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Close-to-nature management positively improves the spatial structure of Masson pine forest stands

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Abstract. Close-to-nature management (CTNM) has been proposed as a promising forestry management approach to improve the structure and quality of forests, which integrates wood production and ecological service functions. Research on the effect of CTNM on the univariate and bivariate distribution of the spatial structure of forest stands provides a scientific basis for the evaluation of CTNM implemented in forestry. Here, we analyzed and compared the spatial-structure characteristics of Masson pine (*Pinus massoniana*) plantations (young, middle-age, and near-mature stages) under CTNM 8 years after selective cutting and unmanaged control. We used univariate and bivariate distribution of three spatial-structure parameters: mingling (M), dominance (U), and uniform-angle index (W). Results showed that the effect of CTNM on spatial structure was more remarkable in middle-aged and near-mature Masson pine forests compared with the young forest. CTNM significantly improved mingling degree and promoted the horizontal distribution, thereby changing from a cluster to a random distribution. Moreover, CTNM improved the proportion of trees with a high mixing degree and random distribution and the proportion of trees having a micro-structure of random distribution with a high degree of mixture and dominance with a high degree of mixture in middle-aged and near-mature Masson pine forest. Overall, the implementation of CTNM 8 years ago showed a positive effect on the improvement of the spatial structure of Masson pine forest, but the present spatial structure is suboptimal. Further implementation of CTNM to adjust the mingling and uniform-angle index is necessary, and CTNM according to this method of frequency distribution of stand structure parameters can improve the success of forest management.

1 Introduction

Close-to-nature management (CTNM) is a promising forestry management approach, which simultaneously integrates wood production and ecological service functions of a forest at a relatively small spatial scale, such as stand level, by developing a structure similar to that of an original forest (O'Hara, 2016; Wang et al., 2018). In this method, trees of different ages and sizes are distributed in the same stand, new trees are established through natural recruitment, and lumber harvest selectively occurs throughout the forest stand (Li et al., 2014a). Since forests should be managed following their natural processes, the stand development stages are key to CTNM, for example arranging corresponding silvicultural and cutting operations along multiple management cycles (Wang et al., 2018). Ultimately, the effect of CTNM on

a forest can be partly reflected in the spatial-structure characteristics of stands.

The species composition, tree size, and distribution pattern are important structural attributes considered in forest management. These attributes directly indicate inter- and intraspecific competition, seedling recruitment, and tree growth, and the use of environmental resources by animals and plants indirectly affects these attributes (Li et al., 2014b). A group of neighborhood-based structural parameters (based on the relationship between a reference tree and its four nearest neighbors) consisting of three indices – mingling (M), dominance (U), and uniform-angle index (W) – can reflect these structural attributes (Chai et al., 2017; Hui et al., 2006). Previous studies mainly used univariate distribution or the average value of these parameters to evaluate the spatial-

structural attributes (mixture, predominance, and distribution pattern of tree species) of a forest (Ghalandarayeshi et al., 2017; Li et al., 2017), and they have demonstrated that these three spatial-structure parameters have a strong operability for guiding forestry (Hui et al., 2019; Zhang et al., 2018b). To provide more important and specific information, and to better understand the fine-scale spatial structure of tree populations and stand structure, the bivariate distribution of structural characteristics was proposed (Li et al., 2012). It has been used to analyze the fine spatial structure of broad-leaved forest of Korean pine in northeast China and has been successfully validated several times (Ghalandarayeshi et al., 2017; Li et al., 2014a; Wan et al., 2019).

Masson pine (*Pinus massoniana*) from plantations is a pioneer coniferous tree species extensively used for afforestation, which is widely distributed in central and southern China (Guan and Wen, 2011; Maleki et al., 2018). It provides a great amount of lumber, making it economically important (Du et al., 2018). Since short-term production of Masson pine plantations has been prioritized for the pursuit of economic interests, the health and quality of the species have been ignored (Chen et al., 2015). For a long time, monoculture has covered a large area, and unreasonable methods of harvest have caused many ecological problems, such as low productivity, soil degradation, pests, diseases, and decreased biodiversity (Zhang et al., 2019). Finding a solution to these problems and implementing sustainable management of Masson pine plantations are the current focus of forest research in these regions. Many international and domestic research and management practices have shown that CTNM is effective at improving the quality and ecological benefits of a plantation (O'Hara, 2016; Sackov et al., 2017; Wu et al., 2013).

