An Index System and Method for Soil Productivity Evaluation on the Hillsides in the Loess Plateau*

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Abstract: For a long time, soil productivity evaluation has been one of the hotspots in soil science. In this article, research conducted to investigate vertical root distribution characters, root drought-resistance ability, the soil physical and chemical properties and the local scio-economical conditions is reported. Based on the principle of the AHP (Analytical Hierarchy Process), a new method is proposed to evaluate the Current Soil Productivity(CSP) and Natural Soil Productivity(NSP). Calculated results indicated that the NSP of *Robinia pseudoacacia* in two villages was above the middle level, while the NSP of *Prunus armeniacia var. ansu*、*Pinus tabulaeformis Platycladus orientalis* was low. CSP of the *Robinia pseudoacacia* and *Prunus armeniacia var. ansu* was higher than the other two tree species. Although the NSP of the 4 tree species in the two villages was similar, the CSP results of the 4 tree species showed a remarkable change in the two villages studied. Further analysis indicated that the attitude and the recognition of the local people concerning problem associated with hillside development play an important role for the success of the hillside development program.
Keywords: hillside development, index system, AHP (Analytical Hierarchy Process), soil productivity evaluation

1 Introduction

In the arid and semiarid areas of the Loess Plateau in China, water is the limiting factor for local agriculture and forestry development (Changzhong Sun, 1998). Recent research (Changzhong Sun, 1998; K. W. Farrish, 1991) have verified that because of the intense absorption of water by the roots, there exists a sharp decrease of soil moisture in certain layers of the soil profile — desiccation layer. The soil moisture content in the desiccation layer lowers to a point that limits root system development at depth, and subsequently the utilization of water and nutrient in deep layer.

In the past, evaluation of the forestland productivity has always drawn the attention of forestry researchers, and many studies have been conducted. Methods of predicting site quality for forested sites have been a topic of much heated discussion since the early 1990s (Carmean, 1975). The use of soil information in the assessment of site quality has been a major part of this discussion. In most cases, people have elected to use site index as a measure of site quality. While site index has been useful, its estimate in stands that is too young, too old, uneven aged, or suppressed is questionable (M. R.Gale, 1991). To solve some of these problems while incorporating biological relationships into the estimation of site quality, new methods are needed for the rational and objective evaluation of the soil productivity that should contain both subjective and empirical information that relates soil properties to productivity.

In recent years, researches have been seeking after the method for soil productivity evaluation that is directly related to the tree growth factors (James A. Burger, 1996; Kiniry *et al*., 1983; M. R. Gale, 1991; K. S. Milner, 1996). The PI (Productivity Index) model developed by Kiniry in 1983 used an integrated approach to describe the relationship between plant productivity and soil properties on optimum vertical root distributions. The main assumption of the model is that a plant's vertical root distribution is genetically controlled and fully expressed under optimum soil/site conditions. If a soil/site property is limiting to root growth, changes from the optimum root distribution will occur, negatively affecting the aboveground biomass and reducing site quality. The *PI* model was:

$$PI = \sum_{i=1}^{r} (A \times B \times C \times D \times E \times RI)_i \quad (1)$$

where *A* is the sufficiency of available water capacity, *B* the sufficiency of aeration, *C* the sufficiency of bulk density, *D* the sufficiency of the pH, and *E* the electrical conductivity. These terms were normalized to range from 0.0 to 1.0.and related the levels of soil properties to their sufficiency, of which a value of 0 indicated an absolutely limiting level of a soil property and a value of 1.0 indicated the optimum level (Kiniry *et al.*, 1983;). The term *RI* is the optimum fraction of the total root found in a soil horizon that is defined as WF in other forms of the equations and calculated by the following equation in the refining models:

