

Article

Response of Stand Spatial Structure to Nitrogen Addition in Deciduous Broad-Leaved Forest in Jigong Mountain

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Abstract: Significant influences on tree growth and forest functionality are attributed to nitrogen (N) addition. However, limited research has been conducted on the effects of N addition on forest spatial structure. In this study, we examined the effects of different N addition methods and concentrations on the stand spatial structure of a deciduous broad-leaved forest over the period 2012 to 2017. Five N addition treatments were implemented: CK (control group without N addition), CN25 (low N concentration added to the canopy), CN50 (high N concentration added to the canopy), UN25 (low N concentration added to the understory), and UN50 (high N concentration added to the understory). The results showed a moderate influence of N addition (CN25, CN50, UN25, UN50) on optimizing the stand spatial structure. CN25, CN50, and UN25 increased the mean values of the mingling degree (M) and neighborhood comparison (U), while decreasing the mean value of the uniform angle index (W), although these effects were not significant. Enhancements in the average value of the crowding degree (C) and comprehensive spatial structure index (CSSI) between 2012 and 2017 were found in all five treatments, demonstrating statistical significance. Assessing the distribution of the stand spatial structure index, CN25, CN50, and UN25 increased the proportion of M at an intensity (M = 0.75) and extreme intensity (M = 1), while decreasing the proportion at zero intensity (M = 0), weak intensity (M = 0.25), and moderate intensity (M = 0.5). A decrease in the proportion of trees was noted when U = 0 (excluding UN50), with no discernible pattern found in the frequency distribution of other values. CN50 and UN25 increased the proportion of W at a moderate level (W = 0.5), while CN25 and UN50 reduced it. No clear pattern was detected in the frequency distributions of other values. All five treatments increased the proportion of C at the maximum level (C = 1), while decreasing the proportions at levels of 0, 0.25, and 0.5 in 2017. Intriguingly, nitrogen addition treatments appeared to optimize the stand spatial structure to some extent and stimulated the growth of trees with larger diameters. Nevertheless, the short duration of the data collection period, spanning only five years, may have influenced the significance of the outcomes, underlining the requirement for extended studies. Conclusively, N deposition adjusted and enhanced the stand spatial structure to various degrees within the research region, providing valuable insights for further optimization of forest management.

Keywords: nitrogen addition; stand spatial structure; deciduous broad-leaved forest; N concentration; canopy



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1. Introduction

Nitrogen (N) deposition is a significant global change problem that has garnered increasing attention [1–5]. The rise in N deposition has detrimental effects on the nutri-

ent cycling of forest ecosystems and poses ecological risks to terrestrial ecosystems [6–9]. This phenomenon can considerably impact the structure and function of forest ecosystems [10–12]. Exogenous N directly alters component characteristics of nutrient elements of forest plant organs [13–20], leading to growth variations among trees of different species composition and sizes [21–24], and subsequently, affecting forest spatial structural diversity.

Forest spatial structure largely determines the state of forest development, stand stability, and the size of management space [25–27]. At present, one of the main research focuses of forest management simulation in the world is the analysis and comparison of spatial structure [28–30]. Previous research on stand structure has primarily focused on site conditions, tending, and felling, while considering environmental conditions, particularly nitrogen (N) addition, has received limited attention [31,32]. N is often a limiting factor for tree growth in the warm and cold temperate zones, and different N deposition levels can have varying effects on tree growth [33–36]. However, with China emerging as the third global hotspot for nitrogen deposition, it is critical to accurately evaluate the impacts of nitrogen deposition and stand characteristics, as key drivers, and the effect their complex interplay has on forest growth [37]. Previous studies primarily focused on the influence of thinning treatments [38] and forest fires [39], among others, on the spatial structure of stands, or the impact of nitrogen deposition on stand biomass [40,41], growth [42], etc. Scant direct research exists exploring the relationship between nitrogen deposition and stand spatial structure. Therefore, it is necessary to investigate the impact of N deposition on stand structure.

The addition of N reduces intense nutrient competition in environments with limited N availability. Trees of different diameter classes show varying responses to N. Small-sized trees show significant growth promotion after N addition compared to large-sized trees [4,43], resulting in greater uniformity in tree size within the stand. However, in N-enriched environments, the addition of N can lead to phosphorus (P) and other element deficiencies, which can restrict the growth of small-sized trees [23,43] and result in greater variation in tree size within the forest. Furthermore, the effects of different nitrogen deposition rates on tree growth also vary. A study has shown that plant growth is affected when nitrogen addition levels are higher than $25 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ [44], but another study showed that when nitrogen addition levels exceeded $10 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$, the tree growth was inhibited [45], indicating that the concentration of N addition affects forest growth. Therefore, long-term and multi-level experiments of N addition in temperate forests can better predict the effects of limiting elements on tree growth [46].

