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Assessment of Soil Fertility Changes Over 7 Years after Strip Clearcutting and Afforestation in a Low-Quality Forest Stand in China

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Abstract

In order to change the low-quality forest stands into qualified forest stands with desirable productivity and other ecological benefits, it is necessary to adjust the stand structure and functions. In this study, a low-quality forest stand after strip clearcutting in the Lesser Khingan Range of China was investigated, and the principal component analysis and membership functions were combined to evaluate the integrated soil fertility in different experimental strips (horizontal strips: S1-6 m×100 m, S2-8 m×100 m, S3-10 m×100 m, S4- 15 m×100 m; Vertical strips: H1-6 m×100 m, H2-8 m×100 m, H3-10 m×100 m, H4-15 m×100 m). Results showed that most soil fertility indexes of the experimental strips showed moderate variation over time, the variation coefficient of soil pH was relatively smaller, and that of total phosphorus was the largest. The integrated soil fertility index (IFI) of different strips generally decreased at the initial period and then increased over time with the lowest value appeared after planting for 3 years. After afforestation for 7 years, the order of the IFI for the horizontal clearcutting strips is: S2>S3>S4>S1, while that of the vertical clearcutting strips is H1>H2>H4>H3. The integrated soil fertility index of S2 was the highest, which was also significantly higher than that of the year of harvest, showing the best effect. The soil fertility of some experimental strips (S2, S3, H1) was improved, however most of the clearcutting strips were remained at moderate level. Compared to vertical strips, the horizontal clearcutting strips showed better improvement in soil fertility. It is recommended that the 8 m×100 m horizontal clearcutting strip can be applied in forestry practice due to the significant improvement in soil fertility. However, soil fertility change is a long-term process, therefore long-term and consecutive observation in combination with scientific and effective study methods is still needed in order to accurately assess the changes of soil fertility in the clearcutting strips.

Keywords

Low-quality forest; Clearcutting; Soil fertility; Principal component analysis; Membership function

Introduction

Forest soil fertility refers to the capability of receiving, storing and transmitting energy to support the growth of forest stands, which is the foundation of sustainable forest development [1-3]. Study of soil fertility in forest ecosystems can be very complicated, because there are complex relationships between soil properties and stand productivity and the properties of soils may vary greatly within relatively small study area [4,5]. Meanwhile, different forest management methods will affect and limit the variation direction and intensity of forest soil fertility [6]. A decrease in soil fertility will affect not only the level of timber harvesting the forest can sustain, but also the other forest values. Therefore, identifying and reducing the negative impacts of strip clearcutting on forest soil should be an essential part of any strategy to achieve sustainable forest management and a better understanding of the variation of forest soil fertility in the long term can help provide scientific basis for the healthy management of forest stands.

The Lesser Khingan Range is one of the major forest regions in China. Due to excessive harvesting and natural disasters, the area of primitive forest in the region decreased dramatically, so did the timber productivity and quality. As a result, massive secondary forests and some over-mature forests with low canopy closure and unreasonable stand structures were formed, so-called low-quality forests [7-9]. In order to improve the ecosystem of the low-quality forests and increase the economic value of the timber products and non-timber products, it is quite necessary to take a series of integrated operating measures such as strip clearcutting and tending management on the low-quality forests [10]. Several studies have been conducted on the soil physical and chemical properties as well as short-term soil fertility of low-quality forests in this region. For example, Liu et al. [11] analyzed the soil physical and chemical properties of low-quality forest stands after strip clear-cutting for 1 year in the Lesser Khingan Range of China and obtained the impacts of different harvesting modes on the properties of surface soil. Mao et al. [6] applied grey relational analysis method to evaluate the soil fertility of low-quality forest stands with different harvesting modes (different harvesting intensity, different horizontal cutting strips, and different vertical cutting strips) after 2 years of clearcutting. However, the studies on long-term monitoring and assessment of the integrated soil fertility of low-quality forest stands after strip clearcutting in this region were rarely documented, which is critically important to evaluate the final forest management effects of different modes.

