Spatial Distribution Pattern of Response of Quercus Variabilis Plantation to Forest Restoration Thinning in a Semi-Arid Area in China

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Abstract: Plantations are increasing in frequency and extent across the landscape, especially in China, and forest thinning can accelerate the development of late-successional attributes, thereby enhancing plantation stand structural heterogeneity. To quantify the effect of forest restoration thinning on the spatial heterogeneity and the structure of Quercus variabilis plantations, a restoration thinning experiment in a 40-year-old Quercus variabilis plantation by removing trees from the upper canopy level was conducted; two one-hectare sample plots with thinning and a control (i.e., unlogged) were sampled; and geostatistics methods were used to analyze the spatial distribution pattern of the DBH, height, and density of the stand. We found that restoration forest thinning in the Quercus variabilis plantation had a significant impact on the average DBH and tree height of the stand. Meanwhile, the coefficient of variation and structure ratio of the DBH, tree height, and stand density in the thinning plot were larger than those in the control plot. The range and spatial autocorrelation distance of the DBH and stand density in the thinning plot were smaller than those in the control plot, but the fractal dimension showed the opposite trend. The range and spatial autocorrelation distance of tree height in the thinning plot were higher than those in the control plot. These findings suggested that, compared with the control plot, the stereoscopic distribution of the DBH and stand density in the thinning plot fluctuated less and changed gentler, and its spatial continuity was not high but its variation was significant; meanwhile, the stereoscopic distribution of the tree height in the thinning plot was highly fluctuating and changed more significantly, with a strong spatial dependence and strip gradient distribution. Hence, forest restoration thinning could improve the distribution of the DBH and stand density and adjust the spatial heterogeneity of the DBH, tree height, and stand density of Quercus variabilis plantations.

Keywords: semi-variance analysis; spatial heterogeneity; forest restoration thinning; Quercus variabilis plantation

1. Introduction

Plantations need to be conscientiously managed to enhance stand quality and maintain ecosystem function and processes. Sustainable management could promote ecosystem function and accelerate the accumulation of carbon for reserves in a plantation forest, thus requiring basic scientific exploration [1]. Hence, the notion of using silviculture to help sustainably reach multiple management objectives in a sustainable manner has been evoked by generations of foresters. Forest thinning is one of the most commonly and importantly silvicultural methods of enhancing wood production [1], regulating stand structure, decreasing severe wildfire events, and increasing forest resilience for environmental disturbances, particularly during drought [2,3]. In addition, forest thinning has generally been prescribed to capture mortality, bring changes to the stand structure and herbaceous community, supply early financial return to landowners, and reallocate the
growing space to fewer trees to increase the future merchantable volume and economic benefit and improve the ecological and recreational values [1,4].

Depending on the purpose of implementation, forest thinning includes restoration thinning and commercial thinning. Among them, commercial thinning mainly promotes the growth of well-growing trees to maximize commercial value by removing branched and stunted trees [5,6]. Meanwhile, restoration thinning is mainly used to reconstruct the stand structure and habitat characteristics, to improve the anti-interference ability, and to re-establish the ecosystem process by the selective removal of trees, especially in degraded stands [7,8]. However, the effect of forest thinning in promoting tree vitality and enhancing the habitat features of ecosystem restoration varies among different and limited forest types [9,10].

There is a general assumption that by redistributing the growing space and reducing competition from neighbors for the surrounding resources, forest thinning improves the growth efficiency of residual trees, compared with the same-sized trees of unthinned stands [11]. However, although forest thinning releases a certain amount of nutrient space, forest thinning can also increase tree mortality by wind damage and water stress [12,13], cause growth stagnation in residual trees, and then decrease the stand volume and increment [14–17]. Recently, correlational studies on the response of forest thinning have mainly concentrated on the growth of individual trees and stands, understory diversity, biomass, carbon sequestration and stock, the physical and chemical properties of soil nutrients, soil microbial community structure, and stand structure. It is generally believed that forest thinning can increase the growth of trees or stands (for example, relative volume growth, cumulative volume growth, and basal area growth) [18–20], enhance biomass accumulation and organic C input into the soil [1], and increase biomass accumulation in the short-term [21]. In terms of the influence of forest thinning on stand structure and diversity and shrub and herb diversity [22], the number of smaller trees is expected to increase rapidly [18].

