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IMPACT OF SELECTIVE LOGGING OF SECONDARY FOREST OF *Tilia amurensis* ON STAND STRUCTURE AFTER 20 YEARS

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Abstract: Natural secondary forests can develop vertical structures of varying complexity. A dominant view in forest ecology is that naturally restored secondary forests tend to have greater structural heterogeneity than managed secondary forests. Structural integrity, however, may differ among forest layers. The present study was aimed to compare tree species diversity and vertical stand structure of natural restoration, and selective logging stand structure after 20 years. In two plots of 0.8 hm^2 of selective logging and natural restoration stands, we found that shade-tolerant tree species were dominant in each layer of both stands and also showed some dominance. The diameter distribution of the upper forest layers was similar in both stands. Furthermore, the proportion of trees with the optimal spatial structure unit in selective logging stand was larger than that in the natural recovery stand, but the spatial complexity was smaller. The proportion of dominant trees in upper forest layer in selective logging stand was also significantly higher than that of the natural recovery forest, and the proportion of inferior trees in other forest layers was larger. The results showed that the short-term restoration of selective forest stand promotes the succession of forests due to strong renewal capacity and suitable spatial structure. By using tri-variate distribution of spatial structure, we found that the restoration state of natural recovery and spatial structure of the selective logging stand play an important role in the process of restoring forests.
Keywords: Vertical structure; tree species composition; diameter distribution; spatial structure; tri-variate distribution.

INTRODUCTION

In the 1960s, many countries began to establish nature reserves to protect forests (Andam *et al*., 2008), and now most of forests in the world are becoming secondary forests (Sung *et al.*, 2012). Artificial logging and natural disaster change the species composition, structure, and ecological functions of forests (Ibanez *et al*., 2017; Mürren *et al*., 2018; Purschke *et al*., 2017). Understanding the state of secondary forest restoration after forest logging helps us to make effective forest restoration planning. Forest restoration refers to the restoration of multiple aspects of an ecosystem, including its composition, structure, and function (McDonald *et al*., 2016). The pattern of forest biodiversity may be different after harvesting, at different stages of forest recovery (Liang *et al*., 2015). Audino (2014) found that the biodiversity loss caused by deforestation may be restored, however, the change of tree species composition leads to significant changes in the species composition and hierarchical species diversity (Zhu *et al*., 1997; Sung *et al*., 2012). Forest restoration stages are reflected in the vertical forest structure. The vertical structure of stand is a means of distribution of internal unit in forest ecosystem, which determines the difference of distribution of different forest layers (Song *et al*., 1997; Fonseca *et al*., 2004). In this study, we further evaluated the recovery of species and the spatial structure of secondary forests by assessing changes in the vertical layer of different types of forest stands over a short period of time.

Currently, although some new indicators can be used to measure the state of forest ecosystem recovery, they are only suitable for measuring changes over a specific time period (Riitters *et al*., 2002; Ritter *et al*., 2009; Vogt *et al*., 2007). At both small and large scales, the spatial intuitive process of observing forest ecosystem restoration is rarely studied. We can intuitively understand the process of spatial structure restoration of secondary forests by studying the spatial structure of the vertical stand. The spatial structure of stand can be described using numerous methods, for example, the isolation index expressed as a single index value (Pielou, 1977), Ripley 'k function (Ripley, 1977) - the double correlation function (Pommerening, 2002), and the semi-variance function (Kuuluvainen *et al*., 1996). The stand spatial structure, based on the spatial relationship of individual trees (uniform angle index, mingling, dominance) could provide more detailed information on stand structure characteristics (Aguirre *et al*., 2003; Hui *et al*., 2011; Li *et al*., 2012). Currently, methods for evaluating stand structure used are mainly univariate distribution of uniform angle index, mingling and dominance (An, 2003; Shao *et al*., 2011; Meng *et al*., 2015; Lv *et al*., 2017). The overall spatial information of stand can be understood by analyzing the bivariate distribution of structural parameters (Hui *et al*., 2014), which could subtly analyze the microstructure of the stand (Zhang *et al*., 2018; Wan *et al*., 2019; Zhang *et al*., 2015). A new spatial structure analysis method, the tri-variate distribution of structural parameters has been used to analyze the fine spatial structure characteristics of *Quercus acutissima* natural forest in Xiaolongshan, Gansu province China (Bai *et al*., 2016). This study showed that the tri-variate distribution of spatial structure parameters, namely the joint distribution of three structural parameters can provide a more comprehensive and systematic understanding of the microscopic characteristics of spatial structure.