In this study, a low-quality forest stand after strip clearcutting and afforestation in the Lesser Khingan Range of China was investigated and a total of eight indicators were selected as evaluation indexes, then principal component analysis (PCA) and membership functions were combined to evaluate the integrated soil fertility in different experimental strips with various adjustment modes at different periods (harvesting year, 1-year after planting, 3-year after planting, 5-year after planting, 7-year after planting). The study can provide theoretical basis and technical support for the long-term monitoring and assessment of soil fertility in the low-quality forests in this region and help understand how forest soil ferity could be better improved with silviculture practices.

Methods

Study area

The study area was located in the 500th forest compartment

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(128°25'20"E, 47°12'10"N) at Mayongshun Forest Farm, which is at the southern part of the lesser Khingan Range of China. Except for slight slope in the southern watershed, the farm has a gentle terrain with average gradient of 10° and elevation being 117-284 m [11,12]. The study area has a continental monsoon climate. The winter is frigid and long, while the summer is short and rainy. The average annual rainfall is 641 mm and the average annual temperature is 1.1°C. The early frost appears in mid-September, the late frost is in mid-May, and the frost-free period can last for 113-126 d every year [11]. The annual sunshine duration is about 2,477h. The type of forest is broad-leaved mixed forest with canopy closure of 0.4, which is a typical low-quality forest stand.

Design of experimental strips

In 2007, horizontal and vertical strip clear-cutting were conducted respectively on the low-quality forest in the study area [11,12]. The settings of horizontal clear-cutting strips were as follows: each clear-cutting strip was set up along the same elevation with length of 100 m. A total of four different strip widths were set up, including S1 (6 m), S2 (8 m), S3 (10 m) or S4 (15 m). The undisturbed forest between the horizontal cutting strips was chosen as the contrast strip (SCK). The settings of vertical clear-cutting strips were as follows: each clear-cutting strip had distinct elevations with length of 100m. Four different strip widths for vertical clear-cutting were set up, including H1 (6 m), H2 (8 m), H3 (10 m) or H4 (15 m). The undisturbed forest between the vertical cutting strips was chosen as the contrast strip (HCK).

In 2008, the *Pinus koraiensis*, *Larix gmelini*, and *Picea koraiensis* seedlings were planted, respectively, in different sections of the clear-cutting strips. The reserved forest stand between the cutting strips was broad-leaved mixed forest with average stand age of 53a, average dbh of 16 cm, average tree height of 14 m, density of 534 trees.hm^{-2}, and canopy closure of 0.3. The soil is dark brown soil with average thickness of 45 cm. The general information about the experimental and contrast strips is presented in Table 1.

Collection, preparation and measurement of soil samples

The experimental strips and the contrast strips were mechanically divided into four sections, and five soil samples were collected from 0-20 cm soil profile in accordance with S-type mixed sampling method in each section. Then mixed samples were collected as per quartering method with each sample weighing 1 kg. The samples were brought back to the lab for air drying, grinding and screening to accept later chemical tests. The soil samples were collected in August every other year to undergo the aforesaid tests from 2007 to 2015. Taking into consideration the long-term monitoring objective and difficulty in actual operation, the study mainly measured the following soil nutrient indexes, including soil pH, soil organic matter content (SOM), total nitrogen content (TN), total phosphorus content (TP), total potassium content (TK), hydrolysable nitrogen content (HN), available phosphorus content (AP), and available potassium content (AK). The soil nutrient measuring methods and criteria refer to the corresponding forestry industry standards of China [13].

Evaluation of soil fertility

The integrated fertility index (IFI) of soil is an index frequently used to quantitatively evaluate the soil fertility, which can well reflect the changes in soil quality [14]. So far, many methods have been used to calculate integrated soil fertility index such as clustering analysis, principal component analysis (PCA), and fuzzy mathematics. Among these methods, PCA is a widely used statistical approach for quantitative soil fertility evaluation. In this study, the membership functions will be combined with PCA to analyze the change of the integrated soil fertility in the low-quality forest experimental strips.

