

Article

Selection of the Optimal Timber Harvest Based on Optimizing Stand Spatial Structure of Broadleaf Mixed Forests

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Abstract: There is increasing interest in optimizing stand structure through forest management. The forest structure influences growth and maintains the structure, promoting sustainability. Structure-based forest management (SBFM), which is based on the spatial relationships between a reference tree and its four nearest neighbors, considers the best spatial structure for the stand and promotes the development towards a healthy and stable state by selectively thinning specific trees. This management method is a scientific approach for sustainable forest management, and appropriate harvesting is the core principle of uneven-aged forest management. However, the application of this approach in the management of uneven-aged mixed stands is a challenge because their dynamics are more difficult to elucidate than those of planted or pure stands. This study presented a stand spatial structure optimization model with a transition matrix growth model for selecting suitable timber harvest during uneven-aged mixed-forest management optimization. The model was developed using three neighborhood-based structural indices (species mingling, diametric differentiation, and horizontal spatial pattern) and diameter diversity indices. The approach was applied to four broadleaf stands in the Maoershan Forest Farm of the Heilongjiang Province. The results demonstrate that optimizing the stand spatial structure with a transition matrix growth model improved the objective function values (F -index) by 23.8%, 12.8%, 14.6%, and 28.3%, and the optimal removal of trees from the stands ranged from 24.3% to 25.5%. The stand structure in the next cycle (after 5 years) was closer to the uneven-mixed state. The main conclusion of this study is that optimizing the stand spatial structure with a transition matrix growth model can improve the speed and accuracy of tree selection for harvesting in unevenly mixed forests, thus helping regulate stable and diverse forest growth.

Keywords: broadleaf forests; matrix growth model; spatial structure; combinatorial optimization; forest management



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1. Introduction

Natural forests have a complex species composition and stand structure compared to planted forests. Therefore, the optimization of forests is often carried out through the management of existing stands to optimize them into a composite, near-natural, mixed heterogeneous stand structure, with the intention of adapting the stand structure and improving the forest quality while enhancing its ecological services [1–3]. Forest growth models are crucial to management because they provide information for harvest schedules by predicting future timber yields. Among them, the transition matrix growth model has been widely used in the management optimization of uneven-aged forests [4,5]. Due to the uncertainty of the age of uneven-aged forests and the complexity of the stand structure, it is difficult to make long-term forest dynamics predictions for them. However, the transition matrix growth model uses vectors to represent the forest diameter distribution, meanwhile simultaneously predicting the change in the diameter structure distribution of uneven-aged forests using a probability transition matrix [6,7]. The variable parameter matrix

model has been proposed since it can consider multiple types of variation (e.g., spatial, site, climate, and environmental variability). Liang et al. (2015) [8] suggest replacing the fixed-parameter model with a variable constrained by stand factors, resulting in variable parameter matrix models that are more comprehensive, accurate, and robust for a wider range of applications [8].

The forest structure can be described by the arrangement of trees across a landscape and their associated characteristics. The forest structure mainly includes the spatial structure and non-spatial structure. The forest spatial structure is the most representative modifiable factor and, to some extent, determines the stability and development of the forest. The spatial forest structure has been identified as a key to the management of uneven-aged forests [9–11]. Mingling, a uniform angle, and dominance indices are the common parameters that can be used to quantify and analyze the stand spatial structure. Diameter class diversity is also very important for forest management optimization as an important aspect of stand structural diversity. Some traditional diversity indices have been widely used in forest management to quantify stand structural diversity, including Simpson and Shannon size diversity indices and Pielou and Simpson evenness indices [12,13]. The rational management of the stand structure can improve stand quality, diversity, and stability by continuously optimizing the distribution pattern, the spatial dominance of tree sizes, and competition among trees.

Currently, models for optimizing the stand spatial structure have been used in the study of natural and plantation forests. A stand spatial structure optimization model is a multi-objective optimization approach that uses selective cutting to remove a certain number of trees to adjust the stand structure to the optimal state and maximize the function of the stand [14,15]. In the 1980s, research on the optimization model of the spatial structure of forest stands began and, according to the current research status, a comprehensive harvest index P was proposed based on the spatial structure parameters of forest stands to optimize the spatial structure of four case studies in northeast China [16]. Li et al. [17] developed bivariate thinning priority indices based on tree neighbor–spatial relationships. They used these indices to parameterize thinning in Korean pine–broadleaved mixed forests in northeast China and pine–oak mixed forests in northwest China. Dong et al. [18] present a tree-level harvest planning tool that considers four neighborhood-based structural indices (species mingling, diametric differentiation, horizontal spatial pattern, and crowdedness of trees) while concurrently recognizing other operational constraints, using a simulated annealing algorithm, and applied this approach to four 1 ha mapped stands in northeast China.

In mixed uneven aged stands, forest management should optimize the spatial distribution, diameter distribution, and species richness in ways that resemble those found in natural stands. In this study, a transition matrix growth model was used to optimize the spatial structure of stands and to compare and analyze growth changes in the stand structure in the next cycle after optimization. This study investigated the following problems: (1) the selection of the optimal timber harvest according to optimizing the stand spatial structure with a variable transition matrix growth model for broadleaf forests, and (2) applying the model to four different mixed broadleaved forests to optimize dynamic structure management, comparing the changes in each parameter before and after optimization to determine the optimal harvesting scheme.

2. Methods

2.1. Study Site

The research area of this study is located in Maoershan Forest Farm in the southeast of Heilongjiang Province ($45^{\circ}20'–45^{\circ}25' N$, $127^{\circ}30'–127^{\circ}34' E$), with a total area of 26,453.7 ha (Figure 1). The area belongs to a typical low mountainous, hilly area, with an average slope of $\sim 10^{\circ}–15^{\circ}$, and each slope level is evenly distributed in the forest, with an average elevation of 381 m. The area has a temperate continental monsoon climate with short summers and long winters, a mean annual temperature of $3.0^{\circ} C$, and a mean annual

rainfall of 723.8 mm. The study area is rich in vegetation types consisting mainly of natural secondary forest stands in different stages of succession, including broadleaf mixed forests dominated by valuable species, birch forests, and oak forests. Natural secondary forests are plant communities that grow and reproduce naturally after the destruction of primary forests. Natural secondary forests are a category of forests that have formed following human or natural disturbances such as clearing, grazing, logging, hunting, and fire in natural forests. The area has an abundance of tree species including: *Pinus koraiensis* Siebold & Zucc, *Picea asperata* Mast, *Larix gmelinii* (Rupr.) Kuzen, *Fraxinus mandshurica* Rupr., *Juglans mandshurica* Maxim, *Quercus mongolica* Fisch., *Tilia tuan* Szyszyl, *Acer pictum* Thunb, *Ulmus pumila* L., *Betula platyphylla* Sukaczew, and *Populus davidiana* Dode.