$$Y=1-ß^{d}$$

where the *Y* is the cumulative root fraction from the surface to soil depth *d* in centimeters, and *ß* the estimated parameters which was used as a measure or index of vertical root distribution. Generally, high values of *ß* are associated with a larger proportion of roots at deeper soil depth relative to low value of ß that is associated with a larger proportion of roots near the soil surface (E. L. Stone, 1991; R. B. Jackson 1996; M. R. Gale, 1987). Recent studies have verified that the value of *ß* varied with regions, species, and topography (E. L. Stone and P. J. Kalisz, 1991; R. B. Jackson, J. Canadell and Mooney. H. A, 1996; M. R. Gale and D. F. Grigal, 1987). Soil physical and chemical properties also have important effects on root distribution characters (U. M. Sainju and R. E. Good, 1993; Pu Mou, Robert J, .Mitohell and Robert H. Jones, 1997; Ronald L, Hendrick and Kurt S. Pregitzer, 1993; Peter R. Troyn, 1983). Also, vertical root distribution characters have close affinities to forest productivity, and productivity of species with a deep root system was higher than one with shallow roots (E. L. Stone and P. J. Kalisz, 1991; R. B. Jackson, J. Canadell and Mooney. H. A, 1996; M. R. Gale and D. F. Grigal, 1987; N. Bartsch, 1987), M.R.Gale (1991) has been successful in using this method for site quality prediction on white Spruce plantations in the USA. Similar studies are also conducted to evaluation the land productivity of corn and other species under different conditions (J.P.Wilson *et al.*, 1991; Rijsberman 1985; Burke T. H, 1984; Pierce F. J *et al.*, 1983; 1984).

Compared to the site index, the *PI* method is based on the logical express of direct effects of soil and site properties on vertical root distribution and subsequently on biomass production. It can be estimated for a wide range of forested and unforested sites and in stands that are young or old (M. R Gale, 1991). But in principle, the *PI* model failed to consider the contribution of every factor to site productivity and cannot release in mechanism the differences of vertical root distributions among species, which limit its application.

In 1990s, with the popularization of sustainable development, the conflict among the human populations-resources-environment become increasing intense (Bojie Fu, 1997), requiring an understanding of land degradation under different utilization and management regimes (J.P.Wilson, 1991). The effects of socioeconomic factors on achieving land potential productivity become more and more important, and are recognized as main factors for land productivity evaluation. Many studies (Bojie Fu, 1997) have been conducted for selection and creation of an index system, the quantification of index and selection of evaluation method that helped to break away from the descriptive qualifier of before.

In this article, research was conducted to investigate the root vertical distribution characters, root drought-resistance capacity, soil chemical and physical features, and local soci-economic conditions. A new method for soil productivity evaluation is proposed based on the principle of AHP (Analytical Hierarchy Process, T. L. Saaty, 1980) that can be applied to the soil productivity evaluation of hillside in Loess Plateau of China.

2 Material and method

2.1 Study area description

The study area is located in Chunhua County on the Loess Plateau with an altitude ranging from 630m to 1,809m. Soils include two zones with the main soil types of cinnamon soil and loess. Soil fertility is lower as the organic matter content is under 1%. The average annual temperature is 9.6℃, with an average temperature in January of –4.3℃, and 23.1℃ in July. The average annual precipitation is 600.6mm with a maximum of 822.6mm and a minimum of 409.5mm. The average rainfall in the growing season is 454mm. Most hillside lands are facing south and southwest, which allows them to have more chances for the sunshine, and leads to intense evaporation of the water.

2.2 Analysis of soil samples

Researches (U.M.Sainju and D.E.Good, 1993) have verified that the root density and abundance is related to the content of nutrient and organic matter. Because the local nutrient environment is a little poor, and most nutrients is concentrated in the surface soil, the plant absorption of nutrients is mainly limited to the soil surface. Thus soil is sampled from the profile at 0cm—50cm on 13 *Robinia. pseudoacacia* forest sites in Xipo and Zuitou respectively, and the soil chemical and physical features were analyzed.

2.3 Investigation of the socioeconomic condition

From September 1996 to November 1999, investigations focused on socioeconomic conditions were conducted according to a pre-designed questionnaire by selecting the households of different income levels in two villages. The directors in the villages helped to divide the income level of the households into three levels. Twenty households were sampled from each level to represent the village's income.

2.4 Evaluation method for natural soil productivity (NSP) and current soil productivity (CSP)

According to the principle of AHP, judging matrixes at different hierarchies are established, and the maximum eigenvalue, $\lambda_{\max}$, together with its corresponding eigenvector, is calculated by the Gauss iteration method. The weight of every factor is calculated after the consistency check of every matrix. After the normalization of the indexes of soil physical and chemical characteristic, root system distribution and drought-resistance ability characteristic, and the socioeconomic conditions, the *NSP* and *CSP* are calculated by the following equation:

$$NSP/CSP = \sum_{i=1}^{n} x_i w_i \tag{2}$$

where i is the serial number of factors, n the number of factors, x_i certain factors for evaluation, and w_i the weight of certain evaluating factors.