Research on the effect of CTNM on Masson pine from plantations and the stage of development where the best effect of CTNM appears lacks the support of relevant literature. Therefore, we analyzed and compared the spatial-structure characteristics of Masson pine plantations (young, middle-aged, and near-mature stages) under CTNM and unmanaged control 8 years after selective cutting. The goals of this study are (1) to compare the spatial-structure characteristics of managed and unmanaged Masson pine and (2) to analyze the spatial-structure characteristics of Masson pine at different development stages. Our results will contribute to the sustainable development of Masson pine from plantations in central Guizhou Province of China.

2 Materials and methods

2.1 Study area

The study area is located in Kaiyang and Xifeng counties of Guizhou Province in China, with geographical coordinates of 26°48′–27°22′ N, 106°45′–107°17′ E and 26°57′–27°19′ N, 106°27′–106°53′ E, respectively. These counties have similar climatic conditions, experiencing a subtropical humid and mild climate with a mean annual temperature of 15.3 °C. The mean annual rainfall is 1200 mm, concentrated from July to September. The original vegetation has been destroyed, leaving *Pinus massoniana*, *Cunninghamia lanceolata,* and evergreen broad-leaved forest as the main forest types.

2.2 Study site and data collection

In the spring of 2009, the CTNM began with the implementation of the Sino-German cooperation project. Different CTNM measures were adopted for different development stages of Masson pine plantations, which contained tending, thinning, selective logging, and natural restoration (Table 1). No forestry operations were conducted during the different development stages, which were referred to as the control.

Nineteen sample blocks were set in the major distribution areas of *Pinus massoniana* CTNM by considering different development stages. Since most Masson pine from plantations was at middle-to-mature development stages, three, seven, and nine blocks were selected for the young, middle-aged, and near-mature forest, respectively. Each block contained a CTNM sample plot (managed treatment) and an unmanaged sample plot (control treatment); they showed similar site conditions at different stages of Masson pine plantations and were randomly established and surveyed at the research area (Fig. 1). The diameter at breast height (DBH), tree height, tree species, and crown width were recorded, and the spatial-structure parameters were calculated using these data to assess the influence of CTNM on the spatial structure of forest stands.

2.3 Data analysis

Importance value (IV)

The importance value (IV) of species is defined as the average relative density (RD), relative frequency (RF), and relative dominance (Rd) and was calculated using the following equations (Chai et al., 2017):

$$\text{density } (D) = \frac{\text{number of individuals of a species}}{\text{area of all sample units}},$$

$$\text{telative abundance } (RD) =$$
$$\frac{\text{number of individuals of a species}}{\text{density for all species}} \times 100\%,$$

$$\text{frequency } (F) =$$
$$\frac{\text{number of quadrats containing a certain species}}{\text{total number of quadrats}},$$

$$\text{relative frequency } (RF) =$$
$$\frac{\text{frequency of a certain species}}{\text{total number of species}} \times 100\%,$$

$$\text{dominance } (d) = \frac{\text{basal area of a species}}{\text{area of all sample units}},$$

Table 1. Close-to-nature management measures at different development stages of Masson pine plantations.

Development stages	Stand DBH	CTNM measures	Target density (trees hm^{-2})
Young forest	DBH <5 cm	Regulate stand density and remove overlord wood and bent trees	About 2500
Middle-aged forest	5 cm ≤ DBH <15 cm	Combination of target tree and thinning density control	1200–1700
Near-mature	15 cm ≤ DBH <34 cm	Combination of target tree and thinning density control	300–850
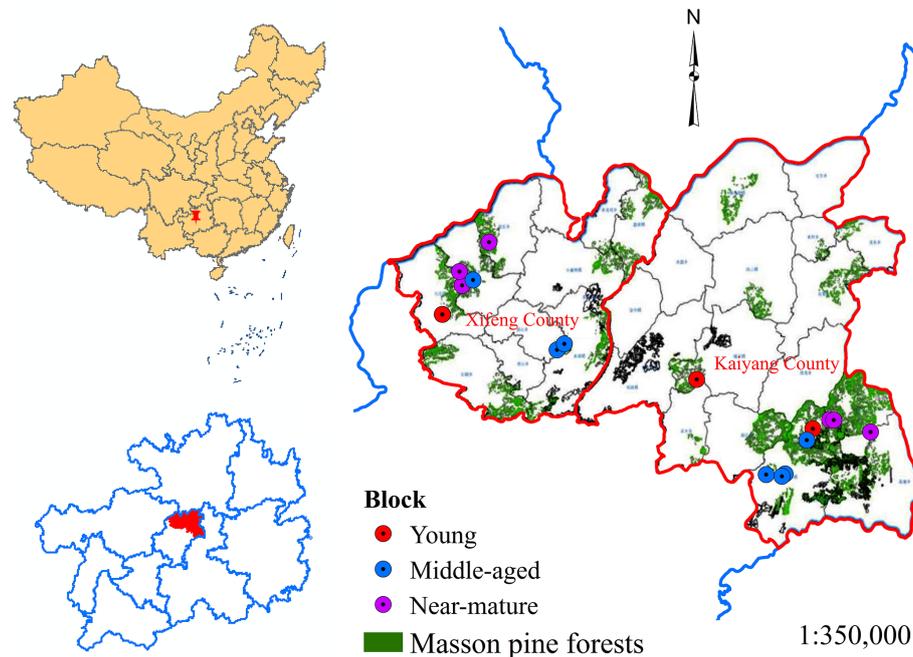
Figure 1. The distribution of the 19 sample blocks (Chai and Tan, 2020).