Establishment of membership matrix

Since soil property indexes have spatial and temporal variability and their impacts on soil fertility are also dynamically changing, the membership function (MF) was introduced to achieve fuzzy evaluation of all the indexes. A membership function is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. Based on the membership values, each single soil fertility index can be compared and the contribution to the impacts of soil function can be evaluated [14]. There are two types of commonly used membership functions, namely S-type and parabola-type [15]. The soil organic matters (SOM), total nitrogen content (TN), total phosphorus content (TP), total potassium content (TK), hydrolysable nitrogen content (HN), available phosphorus content (AP), and available potassium content (AK) can be expressed by S-type function as follows:

$$f(x)=\begin{cases}1.0 & x\ge x_2\\ 0.1+0.9(x-x_1)/(x_2-x_1) & x_1<x<x_2\\ 0.1 & x\le x_1\end{cases} \tag{1}$$

The soil pH can be expressed with parabola-type function as follows:

$$f(x)=\begin{cases}0.1 & x\le x_1, x\ge x_4\\ 0.1+0.9(x-x_1)/(x_2-x_1) & x_1<x<x_2\\ 1.0 & x_2\le x\le x_3\\ 1.0-0.9(x-x_3)/(x_4-x_3) & x_3<x<x_4\end{cases} \tag{2}$$

Where, *f*(*x*) means the membership function, *x* is the measured

Table 1: General information about the experimental strips.

Plot no.	Slope (°)	Aspect	Slope position	Understory coverage (%)	Dominant species	Average dbh (cm)	Average tree height (m)
S1	3	North	Down	15	*Betula platyphylla*	21	15
S2	4	North	Down	10	*Betula costata*	18	13
S3	5	North	Down	10	*Betula costata*	20	14
S4	4	North	Down	10	*Tilia amurensis*	21	15
SCK	4	North	Down	15	*Betula platyphylla*	21	15
H1	6	Northeast	Down	50	*Ulmus pumila*	12	12
H2	6	Northeast	Down	45	*Ulmus pumila*	12	12
H3	6	Northeast	Down	40	*Betula costata*	12	12
H4	5	Northeast	Down	35	*Betula costata*	14	13
HCK	6	Northeast	Down	40	*Betula platyphylla*	14	14

value of the soil nutrient index, and X_1, X_2, X_3 and X_4 are the values at the turning points of the membership function. After processing by membership function, the membership matrix $A_{m\times n}=\{a_{ij}\}$ can be established, where j=1~m indicates the soil sampling quantity, and i=1-n indicates each soil fertility index. The calculated membership value is between 0.1 and 1.0, and the value indicates the membership degree of the index. The larger the membership value, the better the index. When the membership value is approaching 1.0, it means that the soil nutrient index can meet with the plant growth. On the contrary, when the membership value is close to 0.1, it means that the index can't meet the requirements of the plant [16,17].

Determining the weight of soil fertility index by PCA

Firstly, figure out the eigenvalue and variance contribution of each principal component. The number of components selected is based on the criteria of eigenvalue greater than one and the selected components can explain the most information of the dataset. The relationship between each component and the standardized evaluation indexes can be expressed as:

$$Y_k = u_{k1}X_1^* + u_{k2}X_2^* + \cdots + u_{kp}X_p^* \quad (3)$$

Where, Y_k is the k^{th} principal component (k=1,2,3,…,m), U_{k1} is the factor loading of the k^{th} principal component, and X_p^* is the standardized value of the evaluation index.

Secondly, for each evaluation index, the sum product function in MS Excel can be used to get the linear combination of the product of variance contribution percentage (λ_k) and index coefficient in the selected principal components. The index weight is then obtained by dividing the previous result by the accumulative variance contribution. For example, the first index weight can be calculated as:

$$w_1 = \frac{\sum_{k=1}^{m} u_{k1}\lambda_k}{\sum_{k=1}^{m} \lambda_k} \quad (4)$$

Since the sum of all the index weights should be equal to 1, it is necessary to carry out normalization on the index weights so as to get the final weights of the indexes.

