International Journal of Multimedia and Ubiquitous Engineering
Vol.9, No.7 (2014), pp.415-426
http://dx.doi.org/10.14257/ijmue.2014.9.7.35

A Composite Index-based Approach for Hierarchical Assessment of Forest Ecosystem Health: An Example of *Pinus tabulaeformis*

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Abstract

Assessing forest ecosystem health is an effective way for forest resource management. Taking as an example Pinus tabulaeformis Carr., a superior afforestation species in northern China, this study establishes a forest health assessment model and a three-level indicator system using the analytic hierarchy process. The results showed that Pinus tabulaeformis forest health is proposed for evaluation into four grades by composite index (HI), ill-health forest was 48.39% among the sample plots, and average HI was accounted for 25% of healthy forest. So Pinus tabulaeformis forest ecosystem was in development stage; additionally, at an altitude of 1500 ~ 1800 m, slope 35 ~ 40 °, Pinus tabulaeformis forest were the most healthy in western Qinling Moutain. Forest community stability change with altitude is evident unimodal curve form, stability is a downward trend when the elevation and slope is too low or too high. This evaluation indicator system is suitable for extending its application in forest health judgment. The evaluation results have certain guiding significance for regional forest management and nurturing.

Keywords: *Forest health management, indicator system, analytic hierarchy process, Chinese pine*

1. Introduction

In recent decades, rapid economic development, substantial population growth, and continuous improvement of people's living standards have led to increasing demands for forest products such as timber. Due to extensive deforestation, there are dramatic decreases in the biodiversity in forest ecosystems, continuous degradation of forest-associated eco-environment, and significant declines of forest ecosystem services; together with the frequent occurrence of natural disasters result in different degrees of forest degradation in many countries of the world [1, 2]. Therefore, effective management of forest resources has become a tough issue raised in forestry [3, 4]. In this context, forest health assessment is developed as an effective way for forest research management [5, 6].

In the 1990s, scholars started to monitor and assess the health condition and variation patterns of forest ecosystems in the United States [7]. A number of studies established specific assessment indicator systems for assessing forest health based on long-term monitoring projects [5, 6]. In China, forest health assessments have been reported since the 2000s [8, 9]. However, there remains great difficulty in accurate forest health assessment due to the complexity of forest ecosystems [1, 3]. Additionally, applications of the existing assessment methods in practice are largely limited due to their high specificity and involvement of various indicators [10]. Because of a lack of reliable and uniform assessment standards, research on the theory and methodology of forest health assessment is still in an exploratory stage [11]. In view of the above issues, we carry out a forest health assessment for

ISSN: 1975-0080 IJMUE

P. *tabulaeformis* in a mountainous forest area of Xiaolong Mountain, Gansu, northwestern China. The results will provide valuable reference data for rational forest management.

2. Study Area Description

The forest area of Xiaolong Mountain (104°22'-106°43' E, 33°30'-34°49' N) is part of the west Qinling Mountains in southeast Gansu Province, China. The mountain (EW length 212.5 km, NS width 146.5 km) is a watershed located in the upper reaches of Yangtze and Yellow River, which serves as an ecotone of the Loess Plateau and Qinling Mountains. It is a typical natural secondary forest area with a great variety and rich resources of trees. The Forestry Experimental Department of Xiaolong Mountain presently manages a total area of 82,870,000 ha, including 68,590,610 ha (82.8%) of forest area and 14,279,390 ha (17.2%) of non-forest area. The state-owned forest area is 62,919,310 ha, with a standing tree volume of 33483324 m^3; the total stand area is 52,713,060 ha, including 41,594,730 ha of natural forest (78.9%) with the standing tree volume of 30,442,624 m^3 (88.4%).

The forest area of Xiaolong Mountain lies in the transition zone between the southern edge of temperate region and the northern subtropical region in China. The continental monsoon climate is mild and humid, characterized by short summer without intense heat, long winter without severe cold. Spring warms fast while autumn cools fast. There are overcast and rainy days suitable for forest reproduction and growth. Annual mean temperature is 7-12°C; extreme maximum and minimum temperatures are 38.3°C and -18.2°C, respectively; ≥10°C annual accumulated temperature is 3563.9°C; and annual sunshine hours is 2098.7 h. The first frost occurs in mid-October and late frost occurs in mid-April; frost-free period is 185 d, with late frost damage. The maximum depth of frozen soil is 61-129 cm. Annual mean rainfall is 460-800 mm, mostly concentrated in July - September.