2.5 Soil productivity evaluation

Index selection and the hierarchy divination

Locations selected for evaluation is similar, including the gradient and slope direction, climate, (according to former studies), factors of soil chemical and physical features, and tree root distribution characters that have great effect on Natural Soil Productivity (*NSP*). Soci-economic factors were added for the evaluation of Current Soil Productivity (*CSP*).

According to the principle and the relationship among factors, the evaluation system was divided into three hierarchies that formed the hierarchical structure for *NSP* and *CSP* evaluation (Fig. 1 and Fig. 2).

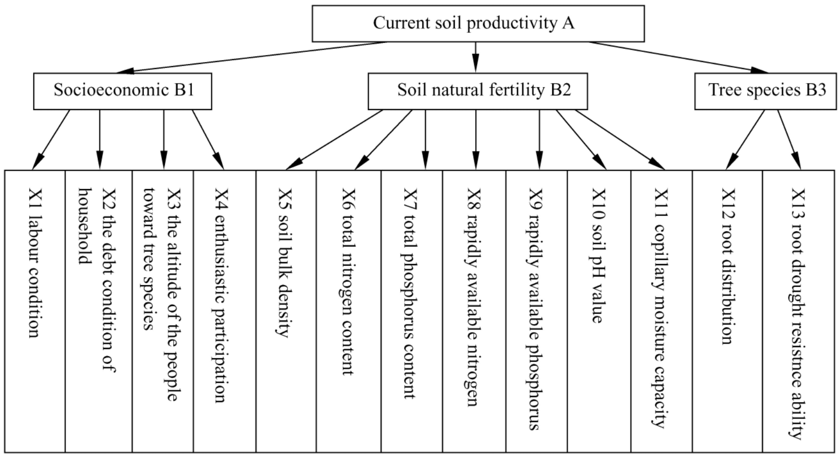

Fig. 1 The hierarchy structure of evaluation factors for slope land CSPI in Chunhua county

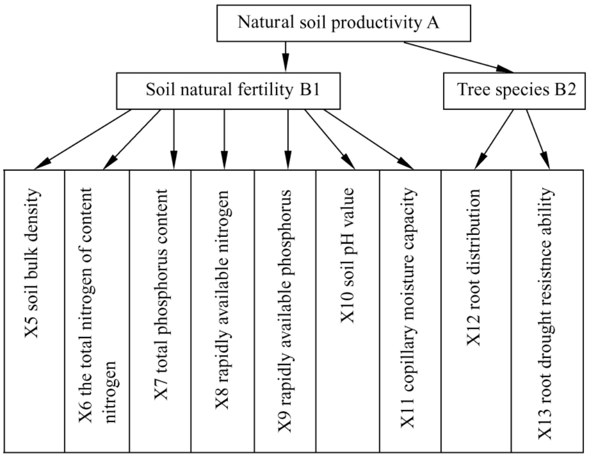

Fig. 2 The hierarchy structure of evaluation factors for hillside land NSPI in Chunhua county

3 Results and discussion

3.1 Soil physical and chemical characteristic

From Table 1, we can see that the soil chemical characters in Xipo Village is better, while its physical characters is not as good as that in Zuitou Village. Generally, the soil physical and chemical characters of the two villages are similar, which indicated that the soil fertility in the two villages is close.

3.2 Socioeconomic condition characters

From the Table 2, it was clear that, there exist remarkably difference of the socioeconomic conditions in the two villages, among which Xipo Village had richer labor resource, less debt burden, and stronger tendency to the hillside development than the Zuitou Village. Thus it was possible for people in Zuitou Village to exert positivism and enthusiasm during the hillside development, which help to fully exert and improve the Current Soil Productivity of hillside land.

Table 1 Soil physical and chemical information on slope land of Zuitou and Xipo in Chunhua County

Layer (cm)	pH	Bulk density ($g \cdot cm^{-3}$)	Maximum moisture capacity (%)	Capillary moisture capacity (%)	Porosity (%)	Total Nitrogen ($g \cdot 100g^{-1}$)	Rapidly available nitrogen ($mg \cdot kg^{-1}$)	Total P content ($g \cdot 100g^{-1}$)	rapidly available P ($\mu g \cdot g^{-1}$)
					Zuitou village				
0—10	8.39	0.32	0.41	0.37	0.36	0.090	2.71	0.099	0.219
10—30	8.49	0.24	0.47	0.40	0.38	0.072	0.87	0.078	0.149
30—50	8.45	1.40	0.44	0.33	0.34	0.055	1.36	0.089	0.082
					Xipo village				
0—10	8.44	0.22	0.44	0.31	0.28	0.106	2.71	0.122	0.355
10—30	8.50	0.25	0.41	0.29	0.26	0.072	2.07	0.119	0.377
30—50	8.51	1.33	0.38	0.30	0.23	0.075	2.09	0.119	0.341