Calculation of soil integrated fertility index

Soil integrated fertility index (*IFI*) can comprehensively reflect the status of soil fertility. Based on the value of this index, the soils in different experimental strips can be classified into different fertility levels. The *IFI* can be calculated as follows:

$$IFI_t = \sum_{i=1}^{n} w_i MF_{it} \quad (5)$$

Where, IFI_t is the integrated soil fertility index at the t^{th} year, w_i is the weight of the i^{th} soil fertility index (i=1,2,3,…,n), and MF_{it} is the membership value of the i^{th} soil fertility index at the t^{th} year.

Results

Summary of soil fertility indexes

The results of the soil fertility indexes in the low-quality forest harvesting strips at different time periods are summarized in Table 2. It is shown that the variation coefficient of soil pH value was the lowest (0.06) showing smaller variations, which indicated that strip clearcutting had the least effect on the pH value of the soil. The index of TP had the highest variation coefficient (0.47), far higher than other fertility indicators, which indicated that strip clearcutting had greater effect on the total phosphorus content of the soil. The variation coefficients of other fertility indicators varied from 0.15 to 0.26, indicating moderate variation.

Evaluation of single soil fertility index

In this study, the membership functions were used to calculate the membership of different soil fertility indexes and normalize the evaluation index dimensions so that all the indexes become comparable. In accordance with the physical and chemical characteristics of the soil in the study area as well as relevant studies [10,11], the values at curve turning points in membership function are determined (Table 3). Substitute the index values at the turning points into Eqs. (1) and (2), and calculate the membership values of all the indexes. The results are listed in Tables 4 and 5, respectively.

Based on Tables 4 and 5, we can find that the differences of soil pH membership value in the contrast strips at different time periods was insignificant (P>0.05). However, the differences of soil pH membership value in the clear-cutting strips at different time periods were statistically significant (P<0.05). Generally, the pH membership value in the clearcutting strips declined and then slightly increased again over time. In the harvesting year, the pH membership values of

Table 2: Statistical results of single soil fertility index after forest transformation in the Lesser Khingan Range.

Indicators	Max	Min	Mean	Standard deviation	Coefficient of Variation
pH value	6.19	4.77	5.53	0.35	0.06
Soil organic matter (g · kg^{-1})	57.84	20.21	32.74	8.35	0.26
Total nitrogen content (g · kg^{-1})	2.38	0.99	1.53	0.35	0.23
Total phosphorus content (g · kg^{-1})	1.04	0.18	0.41	0.19	0.47
Total potassium content (g · kg^{-1})	21.91	10.40	15.22	2.86	0.19
Hydrolysable nitrogen content (mg·kg^{-1})	91.11	46.53	71.90	10.59	0.15
Available phosphorus content (mg·kg^{-1})	3.80	1.42	2.74	0.53	0.19
Available potassium content (mg·kg^{-1})	38.61	18.46	30.51	4.47	0.15

Table 3: Values of turning points in membership function.

Turning point	pH value	Soil organic matter	Total nitrogen content	Total phosphorus content	Total potassium content	Hydrolysable nitrogen content	Available phosphorus content	Available potassium content
X1	5	20	1.0	0.2	5.0	30	2	20
X2	6	50	2.0	1.0	25	150	30	150
X3	6.5	-	-	-	-	-	-	-
X4	7.5	-	-	-	-	-	-	-

Table 4: Membership value of soil fertility index for the horizontal cutting strips.