The forest area of Xiaolong Mountain has complex topography with multiple ranges of hills, steep slopes, and thin soils. Soil texture mainly belongs to loam, light loam, and light soil, mainly mountain brown soil and dark brown soil with high gravel content. Zonal soils include gray brown soil to the north and yellow cinnamon soil to the south of Qinling Mountains. Soil is 30-60 cm in thickness, relatively humid, with high organic matter content, medium nitrogen content, and low phosphorus and potassium contents (pH 6.5-7.5).

3. Plot Design and Field Survey

Thirty-one sample plots (20 m × 30 m) were set in the major distribution areas of *Pinus tabulaeformis* (Longmen, Liziyuan, Mayan, and Baihua Forest Farm in Xiaolong Mountain) (Figure 1) by considering different altitudes, slope directions, slope positions, and forest types (Table 1). Species composition, coverage rate, and canopy density of plant communities in the selected plots were surveyed during June to August, 2009-2012. Plants with breast-height diameter (BHD) < 4 cm were recorded as seedlings and saplings; standing trees with BHD ≥4 cm were surveyed regarding the height, BHD, and age. The age of trees was determined by field survey of growth cone combined with branch number. Environmental factors, including the longitude, latitude, and elevation; slope degree, direction, and position and forest types (see Supplementary Material); and growth condition, soil property, plant disease and pest, fire disaster, and human disturbance (data not shown) of each stand were recorded in details.