relative dominance (Rd) =

$$\frac{\text{dominance of one species}}{\text{dominance of all species}} \times 100\%,$$

IV = (RD + RF + Rd)/3.

Spatial-structure parameters

In this study, the neighborhood-based indices (mingling, dominance, and uniform-angle index) were used to show the spatial structure of a forest stand. These indices can show small-scale variations in tree species, tree diameter, and distribution patterns in a small structural unit and have proven useful for the analysis of the spatial structure of forest stands (Ghalandarayeshi et al., 2017; Hui et al., 2019). Mingling describes the spatial segregation of different species in a multispecies forest and is defined as the proportion of the four nearest neighbors of different species from the reference tree i (Gadow and Füldner, 1993). Dominance characterizes the size differentiation (i.e., DBH dominance) between a reference tree and its four nearest neighbors and is defined as the proportion of n nearest neighbors larger than reference tree i (Aguirre et al., 2003). The uniform-angle index describes the degree of regularity of the four neighbors nearest to reference tree i and is defined as the proportion of the angle (α) that is smaller than the standard angle α_0 (72°) (Gadow et al., 1998; Hui et al., 2007; Zhao et al., 2014). The bounds [0.475, 0.517] defined the average W for the random case. A W value less than 0.475 most likely corresponds to a regular distribution, and values exceeding 0.517 most likely correspond to a cluster distribution (Hui and Gadow, 2002; Hui et al., 2004).

A univariate distribution of these parameters (mingling, dominance, and uniform-angle index) is widely used to analyze the structural attributes of forest communities and populations, and the mean value of these parameters has been demonstrated to properly reflect the overall attributes of an entire species or stand (Hui et al., 1999, 2007). In addition, these parameters can be analyzed as joint distributions of three pairwise variable combinations (bivariate distribution): M–U, M–W, and U–W. Each joint distribution contains 25 (5×5) structural combinations that enable the analy-

sis of stand micro-structure (Chai et al., 2017; Li et al., 2012, 2014a).

Corresponding equations of three neighborhood-based indices are as follows:

1. mingling (Gadow and Füldner, 1993; Hui et al., 2011):

$$M_i = \frac{1}{n} \sum_{j=1}^{n} v_{ij}, \text{ with } v_{ij} =$$

$$\begin{cases} 1, \text{ species}_j \neq \text{species}_i \\ 0, \text{ otherwise} \end{cases}, \text{ and } 0 \leq M_i \leq 1;$$

2. dominance (Aguirre et al., 2003):

$$U_i = \frac{1}{n} \sum_{j=1}^{n} k_{ij}, \text{ with } k_{ij} =$$

$$\begin{cases} 0, \ d_j < d_i \\ 1, \text{ otherwise} \end{cases}, \text{ and } 0 \leq U_i \leq 1;$$

3. uniform-angle index (Gadow et al., 1998; Hui et al., 2007):

$$W_i = \frac{1}{n} \sum_{j=1}^{n} z_{ij} \text{ with } z_{ij} =$$

$$\begin{cases} 1, \ \alpha_j < \alpha_0 \\ 0, \text{ otherwise} \end{cases}, \text{ and } 0 \leq W_i \leq 1.$$

The variables in these equations are as follows: n is the number of neighbors, and in this study $n = 4$; d_i and d_j are the DBH of the reference tree and neighboring tree, respectively; α_j is the horizontal angle between the reference tree and four neighboring trees; and a standard angle $\alpha_0 = 72°$. All indices have a series of flexible values at five values: 0.00, 0.25, 0.50, 0.75, and 1.00.