Plot no.	Time [a]	pH	Soil organic matter (g.kg-1)	Total nutrients (g · kg-1)			Available nutrients (mg·kg-1)		
				Total nitrogen content	Total phosphorus content	Total potassium content	Hydrolysable nitrogen content	Available phosphorus content	Available potassium content
S1	0a	0.676	0.717	1.000	0.280	0.665	0.276	0.117	0.159
	1a	0.469	0.601	0.586	0.190	0.570	0.435	0.147	0.165
	3a	0.307	0.213	0.523	0.100	0.486	0.421	0.129	0.159
	5a	0.397	0.262	0.497	0.235	0.455	0.433	0.123	0.186
	7a	1.000	0.140	0.219	0.201	0.681	0.237	0.117	0.123
S2	0a	0.775	0.581	0.748	0.696	0.623	0.320	0.117	0.185
	1a	0.640	0.529	0.469	0.235	0.654	0.461	0.122	0.153
	3a	0.370	0.144	0.397	0.111	0.580	0.515	0.136	0.172
	5a	0.559	0.436	0.456	0.224	0.468	0.475	0.137	0.185
	7a	1.000	1.000	0.374	0.213	0.474	0.528	0.146	0.229
S3	0a	0.667	0.775	1.000	0.246	0.422	0.320	0.151	0.149
	1a	0.271	0.810	0.487	0.179	0.719	0.383	0.106	0.157
	3a	0.181	0.429	0.217	0.111	0.577	0.358	0.143	0.180
	5a	0.955	0.617	0.205	0.291	0.630	0.558	0.158	0.185
	7a	1.000	0.650	0.508	0.217	0.705	0.521	0.133	0.202
S4	0a	0.514	0.644	0.685	0.314	0.651	0.334	0.117	0.138
	1a	0.379	0.555	0.325	0.224	0.778	0.381	0.100	0.172
	3a	0.352	0.233	0.325	0.100	0.594	0.366	0.115	0.191
	5a	0.154	0.320	0.330	0.224	0.519	0.419	0.137	0.206
	7a	0.478	0.447	0.690	0.277	0.726	0.417	0.100	0.191
SCK	0a	0.208	0.642	1.000	0.314	0.651	0.311	0.117	0.177
	1a	0.262	0.402	0.208	0.156	0.752	0.310	0.116	0.182
	3a	0.442	0.485	0.379	0.111	0.681	0.342	0.111	0.172
	5a	0.658	0.552	0.550	0.201	0.586	0.548	0.153	0.210
	7a	0.924	1.000	0.431	0.303	0.820	0.334	0.112	0.113

Note: [a]: “0a” means the year after immediate harvesting, “1a” means 1 year after planting, “3a” means 3 years after planting, “5a” means 5 years after planting, and “7a” means 7 years after planting.

Table 5: Membership value of soil fertility index for the vertical cutting strips.

Plot no.	Time [a]	pH	Soil organic matter (g.kg-1)	Total nutrients (g · kg-1)			Available nutrients (mg·kg-1)		
				Total nitrogen content	Total phosphorus content	Total potassium content	Hydrolysable nitrogen content	Available phosphorus content	Available potassium content
H1	0a	0.703	0.402	0.784	0.798	0.548	0.224	0.117	0.167
	1a	0.253	0.423	0.955	0.483	0.612	0.448	0.100	0.169
	3a	0.451	0.106	0.541	0.269	0.472	0.395	0.126	0.188
	5a	0.856	0.378	0.330	0.336	0.343	0.503	0.129	0.212
	7a	0.946	0.446	0.802	0.289	0.803	0.425	0.130	0.100
H2	0a	0.757	0.570	1.000	0.876	0.591	0.512	0.149	0.156
	1a	0.163	0.474	0.955	0.415	0.532	0.498	0.100	0.178
	3a	0.586	0.155	0.676	0.235	0.386	0.469	0.130	0.213
	5a	0.100	0.282	0.664	0.213	0.377	0.503	0.139	0.198
	7a	0.982	0.495	0.660	0.215	0.625	0.465	0.148	0.123
H3	0a	0.748	0.707	1.000	0.730	0.651	0.390	0.117	0.199
	1a	0.307	0.549	0.721	0.606	0.438	0.459	0.117	0.201
	3a	0.361	0.201	0.298	0.269	0.430	0.400	0.116	0.194
	5a	0.109	0.339	0.415	0.246	0.350	0.489	0.138	0.202
	7a	0.960	0.539	0.140	0.240	0.683	0.286	0.122	0.135
H4	0a	0.820	0.944	0.937	1.000	0.618	0.482	0.117	0.152
	1a	0.487	0.309	0.937	0.370	0.414	0.367	0.100	0.165
	3a	0.568	0.157	0.325	0.224	0.457	0.349	0.119	0.172
	5a	0.424	0.191	0.156	0.213	0.373	0.397	0.123	0.213
	7a	0.856	0.720	0.100	0.200	0.589	0.426	0.119	0.100
HCK	0a	0.559	0.583	0.442	0.348	0.651	0.433	0.117	0.200
	1a	0.181	0.497	0.541	0.471	0.482	0.344	0.112	0.230
	3a	0.586	0.510	0.532	0.348	0.413	0.331	0.130	0.234
	5a	0.649	0.613	0.532	0.460	0.606	0.358	0.117	0.198
	7a	0.915	0.858	0.245	0.471	0.714	0.166	0.104	0.100