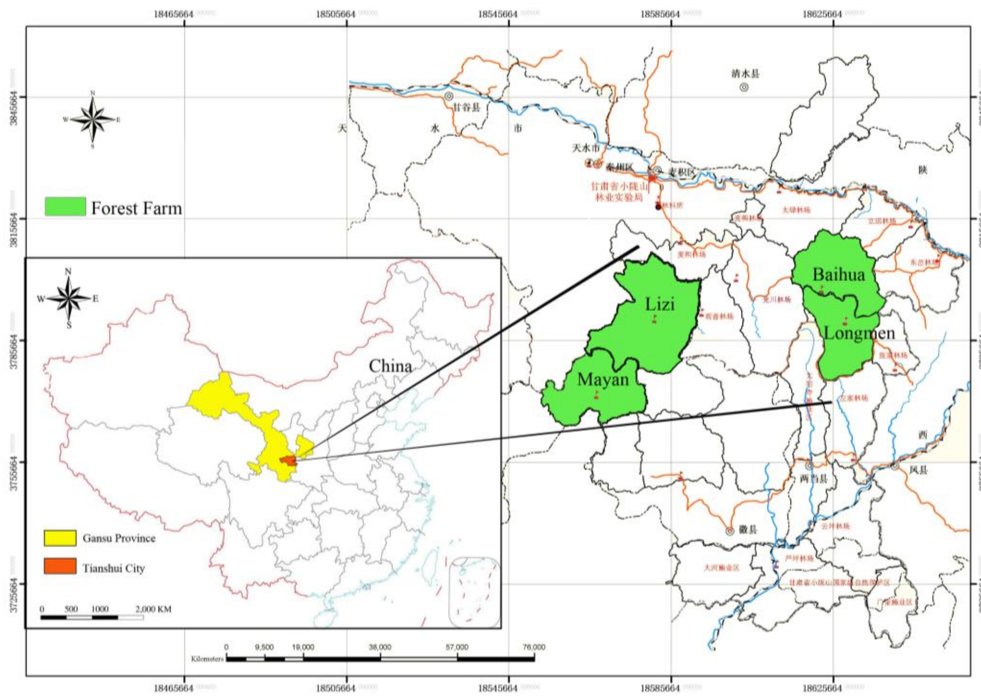

Figure 1. Location of the Study Area in Xiaolong Mountain, Gansu Province, China

In each plot, five sub-plots were respectively set for the shrub (2 m × 2 m) and herb layers (1 m × 1 m). The abundance, coverage, frequency, mean height, number of plants, and ecological niche condition (*e.g.*, growing on blow-down trees or in forest gap) of shrub and herb plants in the sub-plots were surveyed and recorded. For different species of shrubs, individual plants of average growth condition and size were selected and dug out with roots; each plant was cut into five parts (main roots, lateral roots, stem, branches, and leaves) using a pair of pruning shears. Different herb species were dug up with roots and then divided into the above- and below-ground parts. The fresh weight of each part of shrub and herb plants was determined in field; multiple sub-samples were weighed into plastic bags and sealed for transportation.

After transported to the laboratory, the shrub and herbaceous samples were oven-dried at 80°C to constant weight and then weighed to calculate the biomass [12, 13]. For shrub species, the total biomass of all shrubs in a stand was taken as the stand shrub biomass [14]. Water contents of the main roots, lateral roots, stem, branches, and leaves were determined for a standard shrub species and then used to calculate the dry weights (biomasses) of individual organs [15]. The biomasses of individual organs from the standard shrub species was summed up as its total biomass and then multiplied by the plant number of this shrub species in a specific forest stand to obtain the biomass of this species in the stand [16]. For herbaceous species, the above- and below-ground biomasses of a standard species were summed up to obtain its total biomass. Water contents of individual organs of this herbaceous species were determined to calculate the corresponding dry weight (biomass) of each organ. The biomasses of individual organs of herbaceous species were then summed up to obtain the herb biomass in a forest stand [17, 18]. The tree volume of each plot was measured with the unit of standing tree volume per hectare.

Table 1. Sample plots of *Pinus tabulaeformis* Forest Stands in western Qinling Mountains

Plots No.	Location	Elevation (m)	Slope grade	Slope direction	Slope position	Stand age	Stand density (N/hm²)
1	N34°16′575″E106°23′585″	1582	34	W	Low	45	1100
2	N34°16′539″E106°23′627″	1605	27	W	Middle	48	1235
3	N34°16′411″E106°23′623″	1579	35	SW	Middle	49	987
4	N34°16′105″E106°23′226″	1478	28	W	Middle	51	1006
6	N34°16′818″E106°23′386″	1478	38	W	Middle	42	783
8	N34°16′854″E106°23′206″	1550	32	SE	Middle	47	900
9	N34°16′796″E106°23′172″	1554	43	SE	Middle	46	1067
13	N34°15′479″E106°24′111″	1655	39	E	Up	59	917
14	N34°15′559″E106°24′172″	1694	39	SW	Up	50	1617
15	N34°11′411″E106°23′511″	1338	28	N	Up	61	917
16	N34°11′385″E106°23′546″	1352	26	N	Up	74	950
17	N34°11′301″E106°23′699″	1322	40	N	Up	65	367
19	N34°15′108″E106°23′696″	1424	38	E	Up	45	850
20	N34°14′818″E105°48′810″	1665	38	SW	Low	30	1367
21	N34°14′918″E105°48′967″	1634	38	SW	Low	31	1867
22	N34°15′042″E105°48′789″	1604	40	W	Low	30	2517
23	N34°15′355″E105°49′247″	1683	37	W	Low	30	1367
24	N34°10′352″E105°42′829″	1798	39	SW	Middle	40	1100
29	N34°15′271″E105°52′777″	1543	39	W	Middle	30	3183
30	N34°15′210″E105°52′666″	1505	40	W	Middle	30	1717
31	N34°15′232″E105°52′803″	1584	38	N	Middle	40	2750
32	N34°16′447″E105°52′934″	1545	40	W	Middle	30	2617
33	N34°17′300″E106°49′721″	1593	36	SW	Up	28	2867
34	N34°16′684″E105°53′836″	1508	40	W	Up	30	3683
35	N34°16′723″E105°53′723″	1530	41	E	Up	40	983
37	N34°18′270″E105°48′822″	1630	36	NE	Up	24	3733
38	N34°01′201″E105°45′412″	1525	30	E	Up	36	1433
39	N34°01′180″E105°45′466″	1537	35	W	Up	39	1600
40	N34°01′484″E105°45′190″	1546	34	N	Low	36	1733
46	N34°18′167″E106°20′475″	1567	34	E	Low	33	683
49	N34°19′638″E106°20′564″	1553	38	W	Low	39	1017