3 Results

3.1 Tree species composition

The 38 sample plots contained 20 tree species and 2070 trees (DBH $\geq$ 5 cm), 1792 of which were *P. massoniana* (86.57 % of the total). Table 2 shows a list of the abundance and importance values of each species in the managed and control treatments at three stages of development. The species abundance in managed treatments was higher than the control, especially for the managed middle-aged and near-mature stands. Correspondingly, the importance values were lower in managed treatments compared with the control (80.448 vs. 88.585 for young stands, 71.821 vs. 82.792 for middle-aged stands, and 69.822 vs. 84.068 for near-mature stands) (Table 2).

3.2 Univariate distribution of spatial-structure parameters

Average spatial-structure parameters showed that mingling in the managed treatments was significantly higher than mingling in the control, and all mingling values were lower than 0.5. Only the young stand showed a higher dominance in the managed than in the control treatment. The uniform-angle index in middle-aged and near-mature stands was 0.491 and 0.504, respectively, which were between 0.475–0.517, whereas the uniform-angle index in all other stands was higher than 0.517 (Table 3).

The frequency distribution of spatial-structure parameters indicated that trees in the control treatment were concentrated with a low degree of mixture ($M = 0.00, 0.25$) regardless of the stage of stands, while the relative frequency of trees with a medium–high degree of mixture increased in the managed middle-aged and near-mature stands. Trees in all stands were evenly distributed at each level of dominance, and no significant differences were observed between the control and managed treatments. Most trees in all stands were located at random ($W = 0.50$), and the relative frequency of trees with clumped distribution ($W = 0.75, 1.00$) decreased in managed treatments compared with the control (Fig. 2).

3.3 Bivariate distribution of the spatial-structure parameters

3.3.1 Mingling (*M*)–dominance (*U*) distribution

Most trees in all stands were concentrated with a structural combination of $M = 0.00$ and $U = 0.00$–1.00, which showed a total frequency in the control and managed treatments of 0.885 and 0.697 in young stands, 0.701 and 0.351 in middle-aged stands, and 0.646 and 0.320 in near-mature stands, respectively. Furthermore, the relative frequency of trees with a high mixture ($M = 0.75, 1$) and low dominance ($U = 0, 0.25$) was higher in managed treatments compared with the control, which were 0.071 vs. 0.019 in middle-aged stands and 0.105 vs. 0.011 in near-mature stands, respectively (Fig. 3).