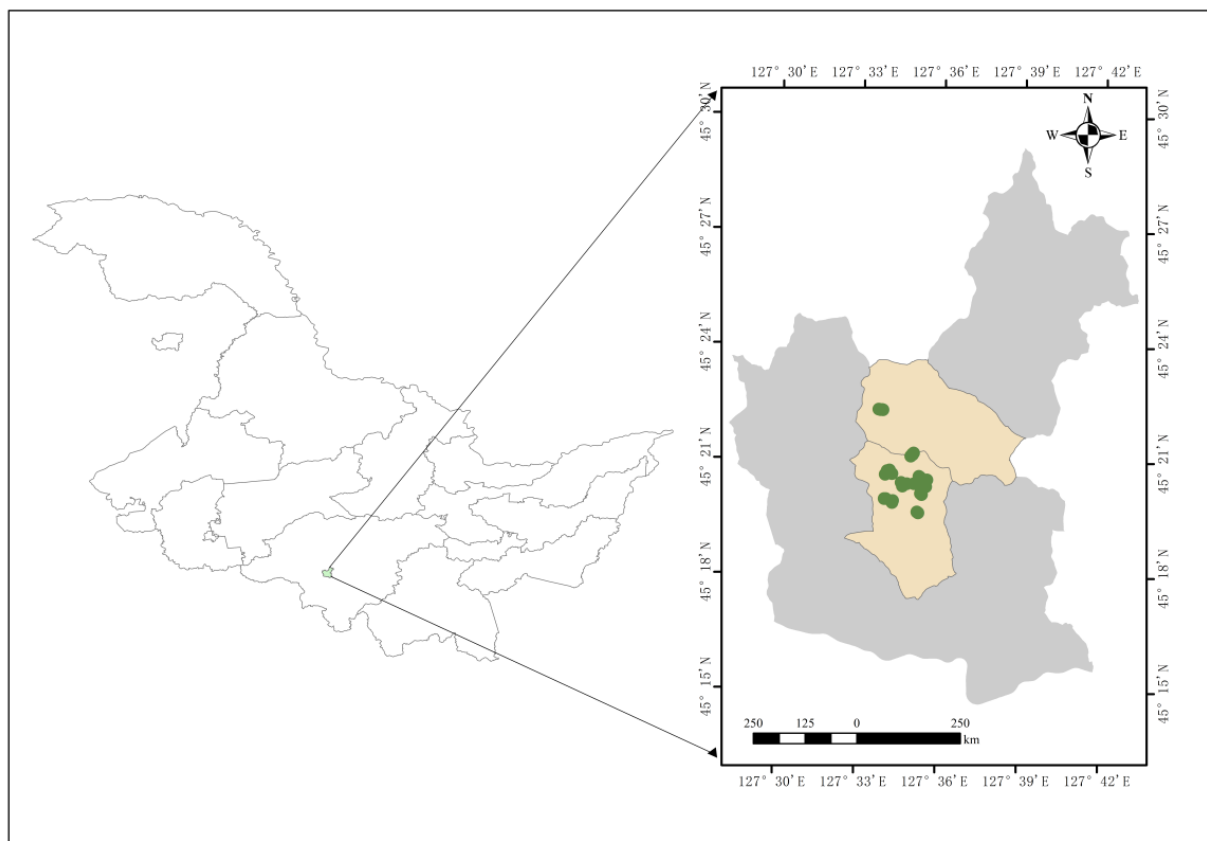


Figure 1. The locations of the studied forest stand in Heilongjiang Province in northeast China and the distribution of the studied plots in Maoershan Forest Farm.

Study data were obtained from 30 plots in broadleaf mixed forest surveyed in both 2015 and 2020 in Maoershan Forest Farm (Table 1). There was no forestry work carried out in these study sites during these 5 years (between 2015 and 2020). Each plot was 0.06 hm which was then divided into 10 m × 10 m grids by the adjacent grid method, and all trees with DBH ≥ 5 cm at breast height were recorded for tree species, number, diameter at breast height (DBH), tree height (*H*), crown width, condition, and coordinates.

Table 1. Basic characteristics of the studied plots.

Plot	Mean Elevation (m)	Slope (°)	Slope Position	Slope Aspect	Number of Species
1	367	<5	Down	South	12
2	357	<15	Medium	South	13
3	459	<15	Up	South	13
4	457	<15	Down	South	11

Table 1. Cont.

Plot	Mean Elevation (m)	Slope (°)	Slope Position	Slope Aspect	Number of Species
5	359	<5	Medium	South	12
6	371	<5	Medium	South	14
7	375	<5	Up	South	13
8	469	<5	Up	South	9
9	475	<5	Up	South	8
10	503	<5	Medium	South	10
11	490	<5	Medium	East	10
12	522	<5	Medium	East	12
13	542	<5	Down	South	10
14	491	<15	Down	South	7
15	501	<5	Up	South	7
16	444	<15	Up	South	11
17	469	<5	Up	South	8
18	465	<5	Medium	North	9
19	415	<5	Medium	North	10
20	396	<5	Medium	South	13
21	363	<5	Flat	None	12
22	402	<5	Down	North	8
23	413	<15	Medium	North	10
24	314	<15	Medium	None	13
25	408	<15	Medium	North	12
26	414	<15	Medium	Southwest	9
27	417	<15	Medium	Northwest	12
28	345	<15	Medium	North	10
29	320	<5	Medium	None	8
30	303	<5	Down	None	6

2.2. Stand Spatial Structure Optimization

The core of the stand spatial structure optimization model is the management objectives, and different management objectives correspond to different stand structures. In contrast, as a directly adjustable factor, the stand structure is an essential parameter of the stand spatial structure optimization model. As a multi-objective planning model, the stand spatial structure optimization model results from the interaction factors of the structure. Therefore, this study adopted the marginal decreasing efficiency of the Cobb–Douglas production function to construct a stand spatial structure optimization model. The main objectives were to (1) reasonably adjust the stand diameter class distribution without destroying the original stand structure to make it closer to the natural uneven-aged distribution and (2) optimize the spatial structure (species mingling, diametric differentiation, horizontal distribution pattern, stand competition, and diameter class diversity).