4. Forest Health Assessment Hierarchical Indicator System

Aiming to accurately and objectively reflect the forest health condition, the present assessment takes full consideration of the current development and future survival potential of the forest ecosystem, including system structure (related to the total performance of forest), system dynamics, and system stability (mainly successional trend). Further, we analyze and compare the indicators involved in the forest health assessment system by considering the actual situation of *Pinus tabulaeformis* health management system construction.

A total of 12 indicators are screened out by including the respective aspects of forest stand vigor (Lorey's mean height, I_1; average BHD, I_2; average canopy coverage, I_3; growing stock, I_4; and shrub - herb biomass, I_5), structure (stand density, I_6; canopy density, I_7; cover degree, I_8; and plant species richness, I_9), and stability (stand age, I_{10}; number of stand layers, I_{11}; and number of renewal seedlings, I_{12}); repetitive indicators or those with difficulty in actual measurement are excluded (Table 2). Finally, the 12 indicators are clustered to form a hierarchical model for assessing *Pinus tabulaeformis* forest health (Figure 2).

Table 2. Health Assessment of *Pinus tabulaeformis* Forest Stands in Western Qinling Mountains

Sample plot	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}
1	10.3	17.5	5	12.01	4.03	1100	60	30	6.269	45	4	11
2	14.7	22.4	7.5	11.18	3.85	1235	60	40	6.659	48	3	4
3	14.1	19.2	10	19.09	1.82	987	60	60	7.138	49	6	9
4	13.5	17.6	12.5	6.61	2.62	1006	60	40	7.549	51	3	5
6	13.2	16.1	15	9.78	5.06	783	70	35	6.896	42	8	13
8	13	18.2	17.5	6.93	9.23	900	80	45	6.454	47	7	28
9	12.4	16.3	20	8.39	4.23	1067	70	10	5.856	46	9	38
13	12.3	14.6	22.5	6.02	10.01	917	80	65	6.814	59	5	14
14	11.7	19.5	25	6.78	7.85	1617	70	15	6.688	50	4	5
15	11.7	12.1	27.5	1.29	3.27	917	70	50	8.222	61	5	11
16	11.3	13.3	30	1.32	2.19	950	70	40	8.163	74	4	6
17	11.3	11.5	32.5	1.09	1.79	367	70	90	6.473	65	5	17
19	11.3	13.8	35	7.17	8.13	850	90	5	4.47	45	3	3
20	11.3	15.8	37.5	1.21	4.38	1367	70	85	6.283	30	5	6
21	10.7	12.6	40	1.13	1.24	1867	70	75	6.985	31	4	15
22	9.8	16.1	42.5	9.93	4.95	2517	60	8	7.219	30	4	5
23	9.7	16	45	3.9	6.01	1367	60	5	8.009	30	3	6
24	9.4	8.3	47.5	13.72	6.05	1100	70	22	6.048	40	5	12
29	8.4	10.6	50	14.06	2.92	3183	80	34	3.131	30	3	5
30	7.5	8.2	52.5	10.13	4.85	1717	55	35	7.606	30	4	5
31	7.4	8	55	6.9	3.45	2750	50	30	7.697	40	5	5
32	7.3	6.3	57.5	13.68	1.95	2617	85	30	7.03	30	4	5
33	6.4	8	60	9.95	2.03	2867	75	15	7.51	28	9	23
34	5.1	4.8	62.5	10.8	3.14	3683	70	20	5.321	30	12	60
35	5	6.7	65	6.89	2.69	983	70	15	6.282	40	4	5
37	4.9	6	67.5	4.71	3.39	3733	65	30	5.575	24	5	14
38	4.6	4.7	70	3.58	6.35	1433	60	30	4.266	36	4	10
39	2.8	4	72.5	1.33	0.41	1600	40	20	3.312	39	6	21
40	4.4	9.8	75	12.47	3.11	1733	80	40	4.577	36	4	15
46	3.4	3	77.5	15.02	2.35	683	85	30	4.695	33	4	5
49	14.5	20.4	80	4.79	9.19	1017	90	20	4.159	39	3	6