This study aimed to estimate the effects of simulated N deposition on the stand structure of deciduous broad-leaved mixed forests in the Dabie Mountains region by comparing changes in stand spatial structure before and after applying different N addition methods at different intensities. We conducted a field experiment incorporating both understory addition of N (UN) and canopy addition of N (CN) treatments at rates of 0, 25, and $50 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. Building upon previous studies, we examined the trends and significance test of the difference in stand spatial structure before and after N addition in the study area. Furthermore, we analyzed the influence of different N addition methods and concentrations on the stand spatial structure of a deciduous broad-leaved mixed forest in the region to provide a theoretical basis for effectively enhancing forest quality in the area.

2. Materials and Methods

2.1. Study Site

The study site is situated in the Jigongshan (JGS) National Nature Reserve ($31^{\circ}46'–31^{\circ}52' \text{ N}$, $114^{\circ}01'–114^{\circ}06' \text{ E}$), located in Henan Province, Central China. The reserve falls within a climate transitional zone, from subtropical to warm temperate. In this region, the mean annual temperature and precipitation are 15.2° C and 1120 mm , respectively. The background rate of N deposition in precipitation is approximately $19.6 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. Deciduous temperate forest is the dominant vegetation in this area, characterized by *Quercus acutissima*

Carruth., *Quercus variabilis* Bl., and *Liquidambar formosana* Hance as the predominant canopy tree species. The region features yellow-brown sandy-loam soil [47,48].

2.2. Experiment Design

In July 2012, we established the field-controlled experimental platform (CN-WE) for “canopy simulated nitrogen deposition and rainfall” within the JGS study area (Figure 1). A comparative experiment with CN and UN at addition rates of 0, 25, and 50 kg N ha^{−1} yr^{−1} was conducted. The experiment employed a completely randomized block design with four blocks (representing four replicates) [47,49,50]. Each block included the following five treatments: (1) CN at 25 kg N ha^{−1} yr^{−1} (CN25); (2) CN at 50 kg N ha^{−1} yr^{−1} (CN50); (3) UN at 25 kg N ha^{−1} yr^{−1} (UN25); (4) UN at 50 kg N ha^{−1} yr^{−1} (UN50); and (5) a control (CK, without N addition). Each plot was circular and had an area of 907 m². The experimental manipulation is detailed in Ref. [48].