2.2.1. A Transition Matrix Growth Model

We selected seven stand factors, such as diameter at breast height (*DBH*), basal area (*BA*), average diameter at breast height (D_g), overall basal area of trees larger than the object tree (*B*), maximum diameter at breast height (D_m), and stand density (*NDD*), two diversity indicators, such as tree species diversity (H_1) and size diversity (H_2), and two site factors, such as slope and aspect (Table 2). Generalized least squares regression and Tobit and Probit models were used to fit the diameter growth, recruitment, and mortality models, respectively, to determine transfer probability and mortality for each diameter class [19,20]. The transition matrix growth model was used to predict the stand diameter distribution for the next cycle.

Table 2. The variables utilized and variable definition in the models.

Variables	Definition	
Variables in 5 years (2015–2020)	G	Tree diameter growth during five years
	R	Number of trees recruited to the minimum diameter class during five years
	Mr	The mortality rate of a live tree during five years; 1 for dead tree and 0 for alive tree
Stand variables	DBH	Diameter at breast height
	DBH ²	Square of diameter at breast height
	NDD	Number of trees per hectare
	BA	Stand basal area
	D _g	Average diameter at breast height
	B	Overall basal area of trees larger than the object tree
	Dm	Maximum diameter at breast height
Diversity variable	H ₁	Tree species diversity ^b $H_1 = -\sum_{i=1}^m \frac{BA_i}{BA} \ln\left(\frac{BA_i}{BA}\right)$
	H ₂	Tree size diversity $H_2 = -\sum_{i=1}^m \frac{BA_j}{BA} \ln\left(\frac{BA_j}{BA}\right)$
Site variables	Aspect	Plot aspect; north as 0, west as 90, south as 180, and east as 270(°)
	Slope ^a	Plot slope

^a, $SL\cos ASP = \text{Slope} \cdot \cos(\text{Aspect})$; $SL\sin ASP = \text{Slope} \cdot \sin(\text{Aspect})$. ^b, where BA_i and BA_j are the basal area of the trees of species group i and diameter class j , respectively.

The general expression for the transition matrix growth can be formulated as follows:

$$N_{t+w} = A_t N_t + R_t \quad (1)$$

Matrices N , A , and R are defined as follow:

$$\begin{bmatrix} N_{1,t+w} \\ N_{2,t+w} \\ \vdots \\ N_{i,t+w} \\ \vdots \\ N_{k-1,t+w} \\ N_{k,t+w} \end{bmatrix} = \begin{bmatrix} a_{1,t} & & & & \\ b_{1,t} & a_{2,t} & & & \\ & & \ddots & & \\ & & & \ddots & \\ & & & & b_{n-2,t} & a_{n-1,t} \\ & & & & b_{n-1,t} & a_{n,t} \end{bmatrix} \cdot \begin{bmatrix} N_{1,t} \\ N_{2,t} \\ \vdots \\ N_{i,t} \\ \vdots \\ N_{k-1,t} \\ N_{k,t} \end{bmatrix} + \begin{bmatrix} R_t \\ 0 \\ \vdots \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

In the formula, w is the interval time of the next period; N_{t+w} is the diameter distribution predicted by the interval time w ; N_t is the actual diameter distribution at time t and A_t is the transition probability matrix at time t ; $N_{i,t+w}$ is the predicted number of trees in the interval w and $N_{i,t}$ is the actual number of trees at time t , $i = 1, 2 \dots, k$; and R_t is the number of recruitment trees at the time t .

$$a_{i,t} = 1 - b_{i,t} - m_{i,t} \quad (3)$$

In the formula, $a_{i,t}$, $b_{i,t}$, and $m_{i,t}$ represent the transition probabilities of survivorship, growth, and mortality, respectively, and they play a crucial role in the matrix models.

In this study, the simulation results of the model were tested using a ten-fold cross-validation method under the R caret package. Then, the root mean square error (RMSE) and coefficient of determination (R^2) were calculated directly from the prediction errors as quantitative measures of accuracy, and then the total RMSE and R^2 were calculated as follows.

$$RMSE = \frac{1}{k} \sum_{j=1}^k RMSE_j = \frac{1}{k} \sum_{j=1}^k \left(\sqrt{\frac{1}{n} \sum_{i=1}^{n_j} (Y_{ij} - \hat{Y}_{ij})^2} \right) \quad (4)$$

$$R^2 = \frac{1}{k} \sum_{j=1}^k \frac{2}{j} R = \frac{1}{k} \sum_{j=1}^k \left(1 - \frac{\sum_{i=1}^{n_j} (Y_{ij} - \hat{Y}_{ij})^2}{\sum_{i=1}^{n_j} (Y_{ij} - \bar{Y}_{ij})^2} \right) \quad (5)$$

$RMSE_j$ and R^2_j represent the $RMSE$ and R^2 in the j th folder where k is equal to 10; Y_{ij} is the i th observed value in the j th fold; $\hat{Y}_{ij}$ represents the i th estimated value in the j th fold; $\bar{Y}_{ij}$ is the mean observed value in the j th fold; and n_j denotes the number of observations in the j th fold.

2.2.2. Optimization Formulations

Three indices were selected to analyze the spatial structure of the stand, including the complete mixing index (M_c), uniform angle index (W), and dominance index (U) (Table 3). To eliminate edge effects, a 5 m buffer area was used. Thus, trees in the core area were treated as reference trees, and the corresponding parameters were calculated, whereas other trees in the buffer area were treated as neighbors. M_c refers to the proportion of different species between the reference tree and its four nearest neighbors, reflecting stand species diversity; W refers to the horizontal distribution pattern of the reference tree and its four nearest neighbors; and U refers to the proportion of neighboring trees larger than the reference tree among all neighboring trees [21,22].

Table 3. Forest spatial structure index and index definition.

Index	Formula	Definition
Complete mingling index (M_c)	$M_{c_i} = \frac{1}{2} \left(D_i + \frac{C_i}{n_i} \right) \cdot M_i$	where C_i/n_i is isolation for nearest neighbor tree species; C_i is the number of different species in adjacent pairs of all neighboring trees; n_i is the number of the nearest neighboring trees; D_i is the Simpson index of the spatial structure unit i , $D_i = 1 - \sum_{j=1}^{S_i} p_j^2$; S_i is tree species of the spatial structure unit i ; p_j is proportion of trees of the j th species; M_i is a simple mingling index, $M_i = \frac{1}{n} \sum_{j=1}^n v_{ij}$, $v_{ij} = 1$, if reference tree i and its neighbor tree j are of different tree species, otherwise, $v_{ij} = 0$
Uniform angle index (W)	$W_i = \frac{1}{n} \sum_{j=1}^n w_{ij}$	Where α is the angle of two neighbor trees of the spatial structure unit, if the angle α of two neighbor trees; where: $w_{ij} = \begin{cases} 1; \text{if } \alpha_j < \alpha_0 = 72^\circ \\ 0; \text{otherwise} \end{cases}$
Dominance index (U)	$U_i = \frac{1}{n} \sum_{j=1}^n z_{ij}$	where z_{ij} takes the value 1 if the j th neighbor (d_j) is smaller than the reference tree i (d_i), and the value 0, otherwise, $z_{ij} = \begin{cases} 1; d_j < d_i \\ 0; \text{otherwise} \end{cases}$