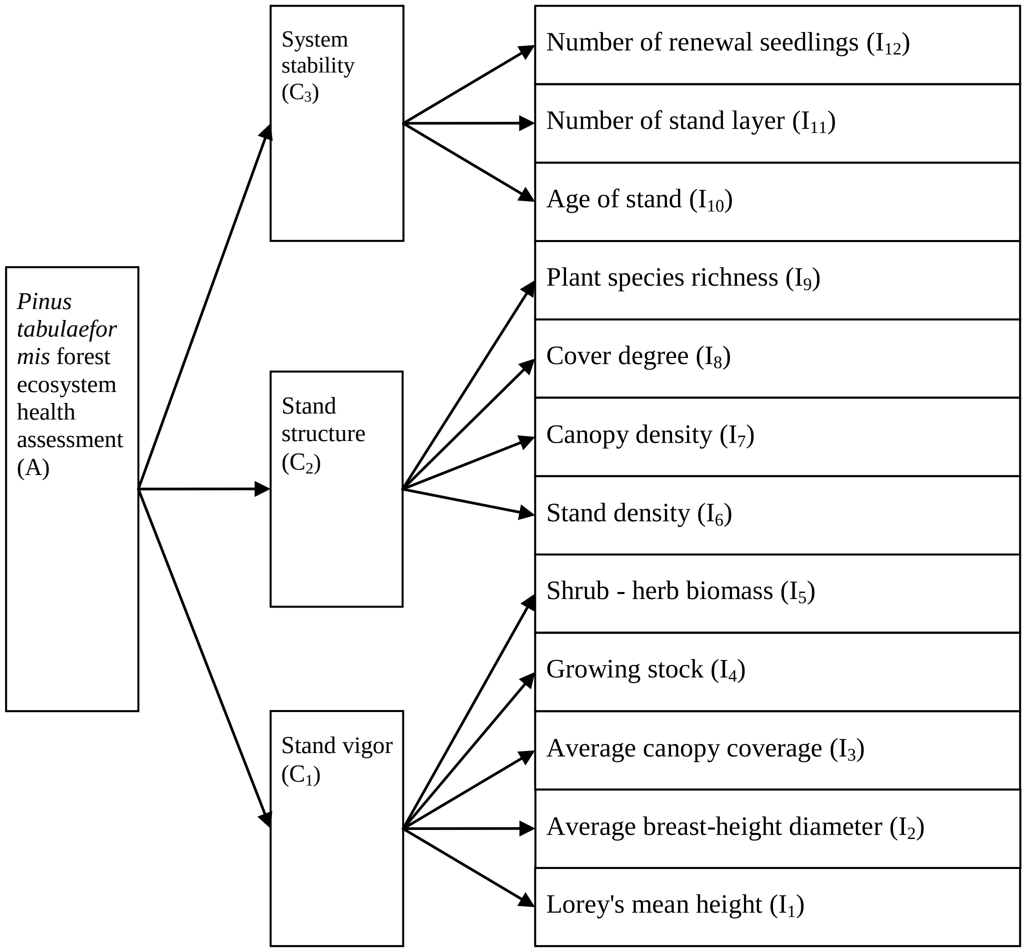

Figure 2. A Hierarchical Model for Health Assessment of *Pinus tabulaeformis* Forest Ecosystem

According to the hierarchical model established for P. *tabulaeformis* forest health assessment, we make judgments on the relative importance of each element in each layer by introducing appropriate scales (Table 3). Judgment matrix of each layer is constructed to compare the relative importance of an element at the higher level and relevant elements at the present level. In this processes, we take full consideration of a variety of factors, such as stand growth, system function, and local environment. Multiple experts are involved in the independent scoring using the scales listed in Table 1, and averages of the scores (round numbers) are used to construct judgment matrices. Then, a quantitative analysis is carried out on the relative importance of the overall target layer, criterion and indicator layers, as well as individual indicators in the forest health assessment system. Because of the complexity of objective things and the diversity and difference of each expert's understanding as well as the potentially resulting one-sidedness, the judgment matrices are impossible to have complete consistency. In order to make the results comply with the actual situation and to draw the conclusions reasonably and correctly, we simultaneously perform consistency check and rationality explanation for the matrices, followed by overall sorting of the elements (indicators). The whole calculation process is accomplished in one run using the AHP software yaahp 0.5.3. To facilitate data input, we list 1/X as -X in the matrices.