The spatial pattern is a fundamental attribute of forest ecosystems and can affect many ecological processes and functions [23]; for example, within-stand tree spatial patterns can significantly affect tree recruitment and mortality [24,25]. There is broad agreement that forest management practices should address spatial aspects of forest structure and aim to conserve or restore spatial heterogeneity [26,27]. Spatial heterogeneity is of great importance in the study of populations, communities, ecosystems, and landscapes and is defined either as the variation in the spatial distribution of a point pattern [28,29] or as the variation in qualitative or quantitative values of a surface pattern [30]. It can be caused by habitat factors and their temporal variations [31,32], individual traits [33], and neutral processes [34].

There is broad agreement that forest management should deal with the spatial aspects of forest structure and aim to conserve or restore the spatial heterogeneity of forests [26,27]. Restoring structural and spatial heterogeneity in forests as a technique to increase the supply of ecosystem services and landscape value has become a major objective of forest management and has garnered a lot of attention in forest research [5,35]. Forest thinning has been promoted as one means of enhancing heterogeneity in secondary forests [5]. Some studies think that traditional thinning methods result in a more uniform tree spacing and a narrower distribution of crop tree sizes [36]. However, more recent approaches such as variable-density thinning create a nonuniform tree spacing, thereby potentially increasing spatial heterogeneity [37]. In addition, the overall influence on the spatial variability of trees and the vertical distribution of canopy layers further depends on the forest thinning method implemented (e.g., thinning from below vs. thinning from above) [38]. In terms of the influence of forest thinning on the spatial heterogeneity, Choe et al. [39] utilized geo-statistics methods to explore the cutting disturbances on the soil nutrient spatial heterogeneity of understory plant diversity in the broadleaf-Korean pine forest in Changbai mountain, and they found that the spatial heterogeneity of soil nutrients was affected and increased by cutting intensity. Kuehne et al. [40], meanwhile,
evaluated the effects of thinning on the structural heterogeneity of growth, ingrowth, and mortality in secondary coastal Douglas-fir forests, and they discovered that differences in stand structural heterogeneity between treatments are mostly nonsignificant and the variable-density thinning showed promise in increasing structural heterogeneity in young even-aged stands, despite the short-term nature of this study. In addition, Larson et al. [41] paid attention to the effect of restoration thinning on spatial heterogeneity in a mixed-conifer forest and found that restoration thinning could reduce spatial aggregation and lead to globally random tree patterns consisting of local tree clumps, openings, and widely spaced single trees, similar to reference conditions. Unfortunately, there is a certain knowledge gap on the influence of thinning on the spatial heterogeneity of broad-leaved forests or stands.

The *Quercus variabilis* plantation is a typical deciduous broadleaf forest in China, especially in the semi-arid areas. Meanwhile, *Quercus variabilis* is a valuable economic tree species with developed roots and drought resistance. Further understanding of the effects of thinning on DBH, tree height (TH), and stand density (SD) would help address how the stand structure and the spatial stability of the stand respond to restoration thinning. In this paper, we conducted a comparative experiment to reveal the general responses of the spatial distribution patterns of *Quercus variabilis* plantations to forest thinning. This study aimed to (1) explore the influence of thinning on the spatial heterogeneity and population dynamics; (2) understand in-depth the ecological process and mechanism of community stability of *Quercus variabilis* plantations responding to thinning; and (3) thus propose more effective management measures to improve the growth of *Quercus variabilis* plantations.