Diameter class diversity is one of the important indices to reflect stand structure diversity. The diversity index can better quantify the diameter class diversity to facilitate structure diversity in forest management. The diameter class diversity dominance index mainly reflects the dominance of the richest diameter class distribution. The evenness index is mainly used to describe the evenness of the range distribution of different diameter classes [23,24]. In this study, the *Margalef*, *Shannon* and *Simpson* indices, and *Pielou* and *Simpson* evenness indices were selected to describe the diameter class diversity change rule to reflect stand structure diversity [25,26] (Table 4).

Table 4. Diameter structure diversity index and index definition.

Index		Formula
Range of diameter index	Margalef index	$D_{Mg} = (S - 1) / \ln(BA)$
	Shannon index	$H' = - \sum_{i=1}^S p_i \ln(p_i)$
Dominance Index	Simpson index	$D_{si} = 1 - \sum_{i=1}^S p_i^2$
Evenness index	Pielou evenness index	$E_{Sh} = H' / \ln S$
	Simpson evenness index	$E_{Sh} = D_{si} / \left(1 - \frac{1}{S}\right)$

S is the number of diameter classes, BA is the basal area per unit area (m^2/ha), and p_i is the percentage of the basal area of the i diameter class to the stand basal area.

Single factor analysis of variance (one-way ANOVA) was used for analysis of stand structure under different plots and years. Significant differences were detected at $p < 0.05$. All data were processed by R software 4.3.1 and Origin Pro 8.0 was used to create the figures.

This study took the ideal spatial structure of a natural mixed stand as a stand spatial optimization objective. We defined the ideal spatial structure as: (a) the mean complete mixing index is as large as possible, a maximum of 1; (b) the spatial distribution pattern of trees is random, that is, the mean angular scale is 0.5; and (c) the dominance index should approach 0.25 [22,27]. The comprehensive F -index of the spatial structure of the stand is constructed based on these above optimization objectives. The minimum F -index value indicates a smaller difference between the optimal spatial structures and the actual structure.

The model is as follows:

$$\min F = \sqrt{(\overline{M_c} - 1)^2 + (\overline{U} - 0.25)^2 + (\overline{W} - 0.5)^2} \quad (6)$$

$$0 \leq m_{i,t} \leq N_{i,t+w} - N_{i,t} \quad (7)$$

$$1.2 \leq q \leq 1.7 \quad (8)$$

$$NS = NS_0 \quad (9)$$

$$ND = ND_0 \quad (10)$$

$$D_{Mg1} \geq D_{Mg} \quad (11)$$

$$H'1 \geq H' \quad (12)$$

$$D_{si1} \geq D_{si} \quad (13)$$

where: $N_{i,t}$ is the number of trees at the i th diameter class in the current period; $N_{i,t+w}$ is the number of trees at the i th diameter class in the next cycle (5 years); $m_{i,t}$ is the number of harvest trees; $i = 5, 10, 15, 20, \dots$; q is a measurement indicator that is used to qualify the diameter distribution and is calculated as $q = \exp(a \cdot d)$; a is the estimated parameter between the number of trees and diameter class when using the negative exponential function, namely $N = k \cdot \exp(-a \cdot d)$; and d is the width of diameter class, which was extracted from the practice of forest resource survey and management in northeast China. Numerous studies have indicated that the reasonable ranges of q value for natural uneven-aged forests usually varied between 1.2 and 1.7 [28,29]. ND and NS are the numbers of diameter classes and

tree species after thinning, while ND_0 and NS_0 are the numbers of diameter classes and tree species before thinning; D_{Mg} , H' , D_{si} ; $D_{Mg}1$, $H'1$, $D_{si}1$ are the diameter class diversity indices (*Margalef*, *Shannon*, and *Simpson* index) before and after optimization, respectively; and $\overline{M_c}$, $\overline{W}$, $\overline{U}$ are the mean values of complete mingling index, uniform angle index, and dominance index, respectively.

The optimal scheme was obtained after 5000 simulations using the Monte Carlo method. Equation (6) is the overall objective function of stand spatial structure optimization, and the smaller the value of the objective function, the smaller the difference between the existing stand structure and the best stand structure. Equation (7) is the harvest number constraint of simulation optimization. Equations (8)–(10) are diameter distribution adjustment and tree species constraint. Equations (11)–(13) are the stand diameter diversity constraints.

3. Results

3.1. Dynamic Analysis of Stand Structure

In Figure 2 and Table 5, the distribution of the complete mixing index ranged from 0.19 to 0.71. The complete mixing index of the stand increased with time, and the overall degree of mixing increased with changes in the stand structure, possibly due to natural regeneration. The range of the uniform angle index was 0.48–0.59. The analysis of variance (ANOVA) results showed that the uniform angle index of different plots in the same year had significant differences ($p < 0.05$). Overall, 80% of trees were in a clumped distribution. However, the uniform angle index of the stands changed little with time and remained in a clumped distribution. This may also be due to the long-term natural regeneration in these stands.

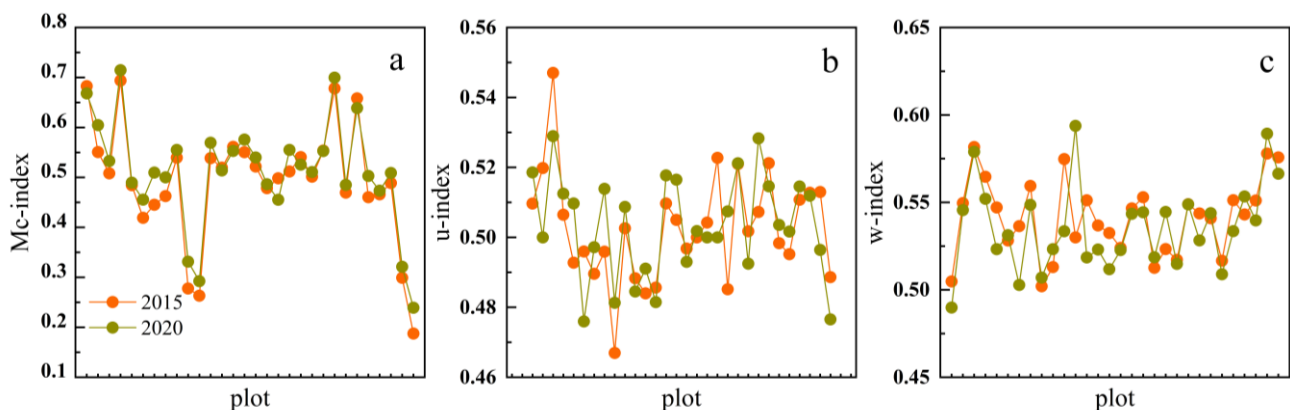


Figure 2. Forest spatial structural index changes with time, where (a), (b), and (c) represent the complete mixing index (M_c), dominance index (U), and uniform angle index (W), respectively.