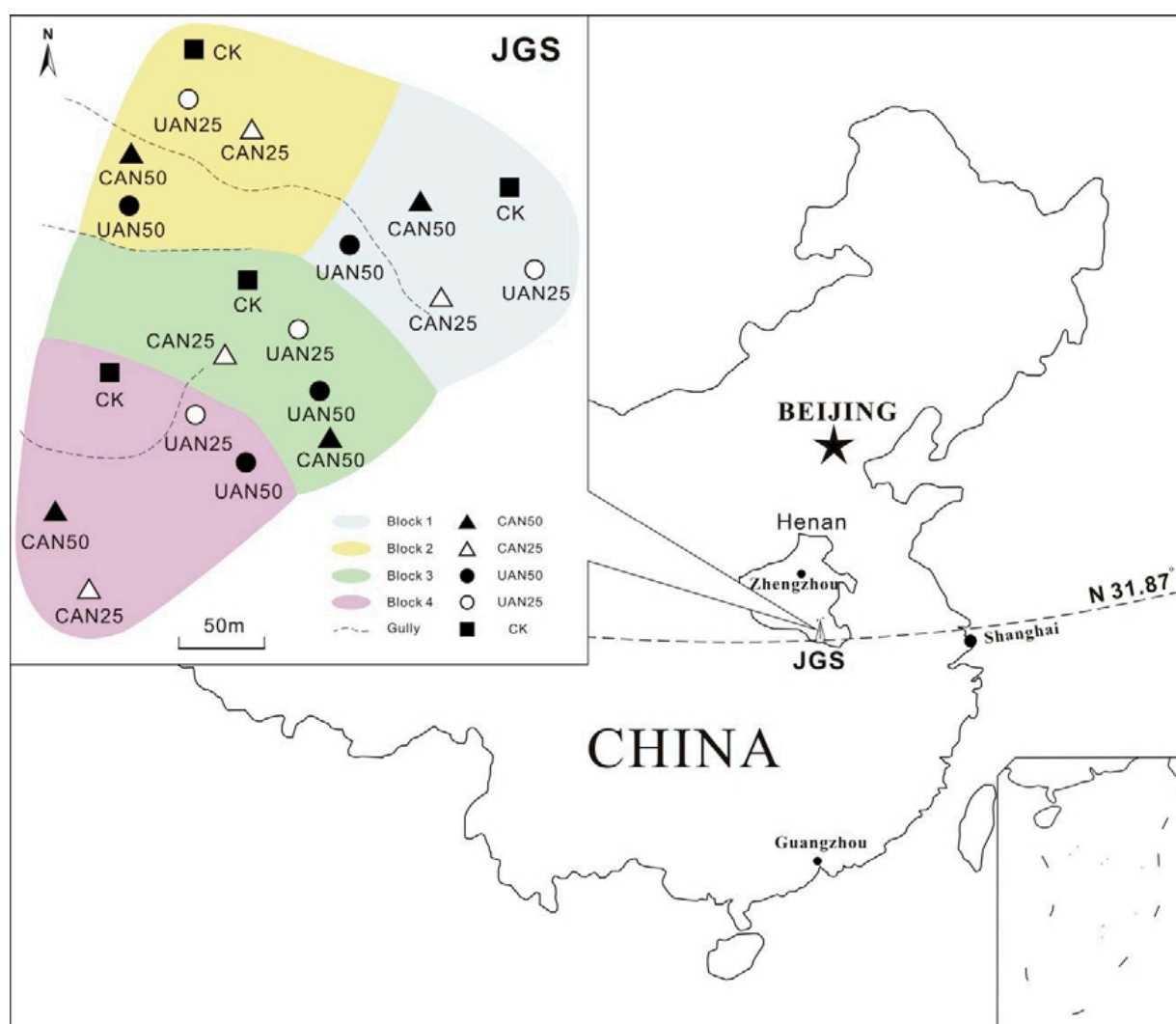


Figure 1. The distribution map of permanent sample plots in “canopy simulated nitrogen deposition and rainfall” experimental platform within the JGS study area.

2.3. Field Data Collection

Immediately after establishing the platform, a background survey of all trees within the sample plots was conducted. The diameter at breast height (DBH), tree height (H), crown width (CW), geographic coordinates, and other relevant information of all trees in

the study plots were measured. Table 1 presents the basic information for the study plots. In August 2017, after 5 years of N addition treatments, the sample plots were re-censused.

Table 1. Stand factors of the study plots for N addition treatments.

Treatment	Stand Density	DBH/cm			H/m		
	n/ha	Min.	Max.	Mean	Min.	Max.	Mean
CK	805	1.2	52.3	9.35	2.0	27.0	7.53
CN25	683	2.1	52.6	12.76	2.1	33.2	10.9
CN50	1025	1.2	55.0	11.21	2.2	33.0	8.9
UN25	706	2.1	61.7	11.43	2.1	28.0	10.0
UN50	775	1.4	57.4	10.16	1.4	28.0	8.36

2.4. Stand Spatial Structure Index Calculation

Based on the relationship between adjacent trees within a forest, stand spatial structure is described using indicators such as mingling degree [51], neighborhood comparison [52], uniform angle index [53–55], and crowding degree [56,57], which are easy to calculate and widely used with good effects. The four spatial structure indexes (M, U, W, and C) can be calculated using the following formula:

$$M_i = \frac{1}{4} \sum_{j=1}^4 v_{ij},$$

where M_i is a discrete variable, with $v_{ij} = 1$ if the species of the reference tree differs from the species of the adjacent trees; otherwise, $v_{ij} = 0$.

$$U_i = \frac{1}{4} \sum_{j=1}^4 k_{ij},$$

where U_i is a discrete variable, with $k_{ij} = 1$ if the reference tree is smaller than the adjacent trees; otherwise, $k_{ij} = 0$.

$$W_i = \frac{1}{4} \sum_{j=1}^4 z_{ij},$$

where z_{ij} is a discrete variable, with $z_{ij} = 1$ if the j th α angle is smaller than the standard angle (72°); otherwise, $z_{ij} = 0$.

$$C_i = \frac{1}{4} \sum_{j=1}^4 h_{ij},$$

where h_{ij} is a discrete variable, with $h_{ij} = 1$ if the crown of adjacent trees coincides with the reference tree; otherwise, $h_{ij} = 0$.

Based on four spatial structure indexes (M, U, W, and C), and according to the relevant references [29,38], we establish the comprehensive spatial structure index (CSSI). The CSSI indicates that as the M of the stand increases, the U and C decrease, resulting in an optimal spatial structure (CSSI = 100) under the condition of a medium W. Since U and C both reflect the competition relationship among trees, their weights are set at 50%. The function expression is as follows [38]:

$$CSSI = \sqrt[3]{\bar{M} \cdot (100 - 2 \cdot |\bar{W} - 50|) \cdot \sqrt{(100 - \bar{U}) \cdot (100 - \bar{C})}},$$

where CSSI is the comprehensive spatial structure index, $\bar{M}$, $\bar{W}$, $\bar{U}$, $\bar{C}$ are the average mingling degree, average uniform angle index, average neighborhood comparison, and average crowding degree, respectively.