In this study, we used *Tilia amurensis* Rupr. as the main indicator tree species of natural secondary forest to evaluate the restoration of the two stands which were a natural stand and a selective logging stand after 20years, measuring the vertical structure, species composition, diameter distribution, and tri-variate distribution of spatial structure parameters. This study aimed to answer key questions: 1) Does selective logging change the species composition of stand? What is the recovery condition of species in the stands of artificial disturbance and natural recovery? 2) What changes have occurred in the non-spatial structure (diameter distribution) of the selectively logged stand? Which stand is best for the restoration of vertical non-spatial structures? 3) What effect does selective logging have on stand space structure? What role does tri-variate distribution of spatial structure parameters play in restoring stand state? Hopefully, our study can comprehensively assess stand restoration status and provide valuable and useful information for improving the design and implementation of forest restoration.

MATERIALS AND METHODS

The study was conducted in Xiaojiu Forest Farm in Shangzhi city, Heilongjiang province (127°38'~127°51'E, 45°11'~45°25'N) which located in the west slope of Zhangguangcai Mountains, the westward extension of the Lesser Khingan Mountains, accompanied by a variety of temperate broad-leaved tree species. Secondary forests of various types are derived according to the degree of damage and regeneration opportunities which often germinate into mixed broad-leaved forests from the associated broad-leaved tree species. Before the implementation of the natural forest protection project in 1998, some broad-leaved secondary forests were selective logging with low intensity.

The altitude of study area was 200~832m. The region has a continental temperate climate, with an annual average temperature of 2.3℃ and annual precipitation of 550~740 mm. The main tree species within the study area were: *T. amurensis*, *Acer mono* Maxim., *Tilia mandshurica* Rupr., *Acer tegmentosum* Maxim., *Betula platyphylla* Suk., *Betula davurica* Suk., *Juglans mandshurica* Maxim., *Phellodendron amurense* Rupr., *Fraxinus Mandshurica* Rupr., *Quercus mongolica* Fisch., *Populus cathayana* Rehd., *Populus davidiana* Dode., and *Betula.costata* Trautv. Shrubs in the area included *Corylus heterophylla* Fisch., *Syringa reticulata* Hara var., *Lonicera japonica* Thunb., and *Spiraea salicifolia* L., *Carex siderosricta* Spp., *Adiantum capillus-veneris* L., *Filipendula palmate* Maxim., *Cardamine leucantha* Schulz., *Apium graveolens* L. were the main herbs species.

Research Methods: In July 2019, the natural restoration and selective logging forests with the similar age, altitude, aspect and slope were selected (Table 1). The main arbor species of the natural restoration forest were *T. amurensis, A. mono,* and *Q. mongolica*, along with a variety of shrubs with no apparent grazing and cutting activities, the average height and coverage of which were 1.65 cm and 41.5%, respectively. The soil thickness was 26.1 cm, the bulk density was 0.84g/cm^3, and the moisture content was 20.4%. We conducted annual ring analysis on trees with a larger diameter at breast height (DBH), which were more than 100 years old. The main tree species in the selective logging forest were *T. amurensis*, *A. mono,* and *T. mandshurica*. There were also vines within the stand. The average height of shrubs in the selective logging forest was 0.69 m, and the average coverage was 19.3%. The soil thickness was 24.6 cm, the bulk density was 0.78g/cm^3, and the moisture content was 23.3%. In 1998, this stand experienced a selective logging utilization and the main trees species selected were *T. amurensis*, *A. mono,* and *Q. mongolica* with large diamters, the accumulation of selective logging intensity was 10%.

In this study, a sample plot of 100 m×80 m was set up in the selective logging and natural recovery stand respectively. Each plot was divided into 20 small plots of 20 m×20 m by

Table 1. The condition of sample plots

Plot Code	Grade (°)	Slope Aspect	Altitude (m)	Crown Density	Basal Area (m^2/hm^2)	Mean DBH (cm)	Stand density (tree/hm^{-2})	Moisture (%)	Density (g/cm^3)	Soil Thickness (cm)	Species Composition
1	27	Sunny slope	398	0.84	30.4	15.1	1051	20.4	0.84	26.1	3*T. amurensis* + 2*A. mono* + 1*Q. mongolica* + 1*B. platyphylla* + 3 others
2	24	Sunny slope	420	0.80	29.8	14.7	1028	19.3	0.78	24.6	4 *A. mono* + 3*T. amurensis* + 1*T. mandshurica* + 1*A. tegmentosum* + 1 others

using the adjacent grid survey method, which was used as the survey unit. The species name, DBH, tree height (Haglöf, Sweden), crown width, branch height, and relative coordinate values of each tree with a DBH≥5 cm were recorded. The range around plots (5 m) was used as a buffer zone to avoid a fringe effect. The trees in the buffer zone were only used as the adjacent trees, and the trees in the core area were used as the target trees when calculated the spatial structure parameters.