Table 5. Forest spatial structure and diameter diversity indices' value changes with time.

Index Value		2015 (Year)	2020 (Year)	Range
Spatial structural index	Number of plots	30	30	-
	Number (N/hm)	1810	1911	-
	M_c -index	0.494	0.512	0.19~0.71
	W -index	0.541	0.536	0.48~0.59
	U -index	0.503	0.503	0.46~0.54
	<i>Margalef</i>	5.089	5.426	2.68~6.23
Diameter diversity index	<i>Shannon</i>	2.645	2.664	2.03~2.93
	<i>Simpson</i>	0.917	0.918	0.86~0.94
	<i>Pielou</i> evenness index	0.925	0.912	0.84~0.98
	<i>Simpson</i> evenness index	0.972	0.970	0.93~0.99

The dominance index ranged from 0.46 to 0.54, indicating that the degree of stand size differentiation was average, trees were in moderate conditions, and the overall stand

variation was low. As the dominance index reflects the relative dominance of individuals within a structural unit, whereas the diameter class reflects the absolute position of trees at the community level, and because competition within the stands changes with succession as stands age over time, it was previously found that the change in the dominance index with diameter was not a simple linear relationship [30,31].

Table 5 and Figure 3 show the changes in each diameter class diversity index over time. From 2015 to 2020, the overall change in each diameter class diversity index was small with a gradually increasing trend, especially the *Margalef*, *Shannon*, and *Simpson* indices. The reason is that tree growth trees and recruitment contributed to increases in the diameter class diversity. The *Margalef* index is mainly used to describe the range of diameter classes, and the index varies with the number of classes of diameter and the BA of the stand. The mean *Margalef* index for the stands increased over time, indicating that the diameter class number increased with tree growth. The range of the *Shannon* index was from 0 to $\ln S$ and the Shannon index was at its maximum when the trees were evenly distributed among all diameter classes. The mean stand total *Shannon* index increased with time, suggesting a trend toward greater uniformity among all diameter classes with time. The *Simpson* index is the dominance index independent of the number of diameter classes. ANOVA showed that the *Simpson* indices of different plots in the same year were significantly different ($p < 0.05$), indicating that the dominance of the richest diameter class was different in different plots. The mean *Simpson* index for the whole stand increased over time. The *Pielou* and *Simpson evenness* indices are both measures of evenness. When the evenness index reaches the maximum, all diameter classes have the same richness. The overall stand evenness index increases and then decreases with time, indicating that the richness of each diameter class is not uniform as the size of the trees differentiates [32].

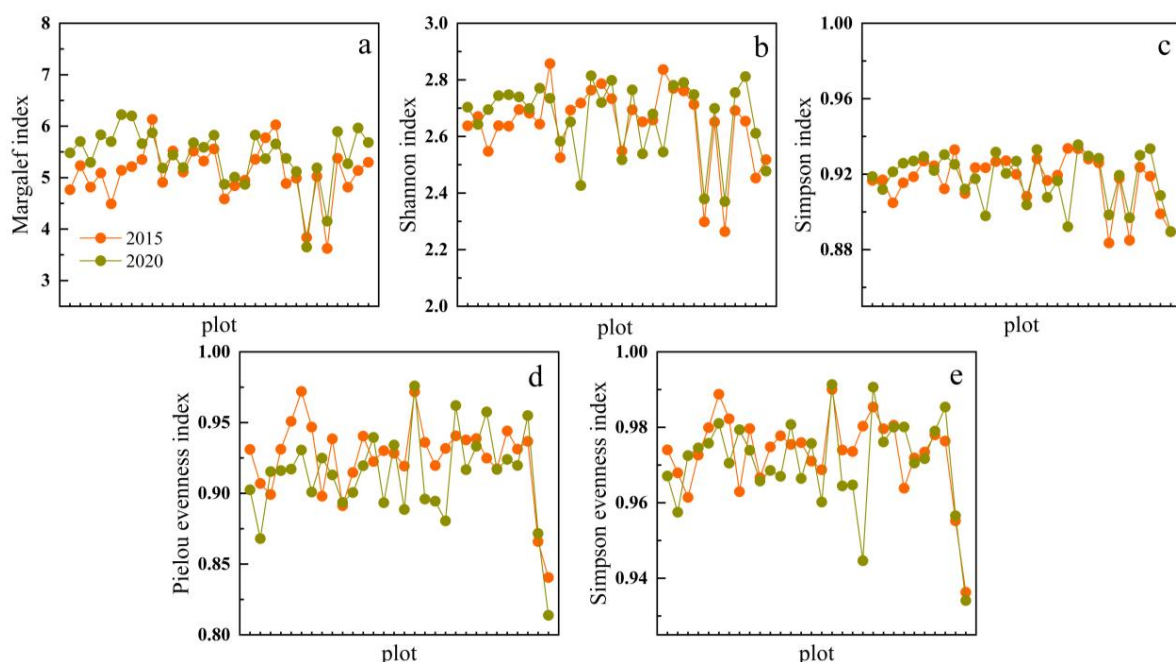


Figure 3. Forest diameter diversity index over time, where (a), (b), (c), (d), and (e) represent the *Margalef*, *Shannon*, *Simpson*, *Pielou* evenness, and *Simpson* evenness index, respectively.