2.5. Statistical Analysis

In this study, a one-way ANOVA was employed to examine the significance of the response to nitrogen deposition on the stand spatial structure index. The stand spatial structure index considered the mingling degree (M), neighborhood comparison (U), uniform angle index (W), and crowding degree (C), as well as the comprehensive spatial structure index (CSSI). The data selected were the differences in their average values in the plots between 2012 and 2017, specifically the average value in 2017 minus the average value in 2012. The data on nitrogen deposition included three types: (1) five nitrogen addition treatments, namely, CK, CN25, CN50, UN25, and UN50; (2) three nitrogen addition methods, namely, CK, CN (combining CN25 and CN50), and UN (combining UN25 and UN50); and (3) three nitrogen addition intensities, namely, CK, N25 (combining CN25 and UN25), and N50 (combining CN50 and UN50). Additionally, a simple linear regression analysis was conducted to explore the relationships between C, CSSI, and stand square average diameter. The one-way ANOVA, simple linear regression analysis, and data visualization were performed using R version 4.2.3 [58].

3. Results and Analysis

3.1. Effects of Nitrogen Addition Treatments on Stand Spatial Structure Index

3.1.1. The Differences in Stand Spatial Structure Index under Five Nitrogen Addition Treatments

Table 2 presents the average values of the stand spatial structure indexes (M, U, W, and C) and the comprehensive index (CSSI) for the forest canopy simulated nitrogen deposition platform under five nitrogen treatments (CK, CN25, CN50, UN25, and UN50) in 2012 and 2017. From 2012 to 2017, the average M values increased under the nitrogen addition treatments CN25, CN50, and UN25 by 5.97%, 1.07%, and 0.45%, respectively, while the average M values decreased under CK and UN50 by 2.11% and 3.81%, respectively. This suggests that the trend in the change of the mixing angle M depends on its initial value. Similarly, the average U values showed the same trend as M, with increases of 1.50%, 0.30%, and 1.69% under CN25, CN50, and UN25, respectively, and decreases of 0.91% and 3.79% under CK and UN50, respectively. In contrast, the average W values exhibited an opposite trend to M and U. They decreased by 2.42%, 0.82%, and 2.27% under CN25, CN50, and UN25, respectively, while they increased by 1.42% and 1.20% under CK and UN50, respectively. The average C values showed an increasing trend under all five nitrogen addition treatments, with increases of 8.51%, 2.06%, 0.85%, 2.54%, and 1.66%, respectively. For the average CSSI values, an increase of 0.70% was observed under CN25, while decreases of 7.25%, 0.88%, 0.83%, and 2.81% were observed under CK, CN50, UN25, and UN50, respectively. Considering the overall change trends in the spatial structure indexes (M, U, W, and C), CK and UN50 showed a similar pattern with decreasing M and U but increasing W and C. On the other hand, CN25, CN50, and UN25 displayed the same trend of increasing M, U, and C, but decreasing W.

Table 2. Stand spatial structure index on five nitrogen addition treatments.

Treatment	Year	M	U	W	C	CSSI
CK	2012	0.7961 ± 0.0376	0.5070 ± 0.0107	0.5110 ± 0.0156	0.7868 ± 0.0323	62.31 ± 1.71
	2017	0.7793 ± 0.0479	0.5024 ± 0.0081	0.5183 ± 0.0124	0.8538 ± 0.0329	57.79 ± 2.52
CN25	2012	0.5672 ± 0.0700	0.4951 ± 0.0103	0.5309 ± 0.0094	0.8360 ± 0.0195	52.94 ± 1.64
	2017	0.6010 ± 0.0625	0.5025 ± 0.0040	0.5181 ± 0.0148	0.8532 ± 0.0122	53.31 ± 1.91
CN50	2012	0.6707 ± 0.0514	0.4758 ± 0.0111	0.5454 ± 0.0073	0.9003 ± 0.0185	51.17 ± 1.92
	2017	0.6779 ± 0.0359	0.4773 ± 0.0072	0.5410 ± 0.0172	0.9080 ± 0.0203	50.72 ± 1.39
UN25	2012	0.6284 ± 0.0765	0.4954 ± 0.0138	0.5384 ± 0.0171	0.7731 ± 0.0396	57.74 ± 4.54
	2017	0.6313 ± 0.0914	0.5038 ± 0.0118	0.5262 ± 0.0163	0.7927 ± 0.0302	57.26 ± 4.60

Table 2. Cont.

Treatment	Year	M	U	W	C	CSSI
UN50	2012	0.7708 ± 0.1087	0.5043 ± 0.0062	0.5320 ± 0.0082	0.7912 ± 0.0369	60.84 ± 4.94
	2017	0.7414 ± 0.1227	0.4852 ± 0.0088	0.5384 ± 0.0088	0.8044 ± 0.0432	59.14 ± 5.75

Note: The data structure in the table is mean ± standard error.