2. Materials and Methods

2.1. Study Area and Experimental Design

The research area was located on the Qingliangsi Experimental Forest Farm (112°44′–13°5′ E, 34°26′–34°33′ N), Dengfeng Forestry Bureau, Henan Province, China, which belongs to the Songshan Mountain of Funiu Mountains. The climate type is temperate continental monsoon with drought and little rain all year-round and is a typical semi-arid area. The total area and the maximum elevation are about 12,207.6 ha and 1512 m, respectively. The annual average rainfall, the annual average temperature, and the frost-free period are 614 mm, 14.2 °C, and 238 d, respectively. The area has predominantly brown and cinnamon soil. Meanwhile, the soil condition is rich in potassium, low in nitrogen, highly deficient in phosphorus, and low in organic matter content. In the research area, the main conifer tree species include *Pinus tabuliformis* and *Platycladus orientalis*, while the main broadleaf tree species include *Quercus acutissima*, *Quercus aliena*, and *Robinia pseudoacacia*.

Based on the distribution characteristics and growth status of vegetation, two representative stands of the *Quercus variabilis* plantation whose stand origin is aerial seedlings, with homogeneous stand conditions within each site, were selected as the experimental stands. The age and canopy density of these two stands were 40 years old and 0.9, respectively. Meanwhile, the tree species composition of these two stands was as follows: *Quercus variabilis* was dominant with a small amount of *Quercus aliena* and *Robinia pseudoacacia*. In 2013, a restoration thinning was conducted in one of the two stands, while another stand was taken as the control stand, which was unlogged. Fieldwork was performed in 2019 in the thinning and control stands. During these six years, there was no more forest management treatment for the thinning and control stands.

Field data were collected from 2 one-hectare permanent sample plots (100 m × 100 m) which were established in these two representative *Quercus variabilis* plantations and named the thinning plot (TP) and the control plot (CP), respectively. The following measurements were made in each plot: tree species, diameter at breast height (DBH), tree height, and relative coordinates of all living trees (DBH ≥ 2.0 cm), as well as elevation, aspect, slope, and other variables (Table 1). Hence, there were 3600 observations in total in these two plots. Based on the adjacent grid method, each one-hectare sample plot was divided into 25 continuous square subplots with an area equal to 0.04 ha, and 50 subplots from two one-hectare samples were obtained in total to determine the relative coordinates of
each living tree in two 1 ha plots (Figure 1). Hence, the relative coordinates (X, Y, and Z) of each living tree in subplots were determined to the nearest 0.1 m using NTS-332R.

Table 1. General characteristics of the thinning and control plots.

<table>
<thead>
<tr>
<th>Plot Type</th>
<th>Geographical Coordinate</th>
<th>Altitude (m)</th>
<th>Slope (°)</th>
<th>Aspect</th>
<th>Stand Density (Stems·ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>112°56′17″ E, 34°27′13″ N</td>
<td>617</td>
<td>9</td>
<td>Northwest</td>
<td>1487</td>
</tr>
<tr>
<td>CP</td>
<td>112°56′21″ E, 34°27′19″ N</td>
<td>630</td>
<td>7</td>
<td>Northwest</td>
<td>2113</td>
</tr>
</tbody>
</table>

Note: TP and CP represent the thinning plot and control plot, respectively, and are the same as those below.

Figure 1. Location of the research area and sampling plots.

2.2. Spatial Autocorrelation and Distribution Analysis

2.2.1. Semi-Variance Function

A semi-variance function can be used for reflecting the overall distribution of the grayscale region and for analyzing the image self-correlation and the relationships between pixels and pixels of the neighborhood [42]. Hence, the formula of the semi-variance function is as follows (Equation (1)):

\[ \lambda(h) = \frac{1}{2N(h)} \times \sum_{i=1}^{N(h)} (Z(X_i) - Z(X_i + h))^2 \]  

(1)

where \( \lambda(h) \) is the value of the semi-variance function; \( h \) is the distance between two sample points; \( N(h) \) is the number of sample pairs whose distances are equal to \( h \); and \( Z(X_i) \) and \( Z(X_i + h) \) are the measured values of \( Z(X) \) at the spatial positions \( X_i \) and \( (X_i + h) \), respectively.