Note: [a]: “0a” means the year after immediate harvesting, “1a” means 1 year after planting, “3a” means 3 years after planting, “5a” means 5 years after planting, and “7a” means 7 years after planting.

all the harvesting strips were higher than that of the contrast strips. After planting for 3 years and 5 years, those values were less than the contrast strips.

The differences of soil organic matter content membership values in the clearcutting strips were statistically significant (P<0.05). The membership value basically declined first and then increased for each harvesting strip and was the lowest after planting for 3 years. After planting for 7 years, besides S2, the membership values of all the clearcutting strips were less than those of the corresponding contrast strips.

There were no significant differences in the membership value of total nitrogen content for the contrast strips at different time periods (P>0.05). However, the differences for the clearcutting strips at different periods were significant (P<0.05), showing a trend of decreasing followed by increasing over time. After planting for 7 years, the total nitrogen content of the clearcutting strips S3, S4, H1 and H2 were higher than the corresponding contrast strips.

The contrast strips had no significant differences in the total phosphorus content at different time periods (P>0.05). However, the differences for the clearcutting strips at different periods were significant (P<0.05). Similar to the variation trend of total nitrogen, the membership value of total phosphorus content in the clearcutting strips decreased first and then increased over time. After planting for 7 years, the membership value of the total phosphorus content in all strips were lower than the corresponding contrast strips.

The contrast strips had no significant differences in the total potassium content membership at different periods (P>0.05). There were significant differences in the total potassium content membership for the clearcutting strips over time (P<0.05). Except for S1, the total potassium content membership of other horizontal clearcutting strips showed the tendency of rise-decline-rise. The vertical clearcutting strips displayed the tendency of declining first and then rising. After planting for 7 years, except for S4 and H1, the membership values of total potassium content in the other strips were less than the corresponding contrast strips.

With regard to the hydrolysable nitrogen content membership, available phosphorus content membership and available potassium content membership in the clearcutting strips, they were all significantly different among different time periods (P<0.05). The membership value of hydrolysable nitrogen content in the soil of horizontal strips generally showed an increase trend over time, while that in the vertical strips were somewhat fluctuating. Except for S1 and S2, all the clearcutting strips displayed the tendency of decline-rise-decline in the available phosphorus content membership. In addition, the available potassium content membership was generally rising in all the strips. After planting for 7 years, for the horizontal clearcutting strips, the hydrolysable nitrogen content membership and available potassium content membership were higher than that of contrast strip, S1 and S2 had higher available phosphorus content membership than the contrast plots, and S2 had the highest hydrolysable nitrogen content membership. For the vertical clearcutting strips, the membership values of hydrolysable nitrogen content, available phosphorus content and available potassium content were all higher than the contrast strip.

Comprehensive Evaluation of Soil Fertility

Determining the weight of each evaluation index

The statistical software SPSS19.0 was used to conduct principal component analysis. The average membership values of the soil fertility indexes such as soil pH (X_1), organic matter content (X_2), total nitrogen content (X_3), total phosphorus content (X_4), total potassium content (X_5), hydrolysable nitrogen content (X_6), available phosphorus content (X_7), and available potassium content (X_8) were used to determine the weight of each soil fertility index.