Table 3. The Weighted Value of Forest Assessment Hierarchical Indicator

Target (A)	Item (C)	Weight	Index (I)	Weight
Pinus tabulaeformis forest ecosystem health assessment (A)	Stand vitality (C_1)	0.0936	Mean tree height (I_1)	0.0076
			Mean breast-height diameter (I_2)	0.0144
			Mean crown width (I_3)	0.0044
			Tree volume (I_4)	0.0432
			Shrub - herb biomass (I_5)	0.0240
	Stand structure (C_2)	0.6267	Stand density (I_6)	0.3393
			Canopy density (I_7)	0.0954
			Shrub - herb coverage (I_8)	0.0471
			Species richness (I_9)	0.1450
	System stability (C_3)	0.2797	Stand age (I_{10})	0.1782
			Number of stand layers (I_{11})	0.0293
			Number of seedling regenerated (I_{12})	0.0722

5. Health Assessment of *Pinus tabulaeformis* Forest Stands

Health assessment model is established based on the analytic hierarchy process. The comprehensive index assessment model is expressed as follows:

$$HI = S\sum_{i=1}^{5} S_i W_i + D\sum_{j=1}^{4} S_j W_j + T\sum_{k=1}^{3} S_K W_k \quad (1)$$

Where HI is the composite health index for *Pinus tabulaeformis* forest stand; S, D, T, is the criterion layer weighted value of the stand vigor, stand structure, system stability; W_i, W_j, W_k, is the index layer weighted value of the each contestant indexes; S_i, S_j, S_k, is the standardized value of the index layer.

Health composite index of *Pinus tabulaeformis* forest weighted by multiple factors, the results were randomly distributed between 0 ~ 1, according to the actual of Xiaolong moutain forest area, to take equidistant method, the forest health status of *Pinus tabulaeformis* is divided into four grades (Table 4), I Health (HI＞0.75), II Good health (0.5-0.75), III Poor health (0.25-0.5), ⅣIll-health (0-0.25).

Table 4. Health Level Division Standard of *Pinus tabulaeformis* Forest

Composite health index HI	Rank	The results of assessment
0-0.25	Ⅳ	Ill-health
0.25-0.5	III	Poor health
0.5-0.75	II	Good health
＞0.75	I	Health

The HI values of *Pinus tabulaeformis* forest stands in western Qinling Mountains are calculated using model (1), which range in Table 5 and Figure 3.