Data Analysis: Forest Layer Division: The differences in trees height and crown length in the forest affects, the output of photosynthesis. Not all leaves have the same intensity of photosynthesis. Photosynthesis is mainly produced in the tree crown above a certain height. This height is called the crown light competition height (CCH). Due to the influence of the heterogeneity of light in the stand, the photosynthesis of a tree mainly occurs above the CCH. Below the CCH, the photosynthesis and respiration of the leaves are almost equal due to the shading effect, and the photosynthesis in this part can be neglected (Zheng *et al*., 2007). The formula for CCH calculation is defined as:

$CCH = a \cdot C_L + H_W$

where a is the cut-off coefficient, C_L is the crown length (that is, the difference between the height of the tree and the height under the branch), and H_W is the height under the branch.

The forest was divided into three layers according to the observation of the sample plots, and the dividing method was listed as follows: Firstly, the tree with the highest tree height and the longest crown length in the stands was identified, and its crown light competition height was calculated as CCH_1. All trees with tree height≥CCH_1 were classified as the first tree layer. The crown light competition height of the remaining trees (CCH_2) was determined according to the above method. The trees with height between CCH_1 and CCH_2 were treated as the second forest layer. Lastly, the trees with a height lower than CCH_2 were classified as the third forest layer. In the formula of CCH calculation, the cut-off coefficient (a) generally ranges from 0.3 to 0.5. After searching the literature and analyzing data, we set the value of a to 0.4 which was best in this experiment.

Diameter Distribution: The DBH of trees in two stands was divided by a diameter distance of 2cm, then the number of trees in a different diameter was calculated. According to the different diameters, Sigma plot software (version 12.5, Systat Software, Inc., San Rafael, CA, USA) was used to establish the distribution curve of the tree number - diameter, and the diameter structure distribution of the stands was analyzed.

Spatial structural parameters and tri-variate distribution: For the calculation of the spatial structure parameters of trees, spatial structure analysis software Winkelmass (1.0) was used to calculate parameters, such as uniform angle index, mingling, and dominance (Table 2). The value and significance of each parameter are shown in Figure 1 and Table 3.

In the process of natural restoration, the change of stand space structure is essentially the continuous improvement of stand function which largely determines the competition between trees and the spatial niches of trees, reflects the healthy condition, growth potential and stability of the stand, indicates the overall function of forest ecosystem. Previous studies have demonstrated that the development of the spatial pattern of forests ranged from aggregation to random distribution and the reasonable horizontal distribution was random distribution (Zhang *et al*., 1999; Chen *et al*., 2015). Similarly, the spatial structure of the stand is more reasonable with high mingling, and the quality of the stand is higher with more dominant trees (Pommerening *et al*., 2017). Therefore, the optimal spatial structure unit for the combination of tri-variate distribution of spatial structure parameters is MWU [1.00, 0.50, 0.00 and 0.25], and the unreasonable spatial structure unit compared with the optimal spatial structure unit is MWU [0.00, 0.00 and 1.00, 1.00].

Table 2. Instruction of spatial structure indices

Parameter	Formula	Remark
Mingling	$M_i = \frac{1}{n}\sum_{j}^{n} V_{ij}$	The value of V_{ij} is 1 when the reference tree i is not the same as that of the adjacent trees of strain j; otherwise, the value is 0
Uniform angle index	$W_i = \frac{1}{n}\sum_{j}^{n} Z_{ij}$	When the first angle a is smaller than the standard a_0, the Z_{ij} value is 1; otherwise, the value is 0
Dominance	$U_i = \frac{1}{n}\sum_{j}^{n} K_{ij}$	When the adjacent wood j is smaller than the reference tree i, the value of K_{ij} is 1; otherwise, the value is 0