3.3.2 Mingling (*M*)–uniform-angle index (*W*) distribution

Regardless of the kind of stand, the M–W bivariate distribution showed that the maximum frequency appears at $M = 0$ at each row of the uniform-angle index (W), and the frequency at each column of mingling (M) initially increased and then decreased with the increase of W classes, which reached its maximum at $W = 0.5$. Moreover, compared with the control, relative frequency of trees in managed treatments with high mingling ($M = 1$) and a random distribution ($W = 0.5$) was improved, showing 0.013 vs. 0.051, 0.037 vs. 0.068, and 0.039 vs. 0.078 for young, middle-aged, and near-mature stands, respectively (Fig. 4).
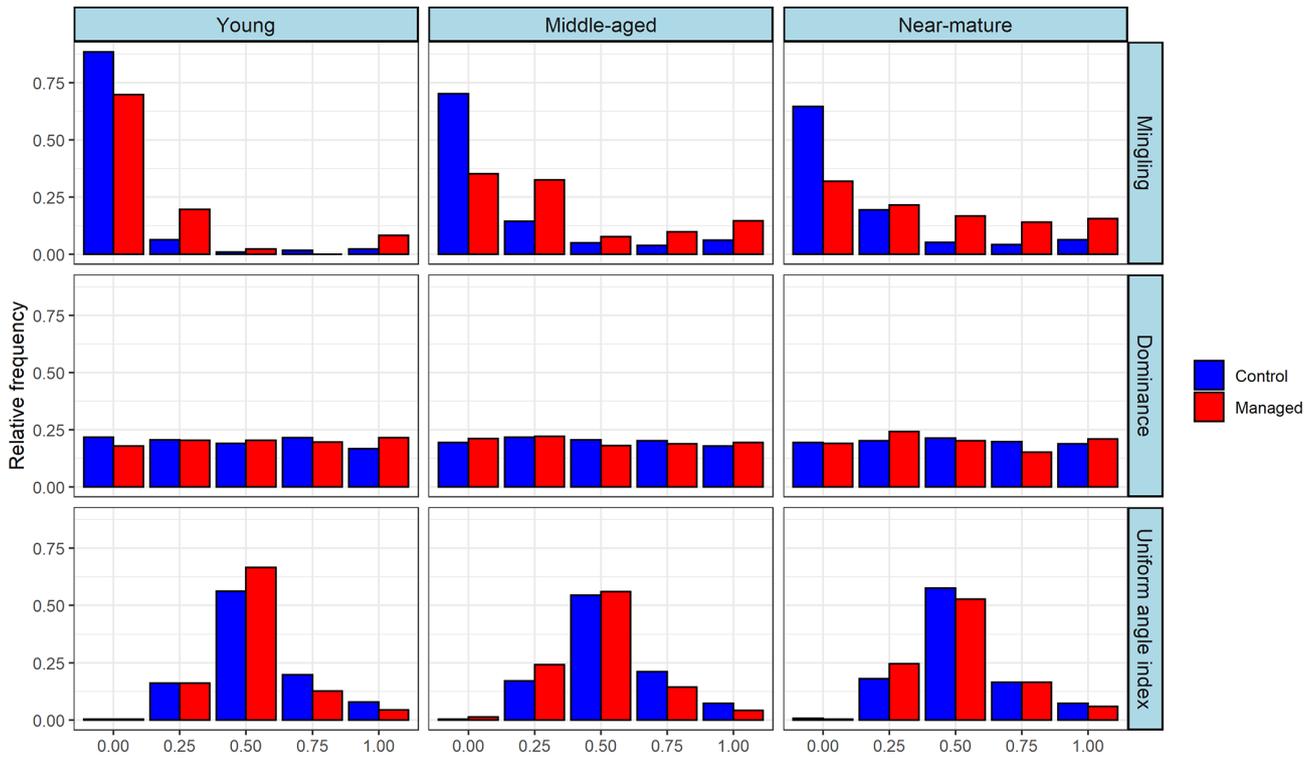
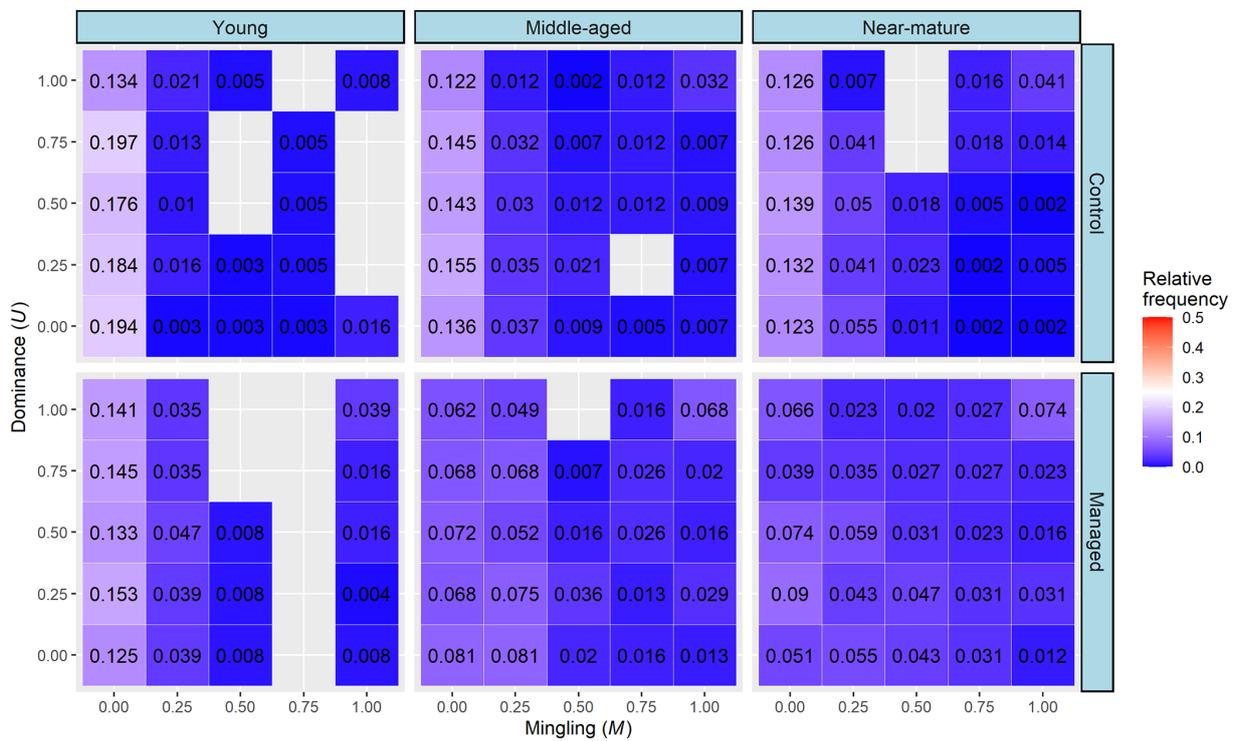**Figure 2.** Frequency distribution of the spatial-structure parameters at different tree ages.