Table 2 Comprehensive social and economic table of Zuitou and Xipo county

		Zuitou village	Xipo village
Income from orchard/household (¥ $unit^{-1}$ $year^{-1}$)		47,848.75/year	30,104.6/year
Ratio of the orchard (percentage of orchard area of the total plowland)		74.37％	57.07％
Orchard areas/manpower		3.25	2.21
Debt condition		7 among 60 households without debt. Average debt 14,917 ¥	12 among 60 households without debt. Average debt 4,527¥
Participating tendency		11.10	13.37
Acceptance to tree species	*Prunus. armeniacia var. ansu*	3.13	2.93
	Robinia pseudoacacia	–0.13	0.03
	Pinus. tabulaeformis	–0.67	–1.10
	Platycladus. orientalis	–0.77	–1.10

3.3 Normalization of results

To eliminate the difference caused by dimension among indexes, the extreme value of every index is determined according to the practical situation and the current conditions of local production during the selection extreme value for normalization.

The normalization results of socioeconomic factors.

Based on the investigation of socioeconomic conditions, combined with the membership grade function, data related to the socioeconomic conditions are normalized, and the results were shown in the Table 3.

From the Table, it is clear that there exists remarkable difference in socioeconomic conditions between the two villages. As there were richer labor resources, less debts, and a stronger tendency of people to participate in hillside development in Xipo village, there was a more positive and active attitude, which helped to shift the potential productivity of the hillside into current soil productivity.

Table 3 Score of social economic conditions in Xipo and Zuitou and its normalized results

		Ziutou village		Xipo village	
		Field Data	Normalized Data	Field Data	Normalized Data
Labour (people per household)		3.2500	0.5715	2.2100	0.7695
Debt (yuan)		14,917.00	0.8508	4,527.00	0.9547
Participating tendency		11.1000	0.3813	12.3700	0.4606
Acceptance to tree species	*Prunus. armeniacia var. ansu*	–0.6700	0.2589	–1.1000	0.2111
	Robinia pseudoacacia	–0.7700	0.2478	–1.1000	0.2111
	Pinus. tabulaeformis	–0.1300	0.3189	0.0300	0.3367
	Platycladus. orientalis	3.1300	0.6811	3.9300	0.7700

3.4 The normalization results of soil factors

Based on the investigation of soil physical and chemical conditions, combined with the membership grade function, data related to the soil conditions were normalized, and the results shown in Table 4.

Table 4 Normalization of soil physical and chemical features in Zuitou and Xipo of Chunhua County

Layer (cm)	pH	Bulk density	Maximum moisture capacity	Total N	Rapidly available nitrogen	Total P	Rapidly available P
Zuitou village							
0—10	0.7564	0.8571	0.8295	0.1323	0.4049	0.515	0.2733
10—30	0.500	0.7423	0.3333	0.0797	0.1735	0.2383	0.1492
30—50	0.6026	0.4286	0.6202	0.0313	0.2951	0.0667	0.0299
Average	0.6197	0.6760	0.5943	0.0811	0.2912	0.2733	0.1508
Xipo village							
0—10	0.6496	0.5241	0.4944	0.1816	0.6304	0.6093	0.5107
10—30	0.4929	0.4283	0.5521	0.0841	0.5785	0.3052	0.5247
30—50	0.4558	0.6430	0.6641	0.1840	0.5605	0.2615	0.4619
Average	0.5328	0.5318	0.5702	0.1499	0.5898	0.3920	0.4991

From the results shown in Table 4, it is evident that, within the profile of 0cm—50cm, soils in Xipo village (mainly focused on the soil chemical index) have better fertility than those in Zuitou village, while soils in Zuitou village have better physical properties. Soils in the two villages have their strong points and are similar in natural conditions.

3.5 The normalization results of tree species factors

According to the investigation of *Prunus. armeniacia var. Ansu*, *Roinia. pseudoacacia*, *Pinus. tabulaeformis*, *Platycladus. orientalis*, there exist remarkable differences in the vertical root distribution characteristics among the 4 species. Changes in root vigor dynamically changed during the experiment, which is not in accordance with the index selection principle, Root drought-resistance ability; the water capacity at which the root system loses its vigor is determined to be an evaluation factor. *Pinus. tabulaeformis* of the four species is highest in drought-resistance ability.

