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RESEARCH ARTICLE

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Assessment of the effect of a fully closed hillside afforestation mode on the natural *Pinus tabulaeformis* forest

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Abstract The Huanglong Mountain forest zone is one of the major natural secondary forest zones in the southern Loess Plateau in Shaanxi Province, China. Since 1950, a mode of fully closed hillside afforestation (FHA) has been applied in the forest. On some special sites, the forest age exceeds 80 years. *Pinus tabulaeformis* forests form the most important vegetation cover in the warm temperate regions of China. Similarly, populations of *P. tabulaeformis* are dominant in existing forest ecosystems. *Quercus liaotungensis*, *Syringa oblata*, *Populus davidiana*, *Prunus davidiana*, *Betula platyphylla* and *Toxicodendron vernicifluum* can be occasionally found in the tree layer and shrub species are abundant. Based on the data collected from 31 plots and 93 soil samples, the state of health of the forest ecosystem is discussed and the appropriate FHA age has been determined. Twelve indices representing vegetation and soil properties in natural, secondary *P. tabulaeformis* forest ecosystems were generated by sensitivity analysis and an assessment index system for the FHA mode was established. According to the equal distance method, a clustering technique and five grades of an integrated index for evaluating the FHA mode were compartmentalized. The effect of the FHA mode on natural secondary *P. tabulaeformis* forests was evaluated by an integrated index method with the aid of an analytical hierarchy process (AHP). The results are as follows: values of the integrated index in the FHA mode of 16, 25, 30, 45, 60 and 75 year old stands were 7.25, 6.88, 7.82, 5.51, 4.78 and 2.79 respectively. With an increase over age of the FHA stands, the effect of the FHA mode deteriorated. We conclude that natural forests should not be protected in the FHA way after 45 years. At that stage, mixing suitable tree species, selection cutting and other silvicultural and management measures should be adopted.

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1 Introduction

In much of the world serious attention has been paid to the health of the forest ecosystem. Recent achievements overseas in this aspect largely involves health monitoring methods of entire systems (Ferretti, 1997; Dobbertin et al., 2003; Seidling, 2005), forest structures and their properties (Hale et al., 1999), dynamic data of heavy metals in forest soils (Eisenbies et al., 2006), environmental pollution (Oszlanyi, 1997; Musio et al., 2004) and plantation productivity (Alexander and Craig, 1999). Experts in China have mainly engaged in discussion of concepts and an evaluation index system on the state of health of forest ecosystems (Yuan et al., 2001; Chen et al., 2002; Kong et al., 2002; Xiao et al., 2003; Xu et al., 2005), assessment of forest soils (Huang et al., 2004; Liu J et al., 2005; Zhang and Shangguan, 2005, 2006), evaluation of the service functions of forest ecosystems (Zhao et al., 2004; Jin et al., 2005) and the effect of actual reservation projects of natural forests on economic and environmental benefits (Liu et al., 2005a). Most results relate to discussion of assessment indices or general research of forest ecosystems. Quantifiable findings to assess the state of health of forest ecosystems (Ji et al., 2002; Dai et al., 2004) and information about the optimal age of closed natural hillside afforestations (Hou et al., 2004, 2005) are rare. We studied community structures and analyzed diversification of soil fertility in *Pinus tabulaeformis* forests in the FHA mode with the following age structures: 16, 25, 30, 45, 60 and 75 years to provide a preliminary estimate of the optimal age of natural, fully closed hillside afforestations.

2 Study area

The study area was located on an ecotone between a plateau and a gully hill region on the Loess Plateau

(35°28′49″–36°02′01″N, 109°38′49″–110°12′47″E) in Huanglong County, Shaanxi Province, with an elevation ranging between 1100 and 1300 m. It is dominated by a warm temperate and semi-humid continental climate. The annual average precipitation is 612 mm, and the mean, highest and lowest atmospheric temperatures are 8.6°C, 36.7°C and −22.5°C respectively. The forest vegetation type is a northern deciduous broad-leaved forest subregion. *P. tabulaeformis* forests in the area are mostly found on shaded slopes. Shrubs and herb species under the tree layer are abundant. Since the 1950s, FHA measures have been adopted in the Qiaoyu gully of the Caijiachuan forest farm in Huanglong County to restore vegetation in the fully closed hillside afforestation (FHA) stands. The dominant species is *P. tabulaeformis* in the currently existing forest types. *Quercus liaotungensis*, *Syringa oblata*, *Populus davidiana*, *Prunus davidiana*, *Betula platyphylla* and *Toxicodendron vernicifluum* are tree species which can be occasionally found in the tree layers.