3.2. A Variable Transition Matrix Growth Model

Table 6 reports the results of the variable transition matrix growth model. The growth model showed that *DBH*, H_1 , *B*, *BA*, and *SLsinASP* were significantly and negatively correlated with tree growth ($p < 0.01$), and DBH^2 , H_2 , D_g , and *Dm* were significantly and positively correlated with tree growth ($p < 0.01$) (Table 6). The mortality model showed that *DBH*, *BA*, H_1 , *B*, and *SLsinASP* were significantly and positively correlated with tree mortality ($p < 0.01$). The recruitment model showed that *BA*, *NDD*, H_2 , *B*, *Dm*, and *SLsinASP*

were significantly and negatively correlated with tree recruitment ($p < 0.01$), and H_1 was significantly and positively correlated with stand recruitment ($p < 0.01$) (Table 6). Larger BA reflected the higher intensity of competition among the trees, which did not promote tree diameter growth or the number of recruits, with increased competition among trees resulting in increased tree mortality; furthermore, tree species diversity (H_1) harmed tree diameter growth and increased tree mortality. Diameter growth increased tree mortality and promoted small tree recruitment, as small trees growing around large heterospecific trees, which means a tree of a different species than the small trees growing around it, are more likely to survive than small trees growing around large trees of the same species [10,32]. Increased tree size diversity (H_2) promoted diameter growth while negatively affecting tree recruitment, as differences in tree size and interactions between neighboring trees can contribute to diversity in stand DBH , tree height, and canopy [33,34].

Table 6. Parameter estimates and the associated lack-of-fit statistics for the variable transition matrix model.

Model	Increment	Mortality	Recruitment
Intercept	−1.09 ***	−1.72 ***	1.31×10^2 ***
DBH	−0.13 ***	0.03 ***	−
DBH^2	0.01 ***	−	−
BA	−0.02 ***	0.04 ***	−2.86 ***
H_1	−0.37 ***	0.62 **	2.39×10^1 ***
H_2	0.69 ***	−	$−0.6 \times 10^2$ ***
D_g	0.05 ***	−	−
B	−0.02 ***	0.05 ***	−2.65 ***
Dm	3.57 ***	−	−0.003 ***
NDD	−	−	−0.007 ***
$SLsinASP$	−0.01 **	0.03 ***	−1.35 ***
$\log\sigma$ ^a	−	−	2.84 ***
R^2 ^b	0.647	0.1	0.259
AIC	3488	1380	2082
BIC	3555	1417	2137
$\log\text{Lik}$ ^c	−1733	−684	−1032
Df ^d	3152	343	−

^a log sigma: log of the standard deviation of residuals. ^b R^2 : Nagelkerke's pseudo r-squared. ^c logLik: log-likelihood value. ^d Df: degrees of freedom in model fitting. Level of significance: * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

Stand transition and mortality probabilities for each diameter class were obtained using the previously established diameter growth, recruitment, and mortality models, as shown in Table 7. The probability of the upward transfer of each diameter class increases and then decreases with the increasing diameter class. The probability of mortality decreases with the increasing diameter class, and the small-diameter class trees have greater mortality due to the natural environment, competition, and other factors; meanwhile, most of the plots are middle-aged forests.

Table 7. Transition probabilities in each diameter class.

Diameter	b_{ij}	m_{ij}	Diameter	b_{ij}	m_{ij}
5	0.198	0.105	30	0.308	0.008
10	0.128	0.076	35	0.420	0.003
15	0.150	0.081	40	0.350	0.001
20	0.185	0.032	45	0.580	0.003
25	0.204	0.017	≥50	0.330	0

b_{ij} denotes the upgrowth transition rate; m_{ij} denotes the mortality rate.

To verify the predictive ability of the variable transition matrix model, the transition matrix growth model constructed above was used to predict the number of trees of different

diameter classes and the basal area per hectare after 5 years based on the 2015 data. The model predictions were consistent with actual observations in 2020 and were all within the 95% confidence interval of the observations; $RMSE$ was 0.325 and 0.123, and R^2 was 0.993 and 0.945, respectively (Figure 4).

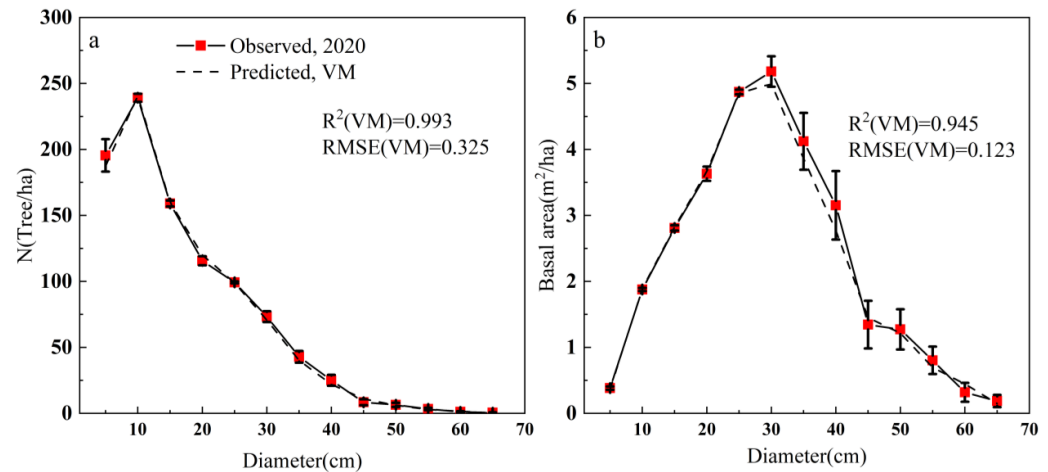


Figure 4. Variable transition matrix model (VM) 5-year short-term projections, where (a) and (b) represent the number of trees (tree/ha) and stand basal area (m²/ha), respectively.

3.3. Stand Spatial Structure Optimization

Four plots were selected from 30 plots, the transition matrix growth model was used to predict the stand diameter distribution in the next cycle, the stand spatial structure was optimized according to the objective function, and the optimization model was solved based on the Monte Carlo algorithm with 5000 simulations to obtain the optimization plan and the predicted diameter distribution in 2025. By calculating each stand structure index and comparing the indices before and after optimization. The results showed that the objective function values of the four plots decreased significantly with the increase in the number of iterations (Figure 5), and the objective function values (F -index) reduction ratios were 23.8%, 12.8%, 14.6%, and 28.3%, respectively, after thinning compared with the statistics before thinning (Table 8). From Table 8, we conclude that the number of diameter classes and the number of tree species remained the same before and after optimization; the complete mixing, *Margalef*, *Shannon*, *Simpson*, *Pielou evenness*, and *Simpson evenness* indices increased before and after optimization; the dominance index decreased; and the q -value was in the range 1.2–1.7. From the objective function (F -index) optimization structure, the optimized intensity of harvesting numbers for the four plots were Plot 6 (24.3%), Plot 10 (25.5%), Plot 11 (24.5%), and Plot 18 (25.0%).