Based on the investigation of tree species, data related to soil conditions were normalized using the membership grade function, with the results shown in the Table 5.

Table 5 Standardized results for vertical roots distribution characteristics of main tree species in Weibei of loess plateau

Items	Robinia. pseudoacacia	Pinus. Tabulaeformis,	Playcladus. orientalis,	Prunus. armeniacia var. Ansu
Maximum root distribution depth (m)	1.4	1.1	0.9	1.1
Normalized data	0.688	0.500	0.375	0.500
Moisture content*(%)	4.500	6.810	3.330	3.800
Normalized data	0.718	0.296	0.932	0.847

*This moisture content is the point at which the root system begins to lose its vigor

3.6 Establishment of the judging matrix and the calculation of the eigenvector

Establishment of the judging matrix

To analyze the relative importance between any two factors, a judging matrix was established with which the maximum latent root and its corresponding eigenvector were calculated. After a consistency check to ensure the results satisfy the requirement, the judging matrixes at different hierarchies were established.

The total random consistency ratio of the entire matrix was calculated to be 0.0489, less than 0.1, which satisfies the requirement of the consistency check in AHP, and indicates that the matrixes above are suitable for the calculation of weights at different hierarchies.

Calculation results of final weights for all factors

To the matrixes established above, the maximum eigenvalue of every matrix and its corresponding eigenvector is calculated using the Gauss iteration method by STATS software. The results are shown in Table 6.

Table 6 The calculating results of every assessing factors' weight for CSPI and NSPI

Current soil productivity			Natural Soil Productivity		
No	Factors	contribution	No	factors	contribution
C1	Labor	8.758E-02			
C2	Debt	4.107E-03			
C3	Reception to certain tree species	0.172			
C4	Participating tendency	1.902E-02			
C5	Soil bulk density	8.791E-03	C5	Soil bulk density	0.0288
C6	Total Nitrogen	4.272E-02	C6	Total Nitrogen	0.1401
C7	total phosphorus content	5.351E-03	C7	total phosphorus content	0.0176
C8	Rapidly available nitrogen	3.335E-02	C8	rapidly available nitrogen	0.1094
C9	Rapidly available phosphorus	1.441E-02	C9	rapidly available phosphorus	0.0473
C10	pH value	2.628E-02	C10	pH value	0.0086
C11	Field moisture capacity	1.471E-02	C11	Field moisture capacity	0.0482
C12	Root distribution depth	0.419	C12	Root distribution depth	0.4500
C13	Root drought-resistance	0.140	C13	Root drought-resistance	0.1500

From Table 11, it is clear that among all three-category indexes for soil productivity evaluation, factors related to tree species have the most important influences on soil productivity. The biological features of the tree species, including root distribution depth and root drought-resistance ability, are essential factors for soil productivity, which indicates that selection of suitable species is the key for success of afforestation on hillside. Except for the biological features of the tree species, participating tendency and labor conditions are also important factors concerning soil productivity. Among all factors related to soil properties, total nitrogen and rapidly available nitrogen are the most important factors. This agrees with factual conditions on the Loess Plateau whose soil lacks nitrogen, and limiting the growth of the plants. Thus, it's important for local agriculture to increase the input of nitrogen to improve the soil productivity.

3.7 Soil productivity evaluation

Evaluation of Natural Soil Productivity of hillside in Zuitou and Xipo village

The results of NSP in the two villages (Table 7) indicated that the natural soil productivity of *Robinia. pseudoacacia* forest sites in the two villages are just above the average, while the NSP of the other three species is lower. Although data indicates that the Natural Soil Productivity of the four tree species in Xipo village is higher than that in Zuitou village, the difference is so small that it can be eliminated as the ratio is not greater than 10%. This agrees with the analysis of soil physical and chemical properties, that hillside lands in the two villages have similar productivity potentials and development values.