3 Materials and methods

3.1 Materials

A series of *Pinus tabulaeformis* forests of FHA ages were selected. Each plot of trees, shrubs and herbs was 20 m × 20 m, 2 m × 2 m and 1 m × 1 m respectively. Five shrub and herbal plots were arrayed diagonally in each tree plot respectively. Height, diameter at breast height (DBH) and crown width of trees were measured. Height, cover ratio and other indices of shrubs and herb species were also determined. All community data were collected from 31 tree plots and 330 shrub and herbal plots.

Three soil samples were obtained randomly by a special drill in each tree plot. All soil samples to a depth between 0 and 20 cm were only collected for remnants of vegetation largely affecting soil fertility below ground cover. The method of soil sample collection followed the protocol by Dai et al. (2004). Each of our 93 soil samples weighed 500 g. All field work was completed in August, 2003.

3.2 Methods

3.2.1 Community indices

The density of *P. tabulaeformis* was calculated by the number of trees in a 100 m^2 area (Hou et al., 2005). Biodiversity indices are cited from Hou et al. (2004).

3.2.2 Indices of soil fertility measurements

All soil samples were treated following the procedures established by Xue et al. (2003) before interrelated indices of soil fertility were determined with our tools.

The pH, amount of organic matter, NO_3^-–N and NH_4^+–N of soil samples were measured by pH meter, potassium dichromate capacity and continuous flow analyzer respectively. The amount of available phosphorus and catalase (CAT) in the soil samples was measured by a colorimeter of molybdenum and titration potassium permanganate respectively. The amount of available potassium and urease in soil samples was again measured following the procedures by Xue et al. (2003) and Guan (1986). The same index was measured three times, with its average becoming the final value.

3.2.3 Assessment method

(1) Selection of assessment indices

The 22 indices obtained and presented in Table 1 were compartmentalized into four grades of sensitivity: high, middle, low and insensitive (Xu et al., 2005). Indices of high and middle sensitivity were selected to establish an assessment index system.

(2) Assessment index system

The assessment index system should have objective, scientific, integrated and valid property principles. The system should also conform to the following principles: 1) healthy principles; 2) integrated, identifiable and previously established principles of ecosystems; 3) comparable and feasible properties; 4) selected factors and standards should be sensitive and suitable for the scale of the study area. The assessment index system in the three strata layers for the evaluation of the FHA effect on forests is presented in Table 2, obtained from an AHP (Wang et al., 2005) method and relative achievements in China (Chen et al., 2002; Kong et al., 2002; Xiao et al., 2003; Huang et al., 2004) and abroad (Ferretti, 1997; Oszlanyi, 1997; Alexander and Craig, 1999; Hale et al., 1999; Dobbertin et al., 2003; Musio et al., 2004; Seidling, 2005; Eisenbies et al., 2006).

(3) Matrix characteristic value

The scale of the discrimination matrix was classified into nine grades according to the table of the assessment index system and its underlying principles. The index values of factors in the matrix were obtained from the opinions of experts (Wang et al., 2005).

(4) Weight values of indices

Each index has various levels of importance and a contribution ratio. The weight of assessment indices was calculated by AHP. After the discrimination matrix was formed, all index layers were ranked and tested for coherence and the weight value of each index in the entire order was allotted one by one. The final weight value of each index in each stratum equaled the weight value of each index in each stratum, divided by the sum of the weight values of each index in the entire order (Xie et al., 2005) (Table 3).

(5) Comprehensive assessment mode

The contribution of assessment indices to the effect of the FHA mode on forests was obtained from AHP.