Figure 3. Bivariate distribution of M and U at different tree ages.

Table 2. Composition and importance value index of tree species under close-to-nature management.

Species	Abundance	Abundance/importance value					
		Young		Middle-aged		Near-mature	
		Control	Managed	Control	Managed	Control	Managed
Pinus massoniana Lamb.	1792	365/88.585	234/80.448	370/82.792	243/71.821	393/84.068	187/69.822
Cunninghamia lanceolata (Lamb.) Hook.	77	2/3.669	7/7.913	25/5.366	12/5.576	20/4.991	11/6.501
Liquidambar formosana Hance	55	–	2/3.816	3/3.624	15/11.874	14/8.200	21/12.038
Quercus fabri Hance	21	4/3.443	2/1.975	1/0.896	3/1.371	–	11/4.626
Quercus acutissima Carruth.	16	–	1/1.172	7/0.976	4/0.755	–	4/2.058
Cryptomeria fortunei Hooibrenk ex Otto et Dietr	15	5/1.536	7/2.974	–	3/0.650	–	–
Fagus longipetiolata	15	–	–	5/2.434	9/3.149	–	1/0.536
Pterocarya stenoptera C. DC	13	5/2.766	2/1.702	–	2/0.525	4/0.756	–
Cinnamomum camphora (L.) Presl.	12	–	–	12/1.292	–	–	–
Phoebe zhennan S. Lee	10	–	–	–	1/0.498	1/0.307	8/2.119
Paulownia	10	–	–	2/0.800	2/0.613	–	6/0.973
The remaining 9 species	34	0/0.001	0/0	8/1.82	13/3.168	6/1.678	7/1.327
Total	2070	381/100	255/100	433/100	307/100	438/100	256/100

Table 3. *t*-test results of the univariate distribution of the spatial-structure parameters.

Parameter	Young		Middle-aged		Near-mature	
	Control	Managed	Control	Managed	Control	Managed
Mingling	0.073 ± 0.074	0.176 ± 0.113*	0.151 ± 0.151	0.347 ± 0.196**	0.171 ± 0.142	0.414 ± 0.220**
Dominance	0.481 ± 0.016	0.520 ± 0.015**	0.490 ± 0.017	0.486 ± 0.017	0.500 ± 0.016	0.488 ± 0.024
Uniform-angle index	0.552 ± 0.018	0.523 ± 0.040	0.545 ± 0.017	0.491 ± 0.023***	0.518 ± 0.056	0.504 ± 0.039

* significant at $P < 0.05$. ** significant at $P < 0.01$. *** significant at $P < 0.001$.

3.3.3 Dominance (U)–uniform-angle index (W) distribution

No change for U was observed with the increase of U classes at each row of W, but the frequency of tress initially increased, reached a maximum at $W = 0.50$, and then decreased with the increase of W classes at each column of U. The frequency of trees with a random distribution increased in young and middle-aged stands but slightly decreased in near-mature stands when comparing managed treatments to the control, which showed values of 0.667 vs. 0.561, 0.560 vs. 0.545, and 0.527 vs. 0.575 for young and middle-aged stands, respectively. However, the frequency of trees with a

low degree of dominance ($U = 0.00, 0.25$) and random distribution ($W = 0.50$) showed no distinct difference between managed treatments and the control for all tree ages (Fig. 5).