Table 7 Results of natural soil productivity for gully slope land in Zuitou and Xipo

Tree species	Robinia. pseudoacacia	Pinus. Tabulaeformis,	Platycladus. orientalis,	Prunus. armeniacia var. Ansu
Zuitou	0.5239	0.3765	0.4156	0.4590
Xipo	0.5672	0.4147	0.4539	0.4972
The ratio of rise of NSP in Xipo to Zuitou	7.31%	10.15%	9.22%	8.32%

Calculation of Current Soil Productivity for hillside land in Zuitou and Xipo village

Calculated results (Table 8) of Current Soil Productivity in Zuitou and Xipo Villages indicate that the CSP of *Robinia. pseudoacacia* and *Prunus. armeniacia var. Ansu* is higher, indicating that these two species are highly accepted by local people, while the CSP of *Pinus. tabulaeformis*, and *Platycladus. orientalis* are lower which limited their use.

Table 8 Current productivity of hillside land at Chunhua County

Tree species	Robinia. pseudoacacia	Pinus. Tabulaeformis	Platycladus. orientalis	Prunus. armeniacia var. Ansu
Zuitou	0.5678	0.4202	0.4548	0.5696
Xipo	0.6057	0.4468	0.4833	0.6197
The ratio of rise of NSP in Xipo to Zuitou	14.60%	6.33%	6.27%	8.80%

Calculated results of CSP of different species on hillside land indicate that, among all the factors affecting the CSP, reception of local people to certain tree species is the key factor. Between the two villages, *Robinia. Pseudoacacia* in Xipo village had higher CSP because people in Xipo village are more eager to accept it as a silvicultural species. On the contrary, the CSPs of *Pinus. Tabulaeformis*,and

Platycladus. orientalis in Xipo village are lower because local people are unwilling to accept them. The order of the four tree species productivity in both villages is *Robinia. pseudoacacia* > *Prunus. armeniacia var. Ansu* > *Platycladus. orientalis* > *Pinus. tabulaeformis*, the same as the order of the root distribution depth. *R. pseudoacacia* shows highest NSP and CSP among the four tree species, and should be the preferred species for local afforestation.

Comparison of the CSP and NSP for soil productivity evaluation

Results of the Current Soil Productivity and Natural Soil Productivity evaluation of four tree species in the two villages indicate clearly that, although the NSP of *Platycladus. orientalis* and *Pinus. tabulaeformis* are higher in both villages, their CSPs have no corresponding trend. The CSP of *Robinia. pseudoacacia* is similar in both villages, but there exists great differences in CSP. *Prunus. armeniacia var. Ansu* is accepted in both villages, and its NSP and CSP is similar in these two villages. Further analysis indicates that the reason for the difference is socioeconomic condition, especially the difference of the altitude of local people toward the hillside development and their acceptance of certain tree species. This indicates the importance of socioeconomic factors in CSP. In addition, hillside development practices in Xipo village have indeed gone ahead of Zuitou with higher productivity. Thus, compared to the NSP, the Current Soil Productivity evaluation more comprehensively reflects factual utilization and soil productivity.

Of course, there exists a close relationship between Current Soil Productivity and Natural Soil Productivity. Natural Soil Productivity reflects the natural condition of certain land, which indicates the possibility and feasibility of land development, and is the necessary part in the land-use program and soil productivity evaluation. In practice, imposing the positive effects of humans by technology popularization, selection of suitable tree species helps transform potential productivity into current productivity, which is important for local economies to step into a positive development stage.

4 Conclusion

Because the Productivity Index (PI) didn’t consider the contribution of every factor for soil productivity evaluation, there exists a kind of distortion in its result. What’s more, it is difficult for the PI method to include the socio-economic factors into the evaluation system. As a result, it is difficult for the PI to evaluate current soil productivity, limiting its application in practice. The AHP (Analytical Hierarchy Process) method successfully overcomes the defects in PI by including the indexes of different hierarchies and dimensions into the evaluation system. Using this concept, 13 indexes from three categories were selected for soil productivity evaluation. The results have verified that AHP is a good predictor for soil productivity evaluation. Results from the two villages also helped prove the importance of socio-economic factors in the current soil productivity evaluation, which is impossible with the PI method.

As soil productivity evaluation is concerned with extensive matters related to soil fertility, tree biological features and socio-economic conditions, detailed information and scientific technologies are needed to support its application. For soil productivity evaluation at the specified sites, single data are useless when related and compared to the background value of the environment. Thus, after the selection of factors, historic and optimum records of local soil productivity together with the critical value of every factor (that is the threshold value of every factor limiting the plant growth and survival) should be determined. Because socio-economic factors can only be descriptive qualifier, new methods are needed for the selection of factors and their quantification described in more scientific ways.

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