Table 1 Sensitivity classification of indices

index	no. of samples	maximum	minimum	average	*SD*	*CV*/%	sensitive class
richness in trees	31	12	1	5.33	3.37	63.1	middle
richness in shrubs	165	23	3	8.83	5.11	57.9	middle
richness in herbs	165	41	7	16.5	9.46	57.3	middle
Alatalo evenness index of trees	31	0.99	0.07	0.60	0.27	44.6	middle
Alatalo evenness index of shrub	165	0.89	0.33	0.64	0.39	60.9	middle
Alatalo evenness index of herb	165	0.787	0.09	0.38	0.18	47.4	middle
tree density/trees·100 m^{-2}	31	24.71	6.75	13.22	8.38	63.4	middle
shrub density/trees·100 m^{-2}	165	515	120	313.3	79.3	25.2	low
canopy closure/%	31	0.6	0.3	0.38	0.12	30.5	low
DBH/cm	31	33.8	4.1	11.1	6.64	59.7	middle
crown diameter/m^2	31	30	3	18.3	7.02	38.4	low
height/m	31	17.8	3.5	11.4	3.12	27.4	low
regeneration seedlings/trees·m^{-2}	31	9.35	0	2.04	3.09	151.6	high
bulk density/g·cm^{-3}	93	1.35	0.9	1.05	0.50	5	insensitive
pH	93	8.56	8.15	8.3	0.11	1	insensitive
organic matter/g·kg^{-1}	93	38.49	17.3	27.3	13.93	51	middle
NO_3^-–N/10^{-3} g·kg^{-1}	93	1.78	8	3.54	2.20	62.2	middle
NH_4^+–N/mg·kg^{-1}	93	33.53	12.55	18.68	3.48	18.7	low
available potassium/10^{-3} g·kg^{-1}	93	248.05	150.24	185.71	21.69	11.68	low
available phosphorus/10^{-3} g·kg^{-1}	93	9.47	3.15	4.62	1.80	38.9	low
urease/10^{-3} g·kg^{-1}	93	0.581	0.085	0.266	0.13	48.8	middle
CAT/0.1 mol·L^{-1}	93	23.03	17.32	18.67	0.54	2.9	insensitive

Note: $CV \leqslant 10\%$,$10\% \leqslant CV \leqslant 40\%$, $40\% \leqslant CV \leqslant 100\%$ and $CV \geqslant 100\%$ implies insensitive, low, middle and high sensitivity, respectively.

Table 2 Assessment index system of the effects on closed hillside afforestation measures

object	item	index
FHA index	vegetation traits	richness in trees
		richness in shrubs
		richness in herbs
		Alatalo evenness index of trees
		Alatalo evenness index of shrubs
		Alatalo evenness index of herbs
		tree density
		average DBH of *P. tabulaeformis*
		regeneration seedlings
	soil traits	organic matter
		NO_3^-–N
		urease

Table 3 Weight value of the assessment indices

item	weight value of item	index number	index	weight value of index
vegetation traits	0.67	1	richness in trees	0.22
		2	richness in shrubs	0.09
		3	richness in herbs	0.04
		4	Alatalo evenness index of trees	0.13
		5	Alatalo evenness index of shrubs	0.05
		6	Alatalo evenness index of herbs	0.04
		7	tree density	0.21
		8	DBH of *Pinus tabulaeformis*	0.42
		9	regeneration seedlings	0.30
soil traits	0.33	10	organic matter	0.65
		11	NO_3^-–N	0.19
		12	urease	0.16

However, they could not be compared directly given their various dimensions. All indices should be in a standardized form (Li et al., 2005).

$$Y = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \times 10 \qquad (1)$$

where Y is the standard value of the assessment index; and x_i, $x_{\max}$ and $x_{\min}$ are the mean, maximum and minimum actual values, respectively.

$$S_i = Y \times W_i \qquad (2)$$

where S_i and W_i are the final and weighted values of the assessment index.

A comprehensive index of the effect of the FHA mode of the forest series by age can be calculated as follows (Li et al., 2005):

$$R = k_{\mathrm{v}} \sum_{i=1}^{n} S_i W_i + k_{\mathrm{s}} \sum_{j=1}^{m} S_j W_j \qquad (3)$$

where R is a comprehensive index; k_{v} and k_{s} are weight values of the index of vegetation and soil stratum items respectively; and n and m represent the amount of vegetation and the soil index, respectively.

R is obtained as the weighted average over many factors. Its value ranges randomly between 0 and 10. We applied the equal distance method of cluster analysis and five grades of the integrated index for evaluating the FHA mode as compartmentalized in Table 4.