4 Discussion

Close-to-nature management significantly improved the mingling of Masson pine forest and improved the proportion of trees with a high degree of mixing ($M = 0.75, 1.00$) in the middle-aged and near-mature forests from the univariate distribution of structural parameters (Table 3 and Fig. 2). Overall, the stand was still in a low–middle mixed state after
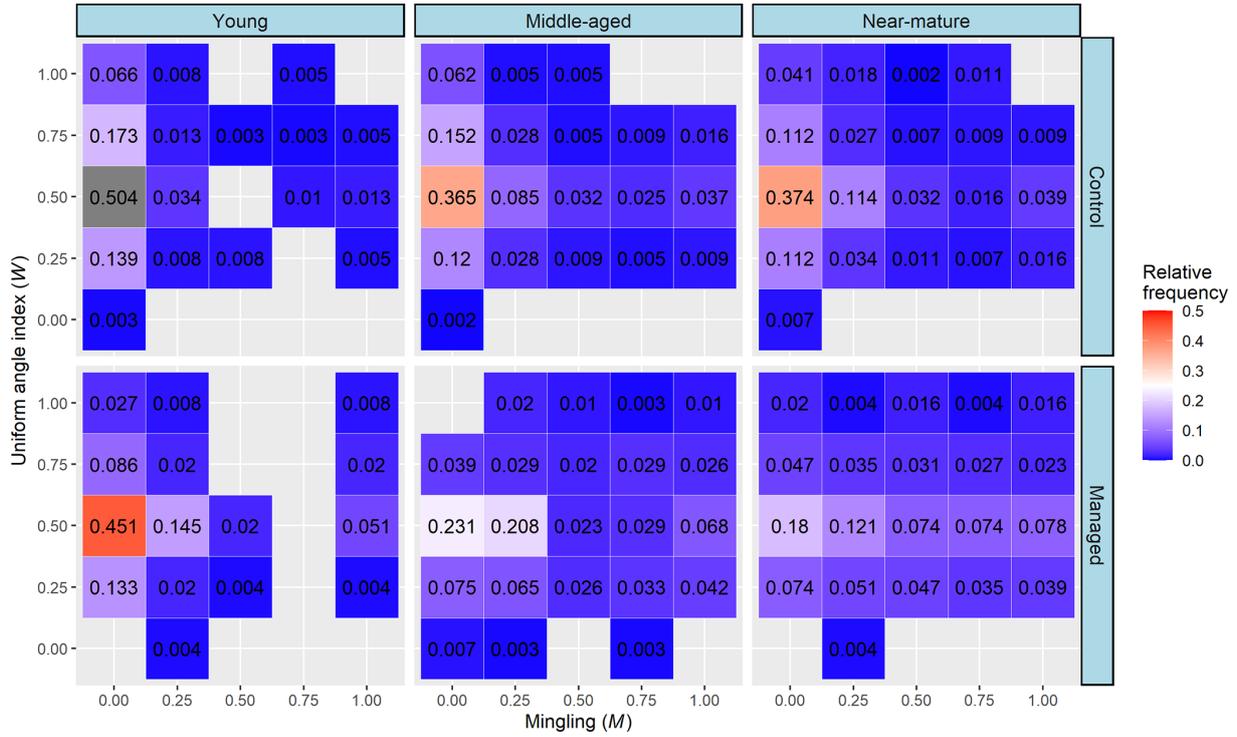
Figure 4. Bivariate distribution of M and W at different tree ages.
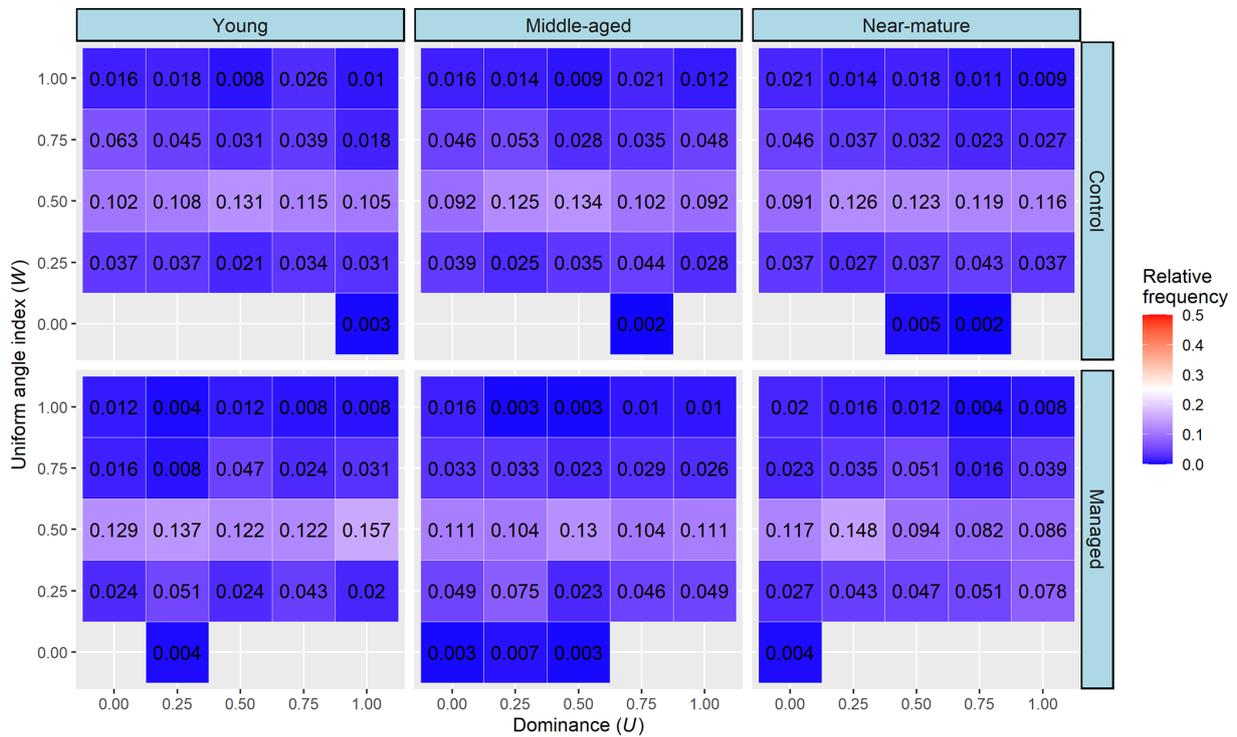
Figure 5. Bivariate distribution of U and W at different tree ages.