3.1.2. One-Way ANOVA of the Stand Spatial Structure Index

The results of the one-way ANOVA for the stand spatial structure index (Figure 2 and Table 3) revealed that the responses of the indexes M, U, and W were not significant across different levels of nitrogen addition treatments, nitrogen addition methods, and nitrogen addition intensities. The multiple comparison tests of mean differences at different levels were also not significant. However, the responses of C and the comprehensive index CSSI were both significant (Table 3). In terms of the multiple comparison tests of the mean difference of index C, the *p*-values of CN25-CK, CN50-CK, UN25-CK, and UN50-CK were 0.044, 0.014, 0.058, and 0.027, respectively, for different nitrogen addition treatments. For different nitrogen addition methods, the *p*-values of CN-CK and UN-CK were 0.0017 and 0.0033, respectively. Among different nitrogen addition intensities, the *p*-values of N25-CK and N50-CK were 0.0041 and 0.0011, respectively. Conversely, the *p*-values of the mean difference of other levels were greater than 0.1. The comprehensive spatial structure index CSSI responded significantly to nitrogen addition treatments (Table 3), with most declining in 2017, except for CN25 which marginally increased by 0.70% (Table 2). In regard to the multiple comparison tests of mean difference of index CSSI, the *p*-values of CN25-CK, CN50-CK, and UN25-CK were 0.025, 0.073, and 0.076, respectively, for different nitrogen addition treatments. The *p*-values of CN-CK and UN-CK were 0.0042 and 0.027, respectively, for different nitrogen addition methods. Among different nitrogen addition intensities, the *p*-values of N25-CK and N50-CK were 0.0043 and 0.026, respectively (Figure 2). Similarly, the *p*-values of the mean difference of other levels were greater than 0.1.

Table 3. Results of one-way ANOVA of the stand spatial structure index. The significance symbol * and ** represent $0.01 < p < 0.05$, and $0.001 < p < 0.01$, respectively.

Index	Nitrogen Addition Treatment		Nitrogen Addition Method		Nitrogen Addition Intensity	
	<i>p</i> -Value	Significance	<i>p</i> -Value	Significance	<i>p</i> -Value	Significance
M	0.1957		0.1530		0.2240	
U	0.4148		0.6606		0.3146	
W	0.4761		0.4535		0.2125	
C	0.0125	*	0.0015	**	0.0012	**
CSSI	0.0277	*	0.0054	**	0.0056	**

3.2. Distribution of Stand Spatial Structure Index under Nitrogen Addition Treatments

Figure 3 illustrates the average values and standard deviations (error bars) of the stand spatial structure index (M, U, W, and C) at different levels (0, 0.25, 0.5, 0.75, and 1) of trees in each plot under five nitrogen treatments (CK, CN25, CN50, UN25, and UN50) in 2012 and 2017. The mingling degree values predominantly ranged from 0.75 to 1, with the lowest proportion being zero values ($M = 0$), indicating a high degree of tree species mixing. The permanent sample plots are predominantly occupied by deciduous broadleaved trees such as *Q. acutissima* Carruth., *Q. variabilis* Bl., and *L. formosana* Hance. The frequency distribution of the neighborhood comparison values showed a uniform pattern, with consistent frequency distribution across different levels, all around 20%. This suggests that the overall level of size differentiation and dominance was close to medium. The frequency distribution of the uniform angle index values exhibited a symmetrical pattern, with the main level being 0.5, which accounted for more than 50% of the distribution. This indicates that most trees were randomly distributed. The frequency distribution of the

crowding degree values displayed an exponential upward trend, with the main levels being 0.75 and 1. The proportion of C at the level 1 was higher than 50%, indicating relatively high competition intensity among most trees in the plots.

