942	0.998	1.000	0.999
4	0.709	0.560	0.683	0.855	0.615	0.611	1.000	0.608	0.615
5	1.000	0.819	0.972	0.674	0.891	0.887	0.776	0.938	0.988
6	0.699	0.656	0.906	0.619	0.788	0.674	0.685	0.993	1.000
7	1.000	0.639	0.442	0.435	0.486	0.753	0.489	0.363	0.390
8	1.000	0.929	0.550	0.407	0.354	0.355	0.492	0.334	0.333
9	1.000	0.653	0.400	0.383	0.520	0.527	0.727	0.530	0.520
10	0.737	0.620	0.967	0.556	0.735	0.627	0.610	0.963	1.000

Table 5. Grey correlation degrees of the physical properties of soil.

r1	r2	r3	r4	r5	r6	r7	r8	r9
0.905	0.699	0.737	0.639	0.687	0.681	0.722	0.722	0.730

Table 6. Grey correlation degrees of the chemical properties of soil.

r1	r2	r3	r4	r5	r6	r7	r8	r9
0.648	0.605	0.517	0.457	0.488	0.518	0.486	0.495	0.527

Table 7. Grey correlation degrees of the microbiological properties of soil.

r1	r2	r3	r4	r5	r6	r7	r8	r9
0.6792	0.6065	0.5289	0.4696	0.5034	0.4912	0.5256	0.5115	0.5158

fertility assessment is calculated from the contribution scores, in order to evaluate the levels of productivity for the different vegetation patterns. From the comparisons, it is shown that pure eucalyptus forest has negative

Table 8. Grey correlation degrees of the enzyme activities in soil.

r1	r2	r3	r4	r5	r6	r7	r8	r9
0.7085	0.6530	0.6398	0.4098	0.5222	0.5065	0.5085	0.5107	0.5248

Table 9. The integrated evaluation of the soil quality from 9 sample areas.

Sample areas	Physical properties	Chemical properties	Microbiological properties	Enzyme activities	Average	Level
r1	0.9	0.9	0.9	0.9	0.90	Very good
r2	0.4	0.8	0.8	0.8	0.70	Relatively good
r3	0.8	0.5	0.7	0.7	0.68	Relatively good
r4	0.1	0.1	0.1	0.1	0.10	Very poor
r5	0.3	0.3	0.3	0.5	0.35	Relatively poor
r6	0.2	0.6	0.2	0.2	0.30	Relatively poor
r7	0.55	0.2	0.6	0.3	0.41	Relatively poor
r8	0.55	0.4	0.4	0.4	0.44	Relatively poor
r9	0.7	0.7	0.5	0.6	0.63	Relatively good

effect on the soil productivity. According to results from the 9 sample areas, they are categorized into 5 levels: very good (0.8 ~ 0.9); relatively good (0.6 ~ 0.7); moderate (0.5); relatively poor (0.3 ~ 0.4); very poor (0.1 ~ 0.2), and are listed in Table 9.

Conclusion

The proposed analysis techniques have been employed for the first time to provide an integrated evaluation of soil fertility. As shown, the proposed use of grey correlation analysis provides good agreement with the actual properties of the differing vegetation patterns. Key outcomes of the research are:

(1) From the evaluation scores, the soil fertility in descending order is: naturally restored forest (r1 = 0.9) > broad-leaved forest (r2 = 0.7) > eucalyptus pine mixed forest (r3 = 0.68) > U6.31 (r9 = 0.63) > W5.31 (r8 = 0.44) > W5.34 (r7 = 0.41) > W5.41 (r5 = 0.35) > W5.44 (r6 = 0.3) > bare land (r4 = 0.1).

(2) Through use of the proposed approach, the sample areas are categorized into 5 levels: Level 1 (very good) is the naturally restored forest, which shows that the soil productivity of natural forest is better than man-made forest. Increasing artificial interference hastens soil fertility degradation. Level 2 (relatively good) includes the broad-leaved forest, the eucalyptus pine mixed forest and the U6.31 pure eucalyptus forest, which shows that, among the planted forest, broad-leaved forest is better than eucalyptus pine mixed forest, which, in turn, is better than pure eucalyptus forest. Among pure eucalyptus forest, U6 clone forest shows better soil fertility than the W5 clone forest. Level 4 (relatively poor) is the pure eucalyptus forest. For the same species of W5 clone pure eucalyptus forest, the degradation of soil increases with increasing tree age and with cropping and planting. Level 5 (very poor) is the bare land, where due to the lack of vegetation protection, every characteristic that is assessed, is ranked as poor.

In summary, planting pure eucalyptus forest is beneficial for recovering land productivity, but it is not as good for soil fertility when compared with other types of vegetation. It is therefore concluded that eucalyptus can be used as a pioneer forest to recover the bare land, but it is not suitable for long-term planting and cropping, which can have detrimental effects on ecological restoration. When considering the planting of a pure eucalyptus forest, the following actions are advised in order to recover / maintain soil fertility viz. regular changes of tree species, crop rotation, mixing with broad leaf forest, saving forest litter coverage, etc.

Conflict of Interest

The authors have not declared any conflict of interest.

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