Table 4 Natural forest health assessment of closed hillside afforestation at Huanglong Mountain

value of integrated assessment	$0 \leqslant R < 2$	$2 \leqslant R < 4$	$4 \leqslant R < 6$	$6 \leqslant R < 8$	$8 \leqslant R \leqslant 10$
assessment	worst	unacceptable	average	adequate	choice

4 Results and analysis

4.1 Data sources of assessment indices

Actual, maximum and minimum values of assessment indices are shown in Table 5.

4.2 Effect of FHA mode on vegetation

Species were flourishing and soil fertility was high (Hou et al., 2005) for smaller crown densities and abundant sunlight in the FHA forests before they were 45 years old. Over time, the DBH of *P. tabulaeformis* increased continuously. Shade intolerant trees, shrubs and herbs quickly intruded into the forest and increased species richness. Simultaneously, competition from species in the tree and shrub layers for growing space intensified. Tree density increased as density of the shrub layer decreased. Moreover, species became distributed asymmetrically and the evenness indices shown in Table 5 appeared to be random values. Thus, the FHA mode at this stage benefitted from the formation of multi-layered structures in the forest and improving the counter measures and stability of the forest.

As a result, the leaf area of *P. tabulaeformis* increased (Zhang and Shangguan, 2006) and sunlight in the forest decreased with an increase over FHA age. The FHA environment gradually stabilized after 45 years. Shade intolerant trees and shrubs petered out and several shade-tolerant tree species occurred occasionally on some sites (Hou et al., 2004). Richness indices in the tree, shrub and herbal layer varied insignificantly. Given the suppression by dominant trees, the evenness indices in the tree and shrub strata decreased. Owing to the improvement of the habitat by herbs with their many roots and occupying appropriate niches, the evenness indices increased in the herbal layer. *P. tabulaeformis* trees had started to regenerate (Hou et al., 2005) since the FHA forest was 45 years old. With an increase over FHA age, both the density of *P. tabulaeformis* trees and the number of seedlings increased substantially. Despite this substantial rise, the increasing number of trees was largely 28 to 33 year old saplings and small young trees with DBH between 2.0 to 3.3 cm under the crown of dominant trees. The shape and quality of these young trees

Table 5 Source of indices

Value	index number											
	1	2	3	4	5	6	7	8	9	10	11	12
closed hillside afforestation at age 16												
x_i	3	4	8	0.12	0.58	0.4	11.5	3.6	0	21.4	2.98	0.206
x_{max}	5	6	12	0.16	0.69	0.5	12.3	4.2	0	25.5	3.36	0.324
x_{min}	1	3	5	0.07	0.35	0.18	4.8	1.9	0	15.3	2.09	0.107
closed hillside afforestation at age 25												
x_i	6	7	16	0.932	0.531	0.124	14.4	4.5	0	20.06	2.89	0.335
x_{max}	8	9	19	0.985	0.64	0.141	19	4.8	0	26.01	2.94	0.403
x_{min}	2	5	10	0.761	0.33	0.08	5.5	4.1	0	15.72	2.27	0.207
closed hillside afforestation at age 30												
x_i	8	18	35	0.713	0.658	0.288	14.2	8.6	0	18.53	8	0.468
x_{max}	10	21	41	0.826	0.722	0.415	15.5	9.3	0	22.54	8.68	0.581
x_{min}	3	7	12	0.454	0.418	0.107	6.8	5.3	0	15.99	7.11	0.247
closed hillside afforestation at age 45												
x_i	4	5	14	0.668	0.885	0.388	9.95	14.6	0.6	23.61	2.31	0.206
x_{max}	6	7	17	0.712	0.891	0.417	21.25	15.9	1.3	29.72	2.88	0.272
x_{min}	1	3	10	0.614	0.837	0.302	6.75	10.7	0.58	21.57	2.19	0.197
closed hillside afforestation at age 60												
x_i	5	8	14	0.644	0.594	0.453	14.68	15.6	7.34	29.75	2.45	0.09
x_{max}	7	9	15	0.739	0.636	0.491	19.7	17.6	9.35	34.01	3.02	0.111
x_{min}	2	7	11	0.639	0.567	0.423	13.95	12.4	6.58	28.69	2.33	0.085
closed hillside afforestation at age 75												
x_i	5	11	14	0.549	0.576	0.649	15.61	19.6	4.29	34.23	2.4	0.29
x_{max}	9	14	16	0.612	0.68	0.787	24.71	23.8	6.58	38.49	2.78	0.37
x_{min}	1	6	9	0.533	0.553	0.645	14.25	19.3	4.19	33.5	1.84	0.27

Note: Indices in Table 5 have the same meaning as in Table 3.

deteriorated and some of them became dead (Hou et al., 2005). The density of *P. tabulaeformis* trees and the number of shrub species had been predicted and given a medium level of sensitivity when the FHA forest was 100 years old (Hou et al., 2004). From this discussion, we concluded that the FHA mode was no longer suitable to forests which were 45 years or older. Management measures such as selection cutting should be adopted to optimize forest structures and provide more space for seedlings growing after the FHA forest becomes a 45-year-old stand.