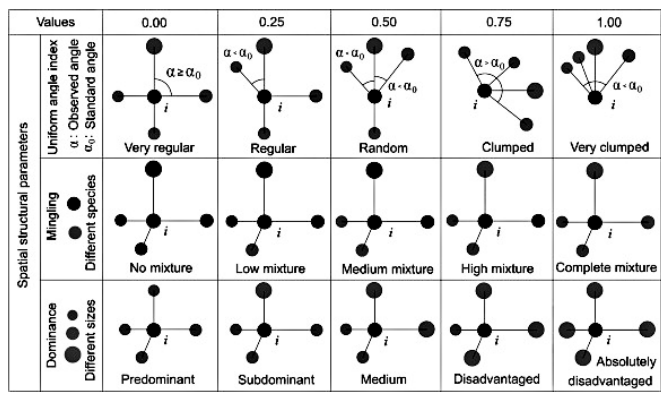


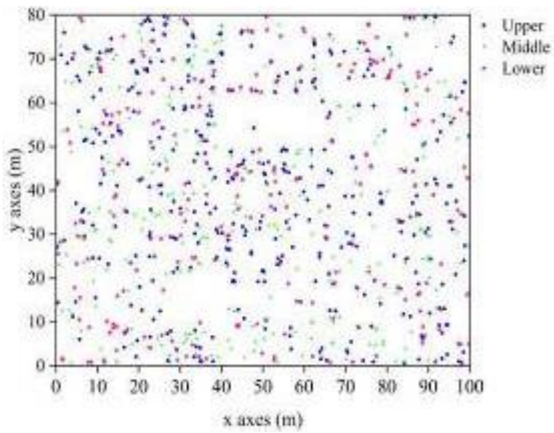
Figure 1. Specific meanings of the uniform angle index, mingling, and dominance.

The three structural parameters are belonged to discrete random variables, thus the combined probability distribution of the three structural parameters should have 125 combinations. Winklemass 1.0 was used to calculate the spatial structure parameters. Microsoft Excel 2016 (Microsoft Inc., Redmond, WA, USA) was then used to calculate the probability statistics of three structure parameters: uniform

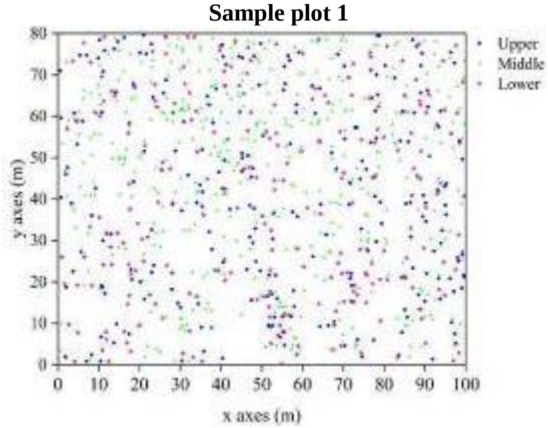
Table 3. The specific values and meanings of the uniform angle index, mingling, and dominance.

Uniform angle index		Mingling		Dominance	
Parameter values	**Meaning**	**Parameter values**	**Meaning**	**Parameter values**	**Meaning**
W=0	Very regular	M=0	No mixture	U=0	Predominant
W=0.25	Regular	M=0.25	Low mixture	U=0.25	Subdominant
W=0.5	Random	M=0.5	Medium mixture	U=0.5	Medium
W=0.75	Clumped	M=0.75	High mixture	U=0.75	Disadvantaged
W=1	Very clumped	M=1	Complete mixture	U=1	Absolutely disadvantaged

angle index, mingling and dominance. The relative frequency values of each combination of the three structural parameters (Xi, Yj, Zk) were then calculated using Excel. Lastly, ternary probability distribution maps of structural parameters were developed using Origin 2018 (Origin Lab Inc., Northampton, Ma, USA). The main data used in this study were from the sample map of sample plots 1 and 2 (Fig. 2).



Sample plot 1



Sample plot 2

Figure 2. Distribution of trees classified by upper, middle, lower forest layers

RESULTS

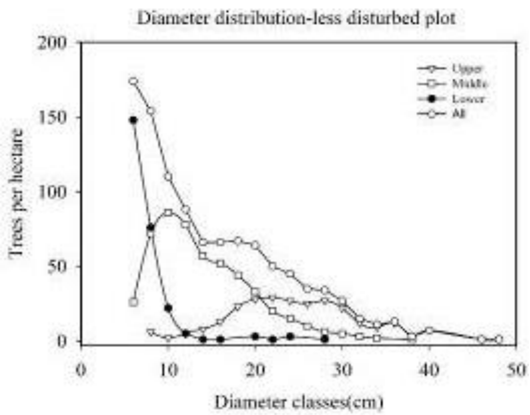
Stratification of two stands and composition of tree species in each forest layer: The stratification and tree species composition of the two sample plots were significantly different (Table 4). The volume of the upper forest layer of the natural recovery and selective logging stand was 94.1m3 /hm2 and 99.1m3/hm2, respectively, accounting for 59.2% and 64.1% of the total stand volume. The volume of the middle forest layer of the natural recovery and selective logging stand accounted for 31.8% and 36.4% of the total stand volume respectively. The volume of lower forest layer accounted for 5.4% and 4.3% of the total volume respectively. Overall, the section area of breast height of T. amurensis trees in all forest strata was the highest in sample plot 1, accounting for 47.2%, 46.0% and 43.8% of the total section area of breast height of trees in the upper, middle, and lower forests layers. The section area of breast height of pioneer tree species, B. platyphylla and Q. mongolica, accounted for 6.5% and 5.3% respectively of the total forest layer, and the section area of breast height of middle forest layer Q. mongolica trees accounted for 8.5%. The section area of breast height of pioneer species (Q. mongolica) was dominant in the forest layer, with a proportion of 6.51%. In sample plot 2, the section area of breast height of T. amurensis accounted for 37.4% of the total trees in upper forest layer. For the middle and lower forest layers, *A. mono* accounted for 44.8% and 41.4% of trees respectively. And the dominant tree species in the upper forest layer was T. mandshurica which section area of breast height accounted for 18.2% of all trees in this forest layer. In sample plot 2, the dominant tree species of the middle forest layer was T. mandshurica, the section area of breast height accounted for 6.9% of the total section area of breast height of trees in this forest layer. The dominant tree species in the lower forest layer include *A. tegmentosum*, which accounted for 23.1% of the section area of breast height of trees in this layer.