The semi-variance function analysis contains three basic parameters: nugget value (\( C_0 \)), sill value (\( C_0 + C \)), and range (\( a \)). The nugget value (\( C_0 \)) is the half-square difference, caused by many factors not equal to 0, when \( h = 0 \). The positive intercept value at the intersection of the semi-variance diagram curve and the vertical axis indicates the variation caused by random factors. The sill value (\( C_0 + C \)) is the maximum value of \( \lambda(h) \) on the semi-variance function curve and it represents the maximum variation in the data. The range (\( a \)) is the abscissa value when the half-square tends to be stable and represents the maximum distance of spatial correlation. The structure ratio (SR) (i.e., \( C_0/(C_0 + C) \)) is the ratio of the nugget value to the sill value, which represents the proportion of heterogeneity caused by random factors in the total spatial heterogeneity. If SR < 25%, the spatial heterogeneity of the regionalized variable is mainly affected by structural factors, and it means that there exists a strong spatial correlation. If SR ranges from 25% to 75%, regionalized variables have a moderate spatial correlation. If SR is greater than 75%, the spatial heterogeneity is mainly influenced by random factors.

The main types of semi-variance function models are the spherical model, linear without still model, linear with still model, exponential model, and Gaussian model. The
formulas of these five models are shown in Table 2. According to the sample fitting variance diagram and determination coefficients \((R^2)\) of the constructed model, the optimal semi-variance function models for the DBH, tree height, and stand density of the *Quercus variabilis* plantation were selected.

### Table 2. The formal list of the semi-variance function models.

<table>
<thead>
<tr>
<th>Model Form</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical model</td>
<td>(\lambda(h) = \begin{cases} 0, &amp; h = 0 \ C_0 + C \times \left[ \frac{3h}{2} - \frac{1}{2} \times (\frac{h}{a})^3 \right], &amp; 0 &lt; h \leq a \ C_0 + C, &amp; h &gt; a \end{cases} )</td>
</tr>
<tr>
<td>Linear without still model</td>
<td>(\lambda(h) = \begin{cases} C_0, &amp; h = 0 \ C_0 + A \times h, &amp; 0 &lt; h \leq a \ C_0 + C, &amp; h &gt; a \end{cases} )</td>
</tr>
<tr>
<td>Linear with still model</td>
<td>(\lambda(h) = \begin{cases} C_0, &amp; h = 0 \ C_0 + A \times h, &amp; 0 &lt; h \leq a \ C_0 + C, &amp; h &gt; a \end{cases} )</td>
</tr>
<tr>
<td>Exponential model</td>
<td>(\lambda(h) = \begin{cases} 0, &amp; h = 0 \ C_0 + C \times \left[ 1 - e^{-\frac{h}{a}} \right], &amp; 0 &lt; h \leq 3a \ C_0 + C, &amp; h &gt; 3a \end{cases} )</td>
</tr>
<tr>
<td>Gaussian model</td>
<td>(\lambda(h) = \begin{cases} 0, &amp; h = 0 \ C_0 + C \times \left[ 1 - e^{-\frac{h}{a^2}} \right], &amp; 0 &lt; h \leq \sqrt{3a} \ C_0 + C, &amp; h &gt; \sqrt{3a} \end{cases} )</td>
</tr>
</tbody>
</table>

Note: \(\lambda(h)\) is the value of semi-variance; \(h\) is the separation distance; \(C\) is the structural variability; \(C_0\) is the nugget variance; \((C_0 + C)\) is a constant; \(a\) is the range of variance; \(A\) is a constant.