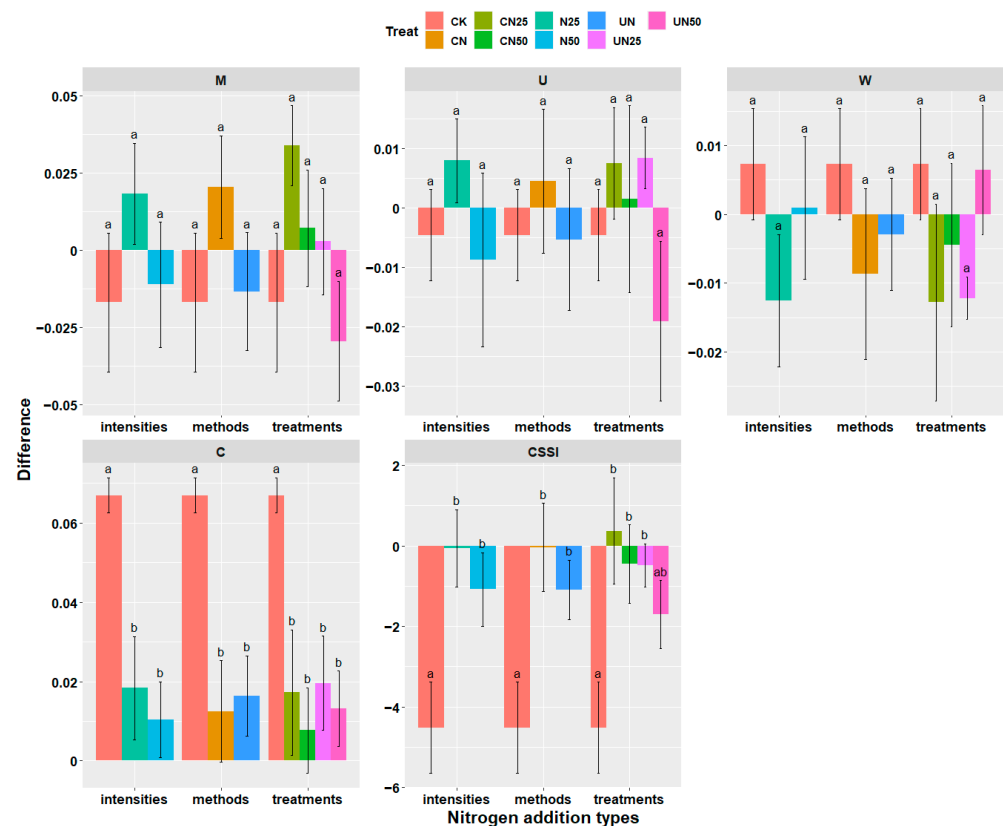


Figure 2. The difference between 2012 and 2017 of stand spatial structure index under three types: (1) Three nitrogen addition intensities, CK, N25, and N50; (2) three nitrogen addition methods, CK, CN, and UN; and (3) five nitrogen addition treatments, CK, CN25, CN50, UN25, and UN50. Means with different letters (a and b) are significantly different ($p < 0.05$) according to the least significant difference test.

3.2.1. Degree of Spatial Isolation of Forest Tree Species

The frequency distribution of M in 2012 and 2017 exhibited a consistent pattern (Figure 3, column M), with the lowest frequency at zero ($M = 0$) and a gradual increase as the level of mingling degree increased. However, the trends in changes in M between 2012 and 2017 varied under the different nitrogen treatments. CN25, CN50, and UN25 increased the proportion of high intensity ($M = 0.75$) and extreme intensity ($M = 1$) levels, while reducing the proportion of zero intensity ($M = 0$), low intensity ($M = 0.25$), and medium intensity ($M = 0.5$) levels. In contrast, CK and UN50 showed the opposite trend, increasing the proportion of zero intensity ($M = 0$), low intensity ($M = 0.25$), and medium intensity ($M = 0.5$) levels, while reducing the proportion of high intensity ($M = 0.75$) and extreme intensity ($M = 1$) levels.

3.2.2. Degree of Neighborhood Size Differentiation in Forest Stand

The frequency distribution of U in 2012 and 2017 under the five nitrogen treatments exhibited a uniform distribution (Figure 3, column U), but the trends in the changes before and after were inconsistent. Specifically, the proportion of U at the 0 level ($U = 0$) generally decreased (except for UN50), while the frequency distribution of U at other levels did not show a clear pattern. Overall, the degree of neighborhood size differentiation among trees remained relatively balanced, indicating that the five nitrogen treatments had little effect on this aspect in the forest stand.