Diameter distribution of different forest layers: The diameter distribution range of sample plot 2 was wider, but there were more small trees in sample plot 1. It showed a trend of the typical distribution of natural forests (Fig. 3). The k-w values of the two upper forest layers, which come from the two sample plots, were 0.836 and 0.442, respectively. In sample plot 1, the trees of upper forest layer were more distributed within the range of 20-28 cm, and the curve tended to be flat. The number distribution of trees with diameter of more than 38 cm was small, and the skewness and kurtosis were 0.2 and 0.115, respectively. In sample plot 2, more trees of upper forest layer were distributed at 18-28 cm, with skewness and kurtosis of 0.257 and 0.352, respectively. The tree diameter distribution in the upper forest layer of two stands was largely

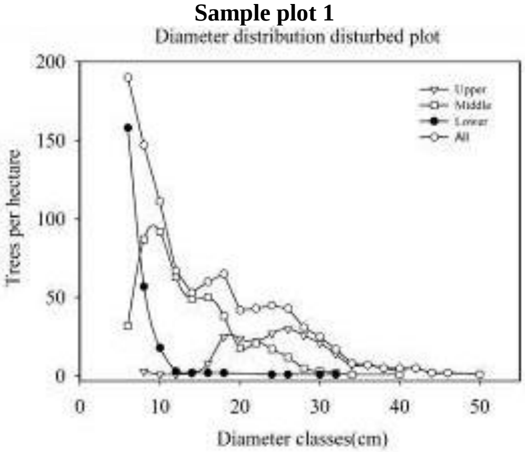
Table 4. The condition and tree species composition of each tree layer in sample plots

Plot Code	Plot Code1 Upper	Plot Code1 Middle	Plot Code1 Lower	Plot Code2 Upper	Plot Code2 Middle	Plot Code2 Lower
Mean DBH/cm	24.1	14.1	7.7	25.4	13.5	7.8
Tree height/m	19.5	12.8	7.3	21.3	13.2	7.4
Total volume ratio/%	59.2	36.4	4.3	64.1	30.5	5.4
The ratio of main species / %	5*T. amurensis* + 2*A. mono* + 1*Q. mongolica* + 1*B. platyphylla* + 1 others	5*T. amurensis*+ 3*A. mono* + 1*Q. mongolica* + 1 others	4*T. amurensis*+ 3*A. mono* + 1*Q. mongolica* + 2 others	4*T. amurensis*+ 2*A. mono* + 2 *Tiliamandshurica* + 2 others	4*A. mono* + 3*T. amurensis*+ 1*T. mandshurica* + 2 others	4*A. mono* + 2*A. tegmentosum* + 2*T. amurensis* + 2 others

normal distribution. In sample plot 1, trees in the middle forest layer within a small diameter range of 6-10 cm that the number was increased with increasing diameter, while trees with a diameter greater than 12 cm, the number showed a decreasing trend, and skewness and kurtosis of 1.005 and 0.865, respectively.



Sample plot 1



Sample plot 2

Figure 3. Diameter distribution in each tree layer in sample plot 1 and plot 2

In sample plot 2, the overall trend of tree diameter distribution in the middle forest layer was around the same as that in sample plot 1, which had skewness and kurtosis of 1.039 and 0.863, respectively, reaching a peak at around 10 cm in diameter, the number of trees in sample plot 2 with diameter of 10 cm was higher than that in sample plot 1. The diameter distribution of the middle forest layer in the two stands showed a single peak right-skewed distribution. The diameter distribution of the trees in lower forest layer showed an inverted "J" type in two samples, and the number of trees with DBH of less than 10 cm was larger in sample plot 2 (Fig. 3).