CTNM, since a high degree of mixing means a high diversity of tree species (Pommerening and Uria-Diez, 2017; Wan et al., 2019). The relatively low average M values ($M < 0.50$) indicate that the diversity of tree species of Masson pine forest is suboptimal, so further CTNM implemented at all stages of Masson pine forest is required. During the process of further CTNM, the target trees with mingling of 0 and 0.25 can be taken as the main adjustment factors; conditions conducive to the initiation and growth of heterogeneous species are created by reducing the number of trees of the same species around the target trees; and the diversity of species is, thus, increased. As we have seen, many new tree species appeared in managed Masson pine forest, especially at the middle and near-mature stages (Table 1). The implementation of CTNM significantly improved the average U in young forest and subtly decreased the average U in middle and near-mature forest. According to the definition of U, the smaller the value of U, the fewer the neighboring trees that are larger than the reference tree (Aguirre et al., 2003; Wan et al., 2019). This result suggests that CTNM in young forests contributes to neighboring tree growth, while CTNM in middle and near-mature forests assists reference tree (target tree) growth to a lesser extent. This is mainly because stands' size structures in managed forests are formed under the influence of the applied cutting method and thinning, which enables the subtle adjustment of microenvironmental conditions (Cogliastro and Paquette, 2012). Moreover, this study showed that CTNM did not significantly affect the W of young forest but decreased the W value to the bounds [0.475–0.517] and increased the relative frequency of trees with a random distribution in middle and near-mature forest. Results obtained show that young Masson pine forest still has a clustered distribution, while middle and near-mature Masson pine forests have changed from a cluster to a random distribution since the implementation of CTNM. Previous studies have demonstrated that the natural forest develops from aggregation to randomization, and the climax forest presents a random pattern (Wan et al., 2019; Zhang et al., 2018a, b); thus, the horizontal distributions of middle and near-mature Masson pine forest have become more reasonable with the implementation of CTNM.

The bivariate distribution of spatial-structure parameters jointly describes the distribution of any two structural parameters and thus can provide more important information about the fine-scale spatial structure of a forest (Chai et al., 2017; Li et al., 2014a). Wan et al. (2019) explained that an ideal bivariate distribution of a forest has three kinds of microstructure: randomly distributed trees with a highly mixed state ($W = 0.5$ and $M = 1$), dominant trees with a random distribution ($U = 0.00$, 0.25, and $W = 0.50$), and dominant trees with a highly mixed state ($U = 0$, 0.25, and $M = 0.75$, 1). In this study, we found that the relative frequency of trees having a micro-structure of randomly distributed trees with a high degree of mixture and dominant trees with a high degree of mixture was improved after the implementation

of CTNM on Masson pine forest at middle-aged and near-mature stages, but the proportion of trees showing a micro-structure of dominant trees with a highly mixed state had no obvious improvement. Combining the results of univariate and bivariate distribution of the spatial-structure parameters, we considered that the effect of CTNM on the spatial structure of Masson pine forest was mainly achieved by changing the distribution pattern and mingling degree; thus, these two parameters are the main adjustment factors for further implementation of CTNM. In addition, the effect of CTNM on spatial structure was more remarkable in middle-aged and near-mature Masson pine forests compared with the young forest. We thus recommend that an extensive CTNM be conducted on middle-aged and near-mature Masson pine forests, with the aim of obtaining an ideal spatial structure.

5   Conclusions

Close-to-nature management effectively improved the stand spatial structure and quality of the studied Masson pine forests, but the present structure situation was still suboptimal, and for the stands with low mixture and poor size differentiation the CTNM needs to be sustained. The method of frequency distribution of stand structure parameters can provide more direct and useful information about the heterogeneity of spatial structure from the size, species, and distribution pattern of tree population and community. CTNM according to this method can speed up the transition to a more natural stand structure and improve the success of forest management.

Author contributions. XF and ZC performed the sample collection, analyzed the data, and wrote the manuscript. WT and XG reviewed the manuscript. All authors approved the final manuscript.

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