#### 2.2.2. Moran’s Index

Moran’s index \((I)\) is a method to quantify the spatial autocorrelation of stands. By comparing with the neighbors’ values, it is widely used to identify spatial clustering and outlier values of variables. The formula of the global Moran’s index is shown in Equation (2):

\[
I = \frac{n}{s_0} \times \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} (x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n} (x_i - \overline{x})^2}
\]

where \(W_{ij}\) is the weight between the \(i\)th observation and the \(j\)th observation; \(x_i\) and \(x_j\) are the measured values of the variable \(x\) at the \(i\)th and \(j\)th observation points, respectively; and \(s_0\) is the sum of values of all \(W_{ij}\). The value of \(I\) is between \(-1\) and 1. When \(I > 0\), the spatial correlation is positive and the intensity of the spatial correlation increases with increasing \(I\). When \(I < 0\), the spatial correlation is negative and the degree of spatial difference increases with decreasing \(I\). When \(I = 0\), the spatial correlation is random.

#### 2.2.3. Fractal Dimension

The formula of the fractal dimension is as follows (Equation (3)):

\[
D = \frac{4 - m}{2}
\]

where \(m\) is the slope of the double logarithm semi-variance curve and \(D\) is the fractal dimension. Among them, the closer the value of \(D\) is to 2, the smaller the spatial heterogeneity and correlation are; the smaller the value of \(D\) is, the greater the spatial heterogeneity and correlation are.
2.2.4. Kriging Interpolation Method

Kriging is a probabilistic interpolation method based on the covariance of a dataset [43–45]. Kriging provides the interpolation estimates and the variances of interpolation errors that contribute to the uncertainty analysis [46]. Spatial Kriging interpolation uses the original data with regionalized variables and the structural characteristics of the semi-variance function to make the linear unbiased optimal estimation of regionalized variable values at the non-sampling points. Hence, giving measured \( n \) data values, i.e., \( Z(s_1), Z(s_2), \ldots, Z(s_n) \), at \( s_1, s_2, \ldots, s_n \) locations, \( \hat{Z}(s_0) \) at the unknown location of \( s_0 \) is estimated by the following equation (Equation (4)) [47]:

\[
\hat{Z}(s_0) = \sum_{i=1}^{n} \lambda_i Z(s_i)
\]

where \( Z(s_i) \) is the measured value at the \( s_i \) location, and \( \lambda_i \) is the unknown weight for the measured value at the \( s_i \) location.

2.3. Data Processing

To calculate the stand attributes (i.e., average DBH, average tree height, stand density) and conduct spatial autocorrelation and distribution analysis, firstly, based on the adjacent grid method and relative coordinates, the thinning and control sample plots were divided into 100 subplots with an area equal to 0.01 ha (10 m x 10 m). The average DBH, tree height, stand density, and the center coordinate for each subplot in the thinning and control plots were calculated. Then, the center coordinates of these subplots were taken as the corresponding coordinates of the average DBH, average tree height, and stand density in these subplots. Next, semi-variance function analysis required the data to obey a normal distribution. If the data did not conform to the normal distribution, it would produce a proportional effect and then affect the accuracy of semi-variance and the fractal dimension. Hence, the normality of the DBH, tree height, and stand density of the TPs and CPs was tested by the Shapiro–Wilk test in SPSS 24.0 software. If \( P_{S-W} > 0.05 \), the data obeyed a normal distribution; otherwise, the data should be transformed by the Box–Cox transformation to conform to the normal distribution. The calculation and analysis of the semi-variance function were measured by the normal distribution data and the GS+ 9.0 software, and then a 3D distribution map was obtained. In addition, the 2D distribution map was generated by Kriging interpolation in ArcGIS 10.6.0 software.