According to the running results of PCA, the first principal component accounted for 32.28% of total variance, and soil pH, organic matter content, and total potassium content had greater loads; the second principal component explained 25.22% of variability of the data and hydrolysable nitrogen content, available phosphorus content , and available potassium content had greater loads; the third principal component contributed 17.52% of the variance and total nitrogen content and total phosphorus content had greater loads. The eigenvalues of the first three principal components all greater than 1.0 and the accumulative variance contribution reached 75%, therefore the first three principal components can explain the major information of soil fertility. The expressions for the first three components are as follows:

$$F_1 = 0.801X_1 + 0.752X_2 + 0.001X_3 + 0.113X_4 + 0.708X_5 - 0.165X_6 + 0.055X_7 - 0.399X_8$$

$$F_2 = 0.156X_1 + 0.07X_2 - 0.006X_3 - 0.061X_4 - 0.441X_5 + 0.793X_6 + 0.858X_7 + 0.521X_8$$

$$F_3 = 0.042X_1 + 0.357X_2 + 0.863X_3 + 0.866X_4 - 0.034X_5 + 0.078X_6 - 0.166X_7 + 0.090X_8$$

Eq. (4) was used to calculate the original weight of each soil fertility index. The resulted index weights were then normalized and the final weights for the eight indexes (X_1-X_8) are as follows: *w* (0.187, 0.205, 0.120, 0.131, 0.047, 0.128, 0.148, 0.034).

Results of integrated soil fertility index

In combination with the membership value of each soil fertility index and the index weights obtained by PCA, the integrated soil fertility index was computed based on Eq. (5) and the results are shown in Table 6 and Figure 1. It is shown that no matter what kind of clearcutting mode was applied; the integrated soil fertility index basically presented the tendency of declining first and then rising. The integrated soil fertility index reached the lowest value after planting for 3 years. After afforestation for 7 years, the order of the integrated soil fertility index for the horizontal clearcutting strips is: S2>S3>S4>S1, while that of the vertical strips is H1>H2>H4>H3. The horizontal clearcutting strip S2 (8m-wide) had the highest integrated soil fertility index, which was significantly higher than that of the corresponding contrast strip. Among the vertical strips, the integrated soil fertility index of H1 was the largest, which was also higher than the corresponding contrast strip.

Table 6: Integrated soil fertility index of low-quality forest experimental strips at different time periods.

Plot no.	0a	1a	3a	5a	7a
S1	0.519	0.416	0.278	0.320	0.352
S2	0.539	0.428	0.280	0.387	0.584
S3	0.524	0.403	0.263	0.499	0.536
S4	0.447	0.359	0.264	0.269	0.409
SCK	0.425	0.275	0.340	0.456	0.571
H1	0.490	0.418	0.304	0.428	0.517
H2	0.613	0.406	0.358	0.293	0.507
H3	0.605	0.439	0.275	0.278	0.430
H4	0.703	0.402	0.296	0.259	0.449
HCK	0.433	0.353	0.412	0.469	0.512

Note: [a]: "0a" means the harvest year, "1a" means 1 year after planting, "3a" means 3 years after planting, "5a" means 5 years after planting, and "7a" means 7 years after planting.