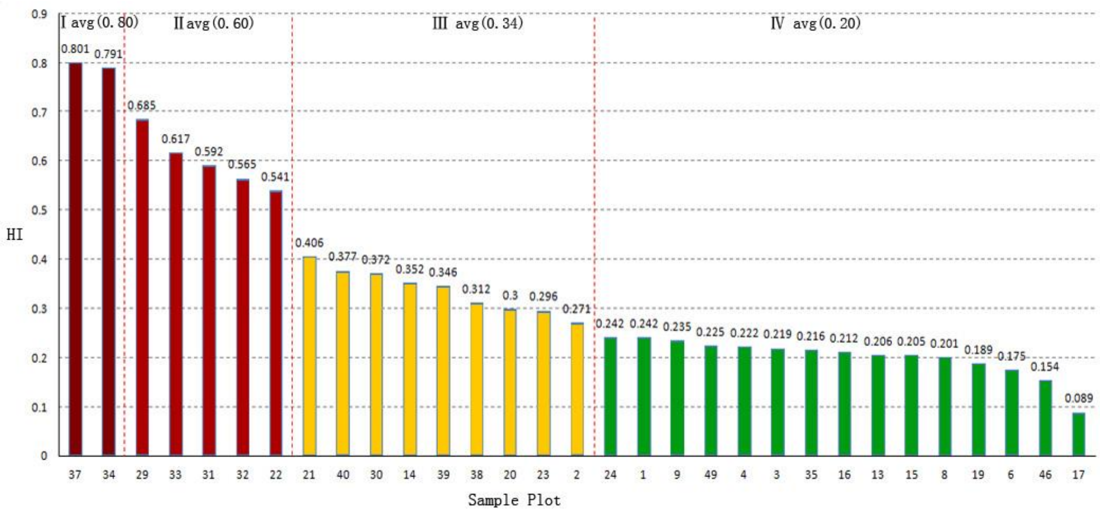

Figure 3. Classification for the Comprehensive Evaluation index of *P. tabulaeformis* Forest

I Health (HI＞0.75), including 2 sample plots, plot 37 (HI=0.801) , plot 34 (HI=0.791) respectively， $\overline{HI}$ =0.80；

II Good health (0.5-0.75), including 5 sample plots, were plot 29 (HI=0.685), plot 33 (HI=0.617), plot 31(HI=0.592), plot 32 (HI =0.565), plot 22 (HI =0.541), $\overline{HI}$ =0.60, accounting for 75% of the average healthy forest;

III Poor health (0.25-0.5), including 9 sample plots, were plot 21 (HI=0.406), plot 12 (HI=0.377), plot 30 (HI=0.372), plot 14 (HI=0.352), plot 39 (HI=0.346), plot 38 (HI=0.312), plot 20 (HI=0.300), plot 23 (HI=0.296), plot 2 (HI=0.271), $\overline{HI}$ =0.34, accounting for 42.5% of the average healthy forest;

Ⅳ Ill-health (0-0.25), including 15 sample plots, were plot 24 (HI=0.242), plot 1 (HI=0.242), plot 9 (HI=0.235), plot 49 (HI=0.225), plot 4 (HI=0.222), plot 3 (HI=0.219), plot 35 (HI=0.216), plot 16 (HI=0.212), plot 13 (HI=0.206), plot 15 (HI=0.205), plot 8 (HI=0.201), plot 19 (HI=0.189), plot 6 (HI=0.175), plot 46 (HI=0.154), plot 17 (HI=0.089), $\overline{HI}$ =0.20, accounting for 25% of the average healthy forest.

Table 5. Composite Health Index Values and the Ranks of the Sample Plots

Sample plots	Composite health index HI	Rank	Sample plots	Composite health index HI	Rank
1	0.242	Ⅳ	23	0.296	III
2	0.271	III	24	0.242	Ⅳ
3	0.219	Ⅳ	29	0.685	II
4	0.222	Ⅳ	30	0.372	III
6	0.175	Ⅳ	31	0.592	II
8	0.201	Ⅳ	32	0.565	II
9	0.235	Ⅳ	33	0.617	II
13	0.206	Ⅳ	34	0.791	I
14	0.352	III	35	0.216	Ⅳ
15	0.205	Ⅳ	37	0.801	I
16	0.212	Ⅳ	38	0.312	III
17	0.089	Ⅳ	39	0.346	III

19	0.189	Ⅳ	40	0.377	III
20	0.300	III	46	0.154	Ⅳ
21	0.406	III	49	0.225	Ⅳ
22	0.541	II			

The forest health composite index (HI) relations with elevation and slope was in Figure 4.