3. Results

3.1. Effect of Forest Thinning on the DBH, Tree Height, and Stand Density of Quercus Variabilis Plantation

The average DBH, average tree height, and stand density of the CP were 10.8 cm, 9.0 m, and 0.21 stems/m\(^2\), while those of the TP were 12.8 cm, 11.3 m, and 0.14 stems/m\(^2\) (Table 3). After thinning, the average values of the DBH and tree height were evidently improved, while that of stand density was decreased.

<table>
<thead>
<tr>
<th>Plot Types</th>
<th>Index</th>
<th>Average ± SD</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Coefficient of Variation (%)</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>( P_{S-W} )</th>
<th>( P^{*}_{S-W} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP</td>
<td>Average DBH (cm)</td>
<td>10.80 ± 1.31 a</td>
<td>17.10</td>
<td>8.80</td>
<td>12.16</td>
<td>1.55</td>
<td>5.10</td>
<td>0.000</td>
<td>0.455</td>
</tr>
<tr>
<td></td>
<td>Average TH (m)</td>
<td>9.00 ± 0.89 a</td>
<td>12.90</td>
<td>7.30</td>
<td>9.89</td>
<td>1.22</td>
<td>3.20</td>
<td>0.000</td>
<td>0.877</td>
</tr>
<tr>
<td></td>
<td>SD (stem/m(^2))</td>
<td>0.21 ± 0.07 a</td>
<td>0.37</td>
<td>0.02</td>
<td>35.31</td>
<td>–0.42</td>
<td>0.18</td>
<td>0.032</td>
<td>0.115</td>
</tr>
<tr>
<td>CP</td>
<td>Average DBH (cm)</td>
<td>12.80 ± 1.36 b</td>
<td>15.80</td>
<td>8.40</td>
<td>10.59</td>
<td>–0.38</td>
<td>2.15</td>
<td>0.032</td>
<td>0.054</td>
</tr>
<tr>
<td></td>
<td>Average TH (m)</td>
<td>11.30 ± 1.13 b</td>
<td>13.90</td>
<td>6.70</td>
<td>9.97</td>
<td>–0.47</td>
<td>1.92</td>
<td>0.014</td>
<td>0.138</td>
</tr>
<tr>
<td></td>
<td>SD (stem/m(^2))</td>
<td>0.14 ± 0.04 a</td>
<td>0.26</td>
<td>0.05</td>
<td>27.86</td>
<td>–0.07</td>
<td>0.59</td>
<td>0.096</td>
<td></td>
</tr>
</tbody>
</table>

Note: Different letters mean a significant difference in the community structure attributes between different plots at the 0.05 level. \( P_{S-W} \) is the normal test probability value of the original data; \( P^{*}_{S-W} \) is the probability value of the normal test after Box–Cox transformation. DBH, TH, and SD represent the diameter at breast height, tree height, and stand density, respectively.
The average DBH and stand density of the TPs and CPs had a moderate variation, and
the average tree height of these two sample plots (i.e., TPs and CPs) had weak variations,
based on the classification of the coefficient of variation (CV, CV ≤ 10%, soft variation;
10% < CV < 100%, moderate variation; CV ≥ 100%, substantial variation) (see Table 3).
However, the CV values of the average DBH and stand density in the CP were higher than
those in the TP, while the CV values of the average tree height in the CP was smaller than
those in the TP. In terms of the range, the range values of the average DBH, average tree
height, and stand density of the CP were 8.30 cm, 5.60 m, and 0.35 stem/m², respectively,
while those of the TP were 7.20 cm, 7.40 m, and 0.21 stem/m², respectively. Generally,
thinning measures made the size distribution of the DBH and stand density more con-
centrated and the size distribution of the tree height more dispersed. The possible reason
for this situation may be that thinning removes the trees which are branched, stunted,
or competitive to promote the growth of residual trees and releases a certain nutritional
space, and then makes the residual trees in the upper layer receive more light resources to
promote their height growth.