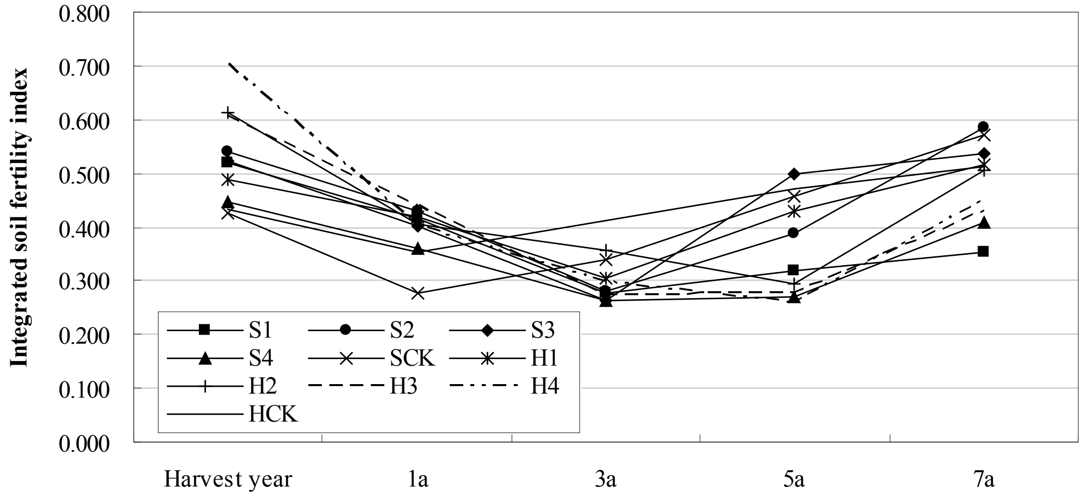

Figure 1: Changes of integrated soil fertility index over time.

Zhang et al. [18] divided the soil fertility quality index into five classes as follows: I: $IFI \geq 0.80$, qualified soil fertility; II: $0.60 \leq IFI<0.80$, better soil fertility; III: $0.40 \leq IFI<0.60$, moderate level of soil fertility; IV: $0.20 \leq IFI<0.40$, relatively poor soil fertility; and V: $IFI<20$, poor soil fertility. In this study, about 87.5% of the clearcutting strips after afforestation for 7 years were within the range of 0.4 and 0.6, indicating moderate level of soil fertility. The horizontal strips S2 (8 m-wide) and S3 (10 m-wide) and the vertical strip H1 (6 m-wide) had higher soil fertility index than the past, which means that the soil fertility of those strips had been improved to some degree, however they were still in the moderate level of soil fertility.

Conclusions and Discussion

The soil fertility in the low-quality forest clearcutting strips at different time periods in the Lesser Khingan Range of China was evaluated based on principal component analysis and membership function. The evaluation method of soil fertility can directly affect the correctness, objectivity and guidance of the evaluation results [19]. Therefore, while assessing the soil fertility, the subjectivity should be reduced as much as possible so that the evaluation result can objectively reflect the true state of soil fertility. Due to the dimensional variance of all the indexes, the membership functions were used to normalize them so that all the soil fertility indexes can be comparable. The weight of each soil fertility index was determined through principal component analysis in consideration of the mutual dependence of some indexes to some degree, which also avoided subjective randomness.

The analyses of this study suggest that strip clearcutting had greater effect on the total phosphorus content of the soil, but had least effect on soil pH in the low-quality forest stand. The soil fertility indexes of different strips generally decreased at the initial period and then increased over time with the lowest value appeared after planting for 3 years. After afforestation for 7 years, the order of the integrated soil fertility index for the horizontal clearcutting strips is: S2>S3>S4>S1, while that of the vertical clearcutting strips is H1>H2>H4>H3. The integrated soil fertility index of S2 (8m) was the highest, which was also significantly higher than that of the year of harvest, showing the best effect. Therefore, it is recommended that the 8 m horizontal strip clearcutting can be applied in forestry practice.

It was also noted that even though the soil fertility of some experimental strips (S2, S3, H1) was improved, most clearcutting strips were remained at moderate level. It is well known that soil fertility quality can be affected by several different influence factors [20]. The soil fertility quality of low-quality forest clearcutting strips differed both in spatial scale and temporal scale. Therefore, long-term and consecutive observation in combination with scientific and effective study methods is critically required in order to accurately assess the change in the soil fertility of the clearcutting strips. Although a lot of soil samples were collected in this study, there are still some limitations in this study. Future research should take into consideration the combination of GPS and GIS in the soil fertility quality evaluation of low-quality forest clearcutting strips, and a complete soil fertility quality database should be established in order to provide importance reference for the sustainable operation and development of the forest.

Competing Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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