4.3 Effect of FHA mode on soil

One of the most important ways of improving soil fertility is for litter to return to the soil (Zhang and Shangguan, 2005). With an increase in the age of FHA stands after 45 years, the amount of organic matter in the soil decreases. Individual trees and shrubs grow quickly, augmenting the abundant herbal index but decreasing the amount of litter returning to the soil and increasing depletion of soil fertility. The amount of organic matter in the soil increased after 45 years as a result of the amount of litter returning to the soil and a decrease in the density of shrubs. Although the number of seedlings and small young trees increased, they consumed less nutrient elements from the soil. In the series of FHA ages, the amount of NO_3^-–N and urease fluctuated. Zhang and Bai (2003) speculated that the preference of trees for $NH^+{}_4$–N and NO_3^-–N might be associated with the soil pH. Nelson and Selby (1974) and Stadler and Gebauer (1992) found that trees in acid, neutral or alkali soils tended to absorb $NH^+{}_4$–N and NO_3^-–N. The variation in the amount of NO_3^-–N in the soil might be associated with the selective absorption of nitrogen by trees. The amount of urease in the soil was small and had relatively little impact on the structure of the community.

4.4 Assessment of the FHA mode

From Table 6, we can see that the trend of *R* decrease with an increase over the age of FHA stands.

Table 6 Integrated evaluation of the effect of age on closed hillside afforested stands

closed hillside afforestation ages	ultimate score	remarks
16	7.25	adequate
25	6.88	adequate
30	7.82	adequate
45	5.51	average
60	4.78	average
75	2.79	average

5 Discussion

The FHA mode of protecting natural forests is not an ideal condition. Liu and Lü (2004) found that selection cutting was a more appropriate logging operation for natural forests. Under this operation, the natural loss of forest trees can be considerably reduced and the growing potential of each tree will be released sufficiently so that the rotation age can be shortened and costs decreased. Furthermore, a niche for other species will occur. The productivity of forest land will be better utilized and soil fertility ameliorated. Biodiversity, as a measured index, counter measures and stability of the forest ecosystem will also be restored. In the process, the natural forest will exert its regenerating potential to improve its structure. In the study area, tree species, DBH and tree density should be continually optimized by diversification of the forest structure, the ability of trees to regenerate, and improved soil fertility after 45 years of FHA management. Measures such as the introduction of broadleaved trees and protecting conifers in the forest by selection cutting will help decrease the amount of combustible material on forest land, reduce the danger of forest fires and establish a stable forest ecosystem at sustainable levels of management.

It is only recently that we have come to a rudimentary level of knowledge about the state of health of the forest ecosystem in China and have started serious studies in this area. The effect of the FHA mode on natural forests, elucidated from our study, has been attained in a small way and we hope our conclusion will be useful in changing current views on the preservation of our forests. Our study has been limited by many factors, which may lead to some deficiencies in the established index system, so it should be improved in future. The task of the assessment of major forest ecosystems and relevant basic studies should be carried out in our country.

6 Conclusion

Given the characteristics of our forests after they have been managed in the FHA mode, 12 assessment indices, including richness and Alatalo evenness indices in tree, shrub and herbal layers, tree density, DBH of *Pinus tabulaeformis* trees, the amount of regeneration in the forest, the amount of organic matter in the soil as well as that of NO_3^-–N and urease have been selected to assess the effect of the FHA mode on natural forests. All indices are easily applied in practice.

Findings by Zhang et al. (2006) indicated that the total amount of nutrients in *Pinus tabulaeformis* trees, exclusive of roots, was maximum in 30-year-old forests. We conclude that the FHA mode is suitable for forests until it reaches an age of 45 years. Natural forests should not be protected in the FHA way after 45 years.

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