In addition, the result of the Shapiro–Wilk test (see Table 3) showed that stand density
conformed to the normal distribution while DBH and tree height should be transformed
by the Box–Cox transformation into a normal distribution to satisfy the conditions of
geo-statistics interpolation.

3.2. Influence of Forest Thinning on the Spatial Distribution Patterns of DBH, Tree Height, and
Stand Density of Quercus Variabilis Plantation

3.2.1. The Semi-Variance Function Analysis of DBH, Tree Height, and Stand Density of
Quercus Variabilis Plantation

The selected semi-variance function models (i.e., exponential model, linear without
still model, linear with still model, spherical model, and Gaussian model) were introduced
to evaluate the variation in DBH, tree height, and stand density of the TPs and CPs in the
Quercus variabilis plantation, respectively. From Table 4, the exponential model was used
to analyze the spatial heterogeneity of the DBH, tree height, and stand density in the TPs
and CPs, with the exception of tree height in the CP and DBH in the TP. The determination
coefficients (R²) of these models, with the exception of the models generated by tree height
in the CP, were higher and ranged from 0.880 to 0.976. Hence, the selected models could
accurately describe and better reflect the spatial correlation and structure characteristics
of the DBH, tree height, and stand density of the TPs and CPs.

Table 4. Types and parameters of semi-variogram model for spatial analysis of DHB, tree height and
stand density in the thinning and control plots.

<table>
<thead>
<tr>
<th>Plot Types</th>
<th>Index</th>
<th>Model Form</th>
<th>Nugget</th>
<th>Sill</th>
<th>Structure Ratio (%)</th>
<th>Range (m)</th>
<th>Determination Coefficients (R²)</th>
<th>Residual Sum of Squares (RSS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP</td>
<td>DBH (cm)</td>
<td>Exponential model</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.16</td>
<td>28.2</td>
<td>0.880</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>TH (m)</td>
<td>Spherical model</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.17</td>
<td>12.6</td>
<td>0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>SD (stem/m²)</td>
<td>Exponential model</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.20</td>
<td>39.3</td>
<td>0.967</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>DBH (cm)</td>
<td>Spherical model</td>
<td>2.1</td>
<td>51.83</td>
<td>4.05</td>
<td>21.9</td>
<td>0.880</td>
<td>18.4</td>
</tr>
<tr>
<td>TP</td>
<td>TH (m)</td>
<td>Exponential model</td>
<td>24.7</td>
<td>264.4</td>
<td>9.34</td>
<td>33.0</td>
<td>0.912</td>
<td>407</td>
</tr>
<tr>
<td></td>
<td>SD (stem/m²)</td>
<td>Exponential model</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>6.54</td>
<td>30.3</td>
<td>0.976</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Note: DBH, TH, and SD are the same as those in Table 3.

As shown in Table 4, the sill values of DBH, tree height, and stand density in the TP
were larger than those in the CP, which indicated that the spatial variability in DBH, tree
height, and stand density in the TP was higher than that in the CP. The structural ratio
values of DBH, tree height, and stand density in the TPs and CPs ranged from 0.16% to
9.34%, which indicated that the proportions of spatial heterogeneity generated by random
factors and structural factors ranged from 0.16% to 9.34% and from 90.66% to 98.84%,
respectively. In addition, the structural ratio values of DBH, tree height, and stand density
of the TP were all larger than those of the CP. In general, the spatial autocorrelation of
the DBH, tree height, and stand density of the *Quercus variabilis* plantation were all strong and caused by structural factors (such as forest stand and soil). Hence, the forest thinning measure could decrease the spatial autocorrelation of the DBH, tree height, and stand density of the *Quercus variabilis* plantation. The main reason for this situation is that thinning reduces the number of neighboring trees among the residual trees and changes the resource allocation in the stand.