Overall spatial structure characteristics of stands: More than 59% of the trees in the two stands were on the level of the uniform angle index (0.5), and more trees were randomly distributed in the two plots. And tree frequency values the combination of spatial structure parameters of 100 in sample plot 1 and 89 in sample plot 2. Under the condition that the dominance and uniform angle index remain unchanged, the tree distribution frequency value of sample plot 1 generally increased first, before decreasing, and then increasing again with the increase of mingling, while the tree distribution frequency value of sample plot 2 increased first, and then decreased with the increase of mingling. The highest proportion of structural parameter combination MWU [1.00, 0.50, 0.00] in sample plot 1 was 3.89%. The highest proportion of trees in sample plot 2, which had a structural parameter combination of MWU [1.00, 0.50, 0.00] was 5.62%. In sample plot 1, the proportion of trees with the optimal spatial structure unit MWU [1.00, 0.50, 0 and 0.25] was 6.08%. In sample plot 2, the proportion of trees with the optimal spatial structure unit was 8.91%. The proportion of trees in the unreasonable spatial structure unit of MWU [0.00, 0.00 and 1.00, 1.00] in sample plot 1 was 0.36%, and 0.00% in sample plot 2 (Fig. 4).

Spatial structure characteristics of stands in different forest layers: The trees in the upper forest layer of sample plot 1 had frequency values on the combination of 64 spatial structure parameters (Fig. 5), while the trees in the upper forest layer of sample plot 2, had frequency values on the combination of 49 spatial structure parameters (Fig. 6). In the upper forest layer of sample plot 1, the proportion of structural parameter combination MWU [1.00, 0.50, 0.00] was the highest at 10.1% (Fig. 5). The proportion of the upper forest layer in the structural parameter combination of sample plot 2 was MWU [1.00, 0.50, 0.00], and was highest at 17.5% (Fig. 6).

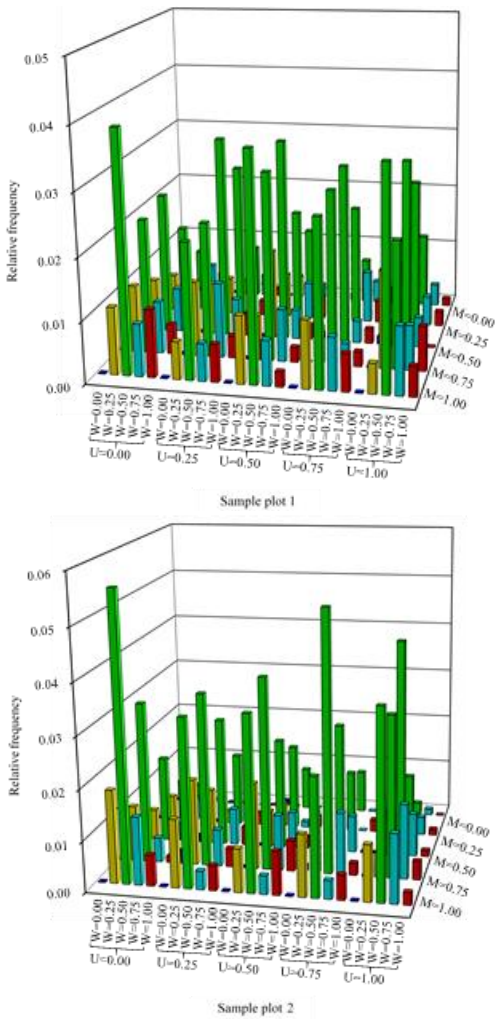


Figure 4. Tri-variate distribution of spatial structure parameters in sample plot 1 and plot 2

The trees in the middle forest layer of sample plot 1 had frequency values on the combination of 87 spatial structure parameters (Fig. 5), while the trees in the upper forest layer of sample plot 2 had frequency values on the combination of 83 spatial structure parameters (Fig. 6). In the upper forest layer of sample plot 1, the trees that had a structural parameter combination of MWU [0.75, 0.50, 0.50] were most numerous, accounting for 4.2%. In sample plot 2, the structural parameter combination proportion was 4.5%. The proportion of structural parameter combination of MWU [0.75, 0.50, 0.75] in the upper forest layer of sample plot 2 was highest at 6.7% (Fig. 6).

The trees in the lower forest layer of sample plot 1 had frequency values on the combination of 55 spatial structure parameters (Fig. 5). The trees in the lower forest layer of sample plot 2 had frequency values on the combination of 47 spatial structure parameters (Fig. 6). The highest proportion of trees in the structural parameter combination of MWU [1.00, 0.50, 1.00] in sample plot 1 was 11.7% (Fig. 5). The maximum proportion of trees in the structural parameter combination of MWU [1.00, 0.50, 1.00] in sample plot 2 was 12.1% (Fig. 6).