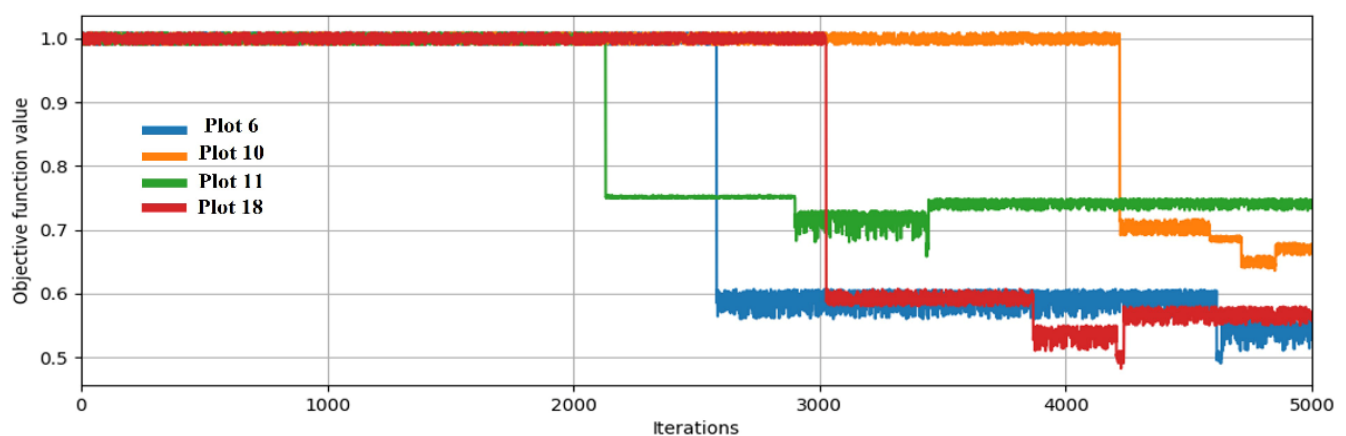
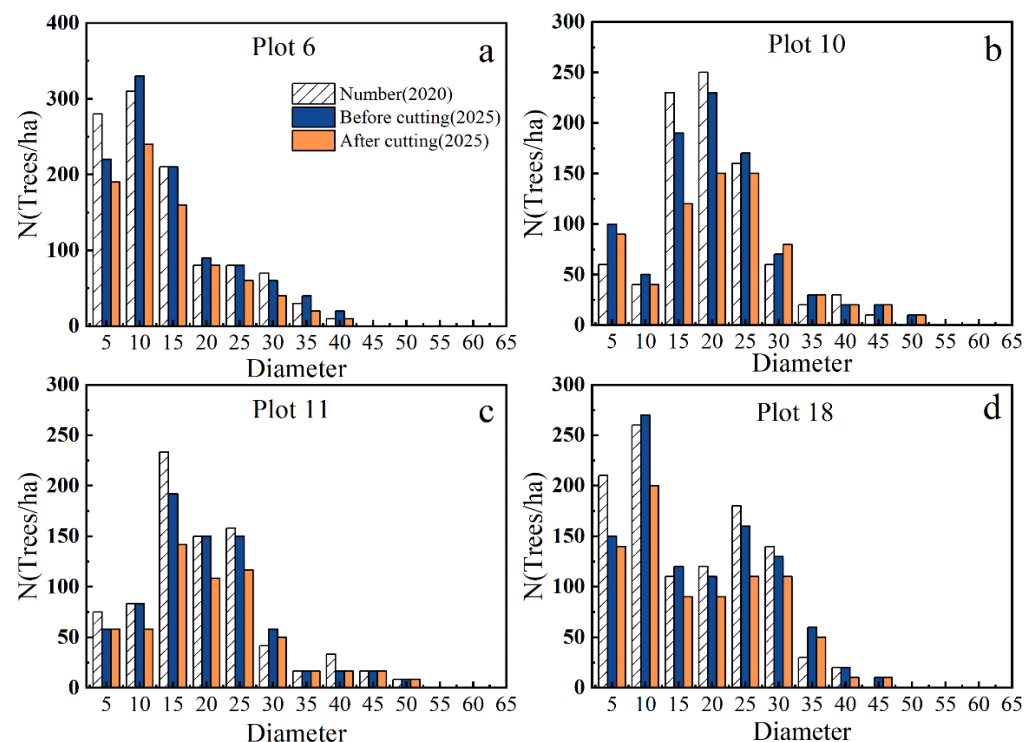


Figure 5. Developments of objective function values of four plots.

Table 8. Results of stand structure optimization for the four plots.

Variables	Plot6		Plot10		Plot11		Plot18	
	Before	After	Before	After	Before	After	Before	After
Number of diameter class	8	8	10	10	10	10	9	9
Number of tree species	14	14	7	7	9	9	8	8
<i>q</i> -value	1.299	1.281	1.188	1.207	1.343	1.317	1.281	1.238
<i>M_c</i> -index	0.439	0.578	0.331	0.407	0.284	0.384	0.450	0.566
<i>U</i> -index	0.542	0.511	0.523	0.495	0.538	0.504	0.548	0.500
<i>W</i> -index	0.478	0.500	0.508	0.481	0.484	0.482	0.504	0.461
<i>Margalef</i>	2.582	2.786	8.415	10.00	2.634	2.919	7.358	7.759
<i>Shannon</i>	1.940	1.956	1.028	1.095	2.040	2.045	1.124	1.155
<i>Simpson</i>	0.844	0.850	0.585	0.619	0.850	0.851	0.608	0.634
<i>Pielou evenness index</i>	0.883	0.890	0.355	0.386	0.886	0.888	0.397	0.416
<i>Simpson evenness index</i>	0.950	0.956	0.620	0.658	0.944	0.945	0.646	0.676
Objective function value	0.607	0.490	0.717	0.635	0.754	0.658	0.617	0.481

The comparison of the changes in the stand structure indices before and after optimization showed that the stand diameter class distribution in the next cycle of 2025 before and after optimization tended to be a reverse “J”-type distribution from the overall stand diameter class distribution, and the stand spatial structure adjustment improved species and diameter class diversity (Figure 6). Meanwhile, the optimized stand diameter distribution in the next cycle (2025) approached the ideal diameter distribution of natural forests, and the objective function *F*-index was significantly reduced. The optimization scheme improves the growing space of trees, speeds up the renewal rate, promotes tree growth and recruitment, and reduces species competition through adjusting species mingling, diameter differentiation, and the horizontal spatial pattern. As a result, the overall stand structure in the growth process is closer to the direction of a reasonable stand structure and improves diameter class diversity and stability.

**Figure 6.** Distribution of diameter after and before cutting for the four plots; where (a), (b), (c) and (d) represent Plot6, Plot10, Plot11, and Plot18, respectively.