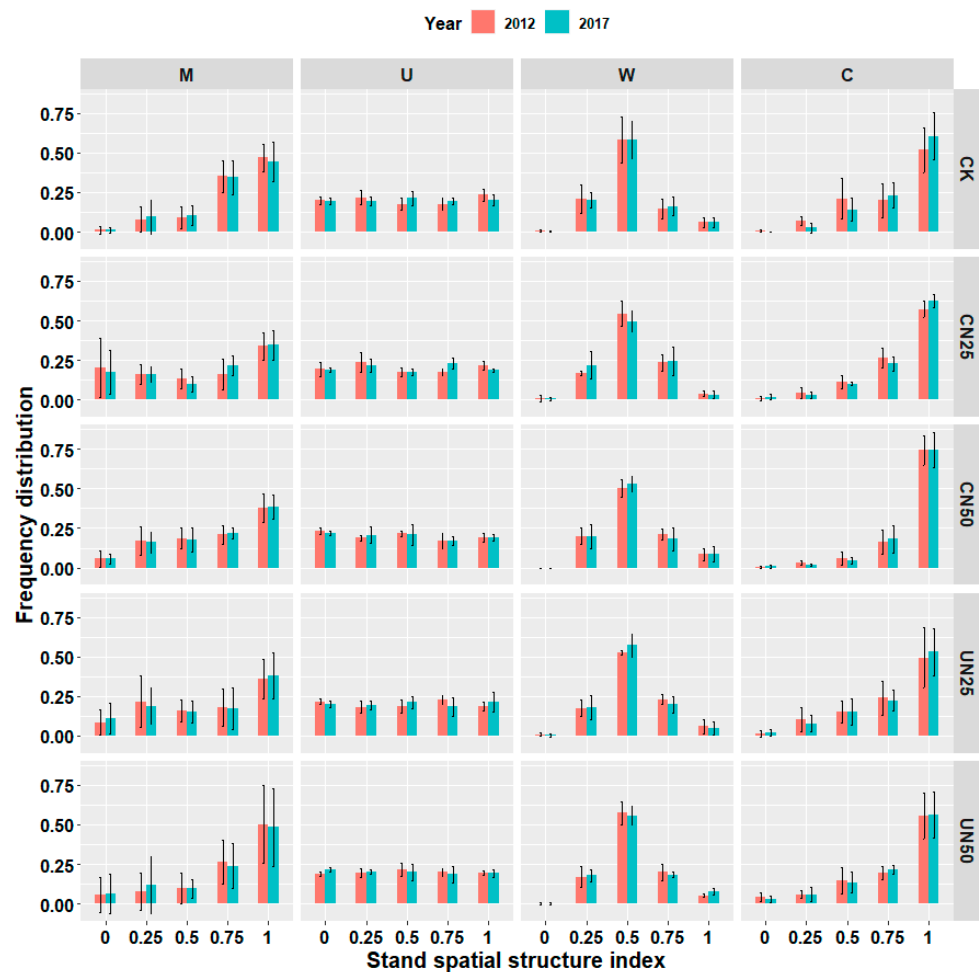


Figure 3. Frequency distribution of stand spatial structure index at different levels (0, 0.25, 0.5, 0.75, and 1) of trees in each plot under five nitrogen addition treatments.

3.2.3. Spatial Distribution Pattern of Forest Stand

The frequency distribution of W in 2012 and 2017 initially increased, and then, decreased with increasing W levels (Figure 3, column W). The highest frequency value was observed at level W = 0.5, while the frequency value at level W = 0 was close to zero. These results indicate that most trees in the plots exhibited a random distribution pattern, and the number of trees in an even distribution was less than in a clustered distribution. The trends in changes in W between 2012 and 2017 varied under the different nitrogen treatments. CK, CN50, and UN25 increased the proportion of the medium level (W = 0.5), while CN25 and UN50 reduced the proportion of the medium level (W = 0.5). The frequency distribution of W at other levels did not show a clear pattern.

3.2.4. Degree of Concentration in Forest Stand

The frequency distribution of C in 2012 and 2017 increased with the increase in C level (Figure 3, column C), with the highest frequency observed at level C = 1, all greater than 0.5, and the frequency value at level C = 0 nearly zero. These findings indicate that most trees in the plots experienced high competition intensity. The trends in changes in C between 2012 and 2017 under the five nitrogen treatments were basically consistent, all increasing the proportion at level C = 1, while reducing the proportion at levels 0, 0.25, and 0.5. The proportion at level C = 0.75 remained relatively stable. These results suggest that, irrespective of nitrogen treatment, there was a general trend towards increased concentration and competition among trees in the study plots.

4. Discussion

One-way analysis of variance in this study showed that CN25, CN50, and UN25 had a beneficial impact on the stand spatial structure indices of mingling degree (M), neighborhood comparison (U), and uniform angle index (W) (Table 2), albeit insignificant (Table 3). This might be attributable to the 5-year time interval being relatively short, such that changes in the stand spatial structure induced by tree growth could not be reflected in this time. The effect of short-term nitrogen addition on tree growth was not significant, which was also reported in other studies [59,60]. Therefore, the effect of nitrogen addition on the stand spatial structure needs to be continuously observed and studied.

The stand spatial structure index C responded significantly to nitrogen addition treatments, and generally exhibited an increase in 2017 (Figure 2 and Table 3), which deviates from most studies, where the crowding degree (C) diminishes [31,38,39]. These studies primarily focused on the impact of thinning treatments or forest fire on stand spatial structure, wherein thinning or fire evidently reduced tree density, and consequently, diminished the crowding degree (C). Furthermore, in the multiple comparison test of mean differences, it was found that compared to CK, the degree of increase in CN25, CN50, UN25, and UN50 was significantly smaller, indicating that nitrogen addition mitigated the competitive pressure among trees in the plots. Indeed, the average values of C of the plots were all above 0.75, and the competitive pressure among trees was relatively high. The notable differences in changes in C could be ascribed to the renewal of trees in the plots. During the period from 2012 to 2017, the number of new trees in the plots CK, CN25, CN50, UN25, and UN50 were 49, 28, 40, 31, and 29, respectively. Additionally, the linear relationship between the average value of C of the 20 plots and the stand square average diameter (Figure 4 left) revealed a significant linear relationship ($R^2 = 0.2179$, $p = 0.0380$), and C decreased with the increase in stand square average diameter. This, combined with the aforementioned information, indicated that nitrogen addition promoted the growth of large-diameter trees, aligning with the research results on *Larix gmelinii* [40].