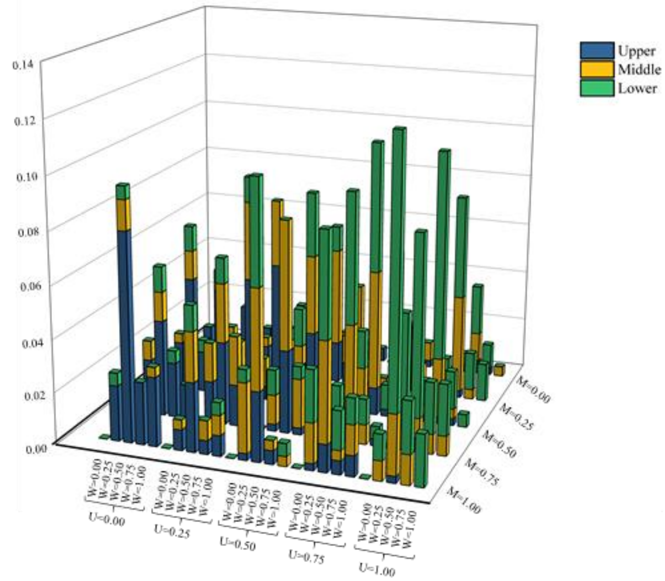


Figure 5. Tri-variate distribution of spatial structure parameters of different layers in sample plot 1

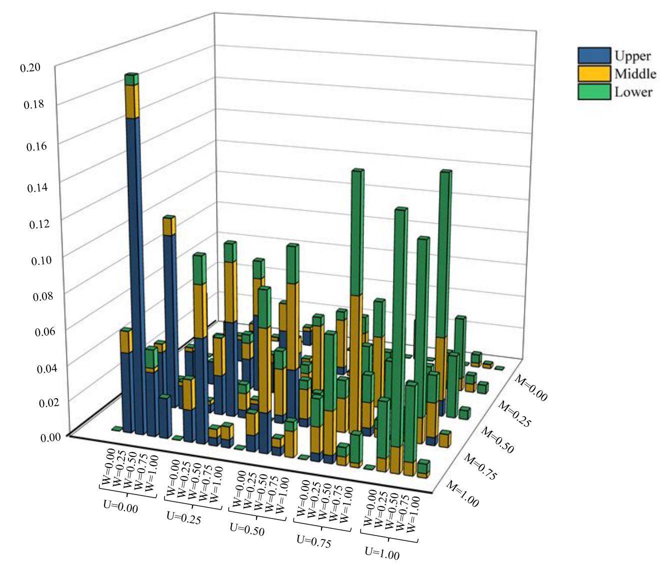


Figure 6. Tri-variate distribution of spatial structure parameters of different layers in sample plot 2.

DISCUSSION

Our results provide strong evidence that selective logging can promote forest succession after 20 years of restoration. Stand stratification method can be used to subtly analyze changes in tree composition and structure of every forest layers. The results explained our question and confirmed that ecological succession changes the composition of tree species and optimizes the structure of forest trees (Taylor *et al*., 2020). The vertical structure of stand plays an important role in the forest ecosystem (Song *et al*., 1997; Spies, 1998; Fonseca *et al*., 2004; Schurr *et al*., 2004). Each forest layer plays a different role with its own functions and impacts. The upper forest affects the structural characteristics of tree height, DBH, species composition, and the stock structure. The middle forest layer assists the main forest layer, which plays an important role in the stand accumulation and distribution pattern, while the lower forest layer determines the future succession direction of stand structurChen *et al*., 2017). This study showed that the vertical structure of the two stands was distinct. Overall, the differences between the number characteristics of stands were not entirely obvious, but the differences between the forest layers were clear. After 20 years, compared with the natural restoration stand, the number of trees in the upper and middle layer of the selective logging stand was less, but the volume was larger, and the number of trees in the lower forest layer was higher. It was therefore close to containing the characteristics of the original natural forest (Zhuang *et al*., 2016), indicating that the selective logging stand, after a long recovery process, promoted the succession of the stand.

In this study, the pioneer tree species advantages in the natural restoration stand, but after 20 years of restoration, shade-tolerant tree species dominants in selective logging stand (Table 2). We had sufficient evidence to show that 20 years restoration of selective logging stand promotes the succession of dominant species, from strong positive species to shade-tolerant species, in each forest layer, and this influence was gradually enhanced with the increase of forest layer. There were two main reasons for this phenomenon: First, with the succession of forest stands, the dominant species in communities gradually shift from pioneer tree species to shade-tolerant species, which has slower-growing and contrasting functional traits (Forrester, 2014; Reich, 2014;). Secondly, in the upper layer, more individual trees gradually shifted to radial growth, and the proportion of tree species with larger breast diameters increased, competition for resources becoming more intensive (Jang *et al*., 2010), with the intensification of resource competition, the influence of succession on tree diversity increased, affirming previous findings (Laganière *et al*., 2015; Gao *et al*., 2018).