4. Discussion

It is difficult to summarize the essential characteristics of stand structure into one precise concept, as stand structure itself is not a quantifiable indicator. It is a very broad concept that encompasses many factors at different levels and, as it is governed by ecological processes, it is highly dynamic with [35]. Traditionally, stand structure characteristics can be described by a set of stand structural variables, such as species composition, tree height, diameter class distribution, stand density, biomass, and stand volume, most of which are related to forest yield [36]. However, stand spatial structure characteristics are ignored in such descriptions of stand structural characteristics. Tree growth and mortality, stand competition, and natural regeneration in a forest are affected by and affect the spatial arrangement of tree characteristics, thus altering stand structure characteristics [37]. The stand structure is formed by complex interactions between natural ecological processes at long time scales and at local (small) spatial scales. Thus, the stand structure is a high-level generalization and measure of stand conditions at the measurement time during forest dynamic change [38].

In this study, we demonstrated that broadleaf mixed forests in the Maoershan Forest Farm of the Heilongjiang Province showed an overall aggregated distribution. The number of homogeneous trees in the moderate and strong degree mixed stands was high, and the uniform angle index increased and then decreased, indicating that the stand spatial structure changed over time.

Zhao et al. [23] show that the uniform angle index showed a small trend of increasing and decreasing over time because the long-term natural regeneration of the stand resulted in the distribution of trees in some plots tending towards an aggregated distribution. Peet et al. [37] show that the competitive pressure between trees increased, and the trees growing in a more competitive environment had a higher mortality with the tree growth. The results from our study are consistent with these findings. The distance between trees gradually widened, and the distribution between surviving trees became more and more uniform. Related studies have shown that the diameter and height size diversity of stands increase with stand development, which is consistent with this study [32,38].

Stand structural diversity is also a goal of forest management as it is an important indicator of forest ecosystem diversity, which should also consider temporal trends related to forest succession [39,40]. The basis for maintaining and increasing the biodiversity of forest ecosystems is to improve the diversity and complexity of the stand structure. To predict stand growth and evaluate forest management activities, measures of stand structural diversity are important [41,42]. Diameter class diversity is important for the health and stability of forest ecosystems as an important component of forest structural diversity [25,26]. Stand diversity can be assessed and used to guide forest management by describing the number and richness of trees based on species richness and abundance indices. In undisturbed primary forests, the values of the diameter diversity indices increase and then decrease within a small range [40,43]. As the trees grow, especially some large trees, the diameter at breast height (DBH) increases, creating new classes that contribute to the increase in the diameter diversity indices [39,44]. When these large trees grow to the over-mature diameter class, they begin to experience natural old age or are disturbed by natural factors, with the death of some trees, and decreases in the diameter class diversity [41–43,45]. The zonal vegetation within this study is mainly a Korean pine–broadleaved mixed forest, a typical natural secondary forest in the mountainous areas of eastern northeast China formed after years of different degrees of human disturbance and various forest protection measures. As a result, stand diameter class diversity is showing a gradually increasing trend over time.

Forest growth and yield models, as well as optimization models, are needed to achieve the goals set for forest management [46]. Transition matrix growth models are widely used in forestry, especially for uneven-aged forests whose diameter transition probability has a complex nonlinear relationship with the stand variables, where stand growth is necessarily limited by the stand conditions, and variable parameter matrix growth models are more

robust to predict future changes in forest growth dynamics [47]. He et al. compared index changes before and after harvesting at different harvest intensities [26]. Diameter class diversity increased at harvest intensities of 20%–30%, but decreased at harvest intensities of 40%, indicating that low and medium harvest intensities could improve the stand diameter class diversity. Previous studies have shown that intensities of 20% and 30% reflect the current status of forest management practices in northeast China, whereas intensities of 10% and 40% are somewhat underestimated or overestimated compared to the actual range [18,46]. The results of our study also show that a simulated harvest intensity close to 25.0% resulted in the minimization of the objective optimization function, and the optimized simulated stand spatial structure index and diameter class diversity index increased between 2% and 18.8%. Adjusting stand diameter classes to improve the stand density reduces competitive pressure among trees, changes horizontal spatial patterns, and increases light conditions, thus promoting regenerating tree growth.

In our study, we selected the optimal timber harvest according to optimizing the stand spatial structure with a variable transition matrix growth model for broadleaf forests. The next cycle of stand diameter distribution was brought closer to the reasonable distribution. The stand spatial structure was brought closer to the ideal stand spatial structure through optimal harvesting by optimally adjusting the diameter class diversity and spatial structure with an interval adjustment period of 5 years. Applying the variable transition matrix growth model to optimize the stand spatial structure predicts the simultaneous optimization of the stand spatial structure from different aspects. These theoretically calculated potential maxima of stand spatial structure indicators can be used in optimizing the spatial structure of forest stands.

The methods used in this study are potentially valuable for managing natural, mixed, and heterogeneous forests. However, the stand structure characteristics of natural forests are more complex, and there are many influential factors. The optimization function constructed in this study mainly considered the diameter distribution, diameter class diversity, and spatial structure characteristics of stands. The dynamic growth optimization adjustment of stands is a transitional process and requires long-term management adjustment; 5 years is not a long time in the growth of trees, hence the small differences which can be considered in the subsequent study of the vertical structure of natural forests and added to the stand spatial structure optimization model.

5. Conclusions

Our results showed that from 2015 to 2020, each diameter class diversity index, generally, did not change much. There were small differences with a gradually increasing trend, especially in the *Margalef*, *Shannon*, and *Simpson* indices. The reason is that the diameter class diversity indices increased with the growth of trees and the increase in the number of recruited trees. Meanwhile, 80% of the plots had a clumped distribution, which was not conducive to tree growth. Some plots had a low degree of mixing and an uneven distribution of diameter classes, whereas the diameter class uniformity index increased and then decreased with time. The stand spatial structure had to be adjusted during stand optimization, as it was somewhat different from the ideal spatial structure of natural mixed forests.

We propose a new methodology to optimize the stand spatial structure with a transition matrix growth model for four broadleaf forests, and the proposed method is universal and can be easily applied to other stands. The results showed that the optimal harvesting intensities of the allocated trees were all ~25.0% [plot 6 (24.3%), plot 10 (25.5%), plot 11 (24.5%), and plot 18 (25.0%)]. The objective optimization function was minimized, and the stand spatial structure index and diameter class diversity index improved after optimization between 2% and 18.8%. The objective function value (*F*-index) was improved between 12.8% (Plot 10) and 28.3% (Plot 18).

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