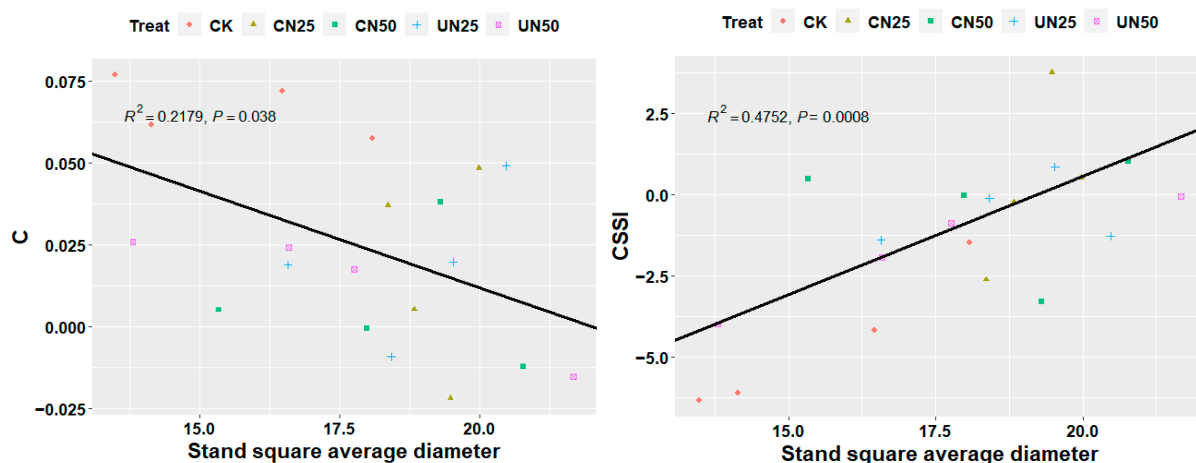


Figure 4. The linear relationship between the changes in stand spatial structure indices from 2012 to 2017 and square average diameter of the 20 plots (**left**: the changes in average values of crowding degree (C) in plots; **right**: the changes in average values of the comprehensive spatial structure index (CSSI) in plots).

The comprehensive spatial structure index CSSI considers the composite value of four different dimensions (M, U, W, and C) of the stand, providing a straightforward basis for comprehensively evaluating the quality of stand spatial structure. Our study's results showed that nitrogen addition treatments optimize the stand spatial structure, which align with the effects presented in Hu et al. [38]. This may provide additional evidence that the size of the tree plays a significant role in its growth. Specifically, the larger the tree's diameter, the more vigorous and competitive it is, resulting in a higher CSSI. Actually, the

data from 20 plots indicate a significant positive linear relationship between CSSI and the stand square average diameter ($R^2 = 0.4752$, $p = 0.0008$, Figure 4 right).

Studies have shown that the number of competing trees based on Euclidean distances can vary [61,62]. This study utilizes a four-neighbor method to calculate the spatial structure indices of trees, and further research is needed to determine the impact of their number on the rules affecting the spatial structure indices of trees and to establish the optimal number. Moreover, Li et al. found that nitrogen addition methods (CN and UN) have a significant effect on the fine root biomass of plot trees in the same platform [41]. However, the differences of stand spatial structure indices between CN and UN was not found in this study, possibly because changes in stand spatial structure require a longer time to manifest. Therefore, the long-term impacts of different nitrogen addition treatments on stand spatial structure and other characteristic indices require longer-term plot data collection to obtain a more stable response pattern of stand spatial structure to nitrogen deposition, which will provide guidance and basis for the management of deciduous mixed forests in the north–south climatic transition zone of the Dabie Mountains.

5. Conclusions

This study used the canopy simulation nitrogen deposition field experimental platform to investigate the impact of different nitrogen addition treatments on the stand spatial structure. Compared with the control plot, canopy or understory addition of low or high levels of nitrogen (CN25, CN50, UN25, and UN50) optimized the stand spatial structure of experimental plots to some extent, promoted the growth of large-diameter trees, and reduced the number of plot renewals. However, due to the data collection interval of only 5 years for the simulated nitrogen deposition plots, the differences in the impact of nitrogen addition methods or intensities on stand spatial structure were not significant, necessitating further follow-up studies. The research results can elucidate the potential significance of nitrogen addition on the structural diversity of stands, further enriching the long-term response of China's forest ecosystems to nitrogen deposition.

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