The change of the dominant tree species in the lower forest layer of the selective logging stand determines that the development direction of the community of the stand deviates from the original stand and it was difficult to restore the ideal state over a short period of time. Therefore, measures should be taken to promote the renewal of the dominant tree species. From the shape of the diameter distribution map, the status of the two stands was basically the same (Fig.3). With the increased of height in each forest layer, the diameter distribution of each sub-layer transitioned from the inverted "J" curve to the right-skewed mountain curve and the normal distribution curve, the peak moving to the right, and the peak decreasing, they conform to that of typical natural forests (Meng *et al*., 2006). There were more small diameter trees in lower forest layer of selective logging forest, due to the change of site conditions in selective logging beneficial to the survival of young trees in the forest stands (Gomez-Aparicio *et al*., 2006; Lucas-Borja *et al*., 2016). The diameter span of trees in the middle forest of natural recovery stand was larger than that of selective logging stand, but the difference kurtosis and skewness were not significant between the two stands. The diameter distribution of trees in the upper forest layer of the two stands was generally normal distribution, with little difference in skewness. The peak value of selective logging stand was closer to 3, which was more in line with normal distribution characteristics, which also aligns with previous research (Wu *et al*., 2015; Xin *et al*., 2012; Bai *et al*., 2020). There was a significant difference in the diameter distribution of different forest layers, and the diameter distribution of the selective logging forest showed stronger regeneration ability. The structure of the upper forest of selective logging stands was more stable, and the diameter distribution characteristics of the stands were closer to those in the original natural forest. The purpose of forest management is to maintain the forest stand structure, cultivate healthy and stable stands (Gadow *et al*., 2012; Petritan *et al*., 2012). The management goal of natural secondary forests is to restore which the structure close to original forest. In this study, the tri-variate distribution of structural parameters was applied to analyze the recovery of selective logging and natural restoration stands. We found that there were 100 spatial structure parameter combinations in the tree distribution frequency value of the natural restoration stand, with only 89 in the selective logging stand (Fig. 5). Therefore, there were more diverse forest spatial structures in natural restoration stands. Overall, the trees in the selective logging stands had a higher mixing and dominance degree. The proportion of trees in the optimal structure unit of the selective logging stand was also larger (Fig.5), and the proportion of trees in the unreasonable spatial structure unit was significantly reduced. This was consistent with previous research and aligns with the concept of forest stand management (Wan *et al*., 2018; Bai *et al*., 2016). This shows that the selective logging stand has a better spatial structure after 20 years of restoration, but that it also reduces the complexity of the spatial structure of the stand.

From the tri-variate distribution of spatial structure parameters of different layers, we know that compared with the naturally restored stand, the dynamic changes in the forest structure of each forest layer in the selective logging stand were shown as the proportion of dominant trees in the complete mixture and random state of the upper forest layer increased. The proportion of disadvantaged and medium trees in the complete mixture and random state of the middle forest layer increased, and the proportion of inferior trees in the complete mixture and random state of the lower forest layer increased significantly (Fig. 6 and Fig. 7). These results show that after 20 years of restoration of selective logging stand, the spatial structure of each forest layer of the forest stand had significantly changed, but only the spatial structure of the upper forest layer was optimized, which dominates the structure and function of the forest stand (Lutz *et al*., 2013). This study provides more structural information than most traditional methods, which may improve our understanding of the spatial structure of stands, and can be conducive to the harvesting and management approaches promoting the full recovery of natural secondary forests of *T. amurensis*.

Conclusions: This study comprehensively explored the restoration effects of natural secondary forests over the past 20 years, in terms of tree species composition, diameter distribution, and spatial structure in the vertical direction. We found that 20 years of recovery of selective logging stand promoted the succession of forest growth. The community of each forest layer was more predominant with shade-tolerant species, and the upper forest layer was closer to a normal distribution, and the proportion of dominant trees in the complete mixture and random state increased. The upper forest layer of the selective logging stand had a more reasonable spatial and non-spatial structure. The overall optimal structure unit of the forest increased, and the unreasonable structure unit decreased of selective logging stand, it showed a better spatial structure. To assess the ecological restoration of natural secondary forests of *T. amurensis* after selective logging, we adjusted the spatial structure parameters according to the stand. The data showed that the dominant degree of trees should be adjusted by employing selective logging and replanting for the middle and lower forest layers, to help renew the dominant species, promote its growth, and stabilize the spatial structure of stands.

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