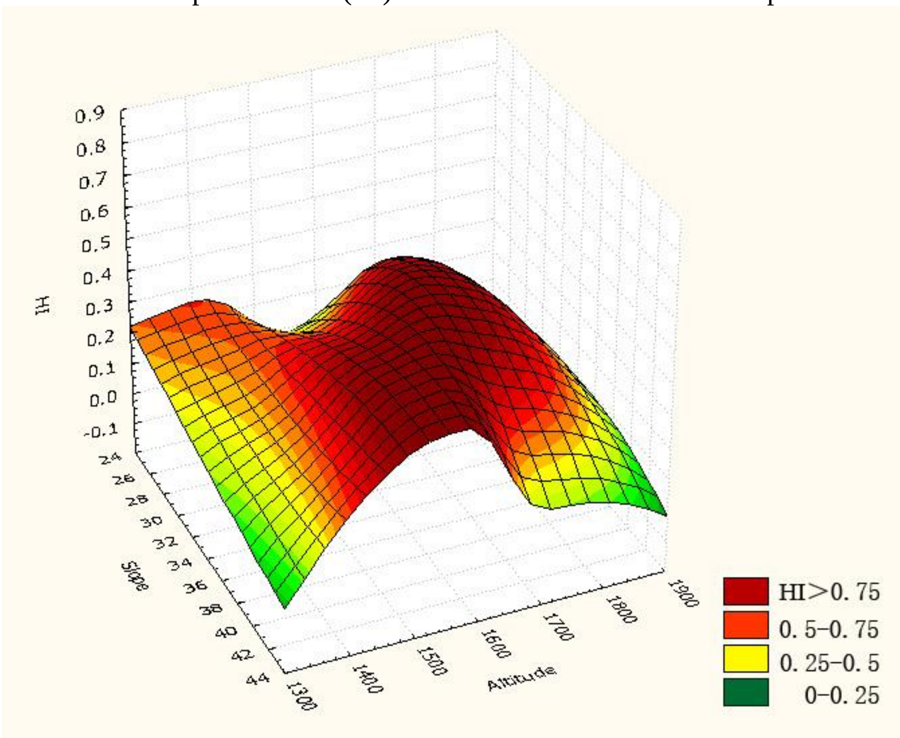

Figure 4. Forest Health Composite Index Relations with Elevation and Slope

The results show that the most healthy *Pinus tabulaeformis* forests were at an altitude of 1500 ~ 1800 m, slope 35 ~ 40 ° in western Qinling Moutain (Figure 4). Forest community stability change with altitude is evident unimodal curve form, stability is a downward trend when the elevation and slope is too low or too high, which showed that the habitat conditions determines the forest community stability.

6. Conclusions and Future Work

This study with a composite index (HI) is proposed for evaluation of *Pinus tabulaeformis* forest health into four grades, ill-health forest was 48.39% among the sample plots, and average HI was accounted for 25% of healthy forest. So *Pinus tabulaeformis* forest ecosystem was in development stage.

The results of canonical correlation analysis show that elevation and the slope are important environmental factors that influence the health of Pinus tabulaeformis stands in western Qinling (Figure 4). This observation is consistent with previous finding that under the same climatic condition, the stability of *P. tabulaeformis* stands is mainly determined by the topography and soil conditions [19]. In Xiaolong Mountain, *Pinus tabulaeformis* mainly occurs on sunny slopes at mid-altitudes in its distribution areas, where relatively poor site conditions influence forest health by changing the temperature and humidity. In terms of heat condition, such slopy areas are unsuitable for either cold-resistant tree species such as larch and spruce, or oriental arborvitae with high demands for heat [20]. In terms of soil condition, the slopy areas are not ideal for broad-leaved species such as maple, basswood, and oak whose growth requriements of soil moisture and fertility can not be met [15].

This study proposes a three-level model for forest health assessment using the AHP process, which enables the whole system analysis by sorting the quality grades of relevant indicators. All the indicators used in the model are parameters commonly used for forest stand survey. The convenience of raw data collection through sample plot survey helps to determine the numerical range and quality grade of each indicator. According to the theory of ecology, the structure of forest ecosystems determines their functions; optimal structure and potential function of forest ecosystems are largely controlled by the quality of forest site while closely related to forest management measures. To establish healthy forests and achieve the best ecosystem services, proper operation measures should be taken for adapting forest structure to the siting potential and functional requirements, ultimately obtaining the uniform of site condition, forest structure, system function, and operational management.

Acknowledgments

This paper is a revised and expanded version of a paper entitled “A composite index hierarchical assessment of forest ecosystem health: an example of *Pinus tabulaeformis Carr*.” presented at CIA 2014, Angeles City (Clark), Philippines, April 24 -26, 2014. This study was supported by the National Forestry Public Sector Research Project of Science and Technology Department, National Forestry Bureau of China (No. 201104045). Prof. Dexiang Wang is the corresponding author.

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