In addition, the semi-variance function values of DBH, tree height, and stand density in the TPs and CPs all first increased as the separation distance increased and then remained stable after a threshold (Figure 2). As shown in Figure 2, the threshold values of the semi-variance function curves of DBH, tree height, and stand density in the TPs were 21.9 m, 33.0 m, and 30.3 m, respectively, and those in the CP were 28.2 m, 12.6 m, and 39.3 m, respectively. This indicated that the DBH, tree height, and stand density in the TPs and CPs had a strong spatial autocorrelation in this range. From Table 4 and Figure 2, the range of tree height in the TP was higher than that in the CP. In contrast, the DBH and stand density all showed the opposite trend, which indicated that the spatial autocorrelation scale of tree height after thinning was large. However, the tree height of the *Quercus variabilis* plantation after thinning showed homogeneity on a large distance scale. In addition, the range of DBH, tree height, and stand density in the TPs and CPs were all larger than the sampling distance (i.e., 10 m), which indicated that the sampling distance met the requirements of semi-variogram analysis.

![Figure 2. Semi-variograms of DBH, TH, and SD in the thinning and control plots. (a) Semi-variances of DBH, TH, and SD of the control plot; (b) semi-variances of DBH, TH, and SD of the thinning plot. (DBH, TH, and SD are the same as Table 3).](image)

3.2.2. Fractal Dimension of DBH, Tree Height, and Stand Density of *Quercus Variabilis* Plantation

As shown in Figure 3, the determination coefficient ($R^2$) values of these models generated by the separation distance and the fractal dimension of DBH, tree height, and stand density in the TPs and CPs, with the exception of tree height in the CP and the DBH in the TP, ranged from 0.861 to 0.992. The regular pattern of the influence of forest thinning...
on the fractal dimension was similar to that of the effect of forest thinning on the range for DBH, tree height, and stand density in the *Quercus variabilis* plantation. The fractal dimension values of DBH, tree height, and stand density in the TP were 1.912, 1.877, and 1.886, respectively, while those in the CP were 1.893, 1.969, and 1.822, respectively (see Figure 3). This indicated that forest thinning could improve the spatial dependence and simplify the spatial distribution of tree height while weakening the spatial dependence and complicating the spatial distribution of DBH and stand density in the *Quercus variabilis* plantation. The main reason may be that thinning decreases the number of competitors around residual trees and leads to the release of nutrient space, changing the allocation of light resources to cause a change in tree height growth to some extent.

**Figure 3.** Fractal dimension of DBH, TH, and SD in the thinning and control plots. (a) Fractal dimension of DBH, tree height, and density of the control plot; (b) fractal dimension of DBH, tree height, and density of thinning plot. (D₀, SE, and R² represent the fractal dimension, standard error, and determination coefficient, respectively; DBH, TH, and SD are the same as those in Table 3).

3.2.3. Spatial Autocorrelation of DBH, Tree Height, and Stand Density of *Quercus Variabilis* Plantation

Figure 4 shows the change in Moran’s I coefficient of DBH, TH, and SD with separation distance in the *Quercus variabilis* plantation. Moran’s I coefficient values of the DBH and stand density in the CP were basically higher than those in the TP. Meanwhile, tree height showed the opposite trend, which indicated that the spatial correlation of tree height was larger and those of DBH and stand density were all smaller after thinning. In addition, there were two trends in the relationship between Moran’s I coefficient and separation distance. One was that Moran’s I coefficient of DBH and tree height in the TP and tree height and stand density in the CP all decreased with the increase in separation distance, and their curves had an intersection point with the horizontal axis. The other was that Moran’s I coefficient of DBH in the TP and stand density in the CP all decreased rapidly, fell slowly, and finally increased with the increase in separation distance, and their curves had two intersection points with the horizontal axis, which indicated that the DBH in the
TP and the stand density in the CP all had a large plaque. Combined with the range, the plaque of DBH in the TP was about 21.9 units and that of the stand density in the CP was about 39.3 units.

Figure 4. Moran’s I coefficient of DBH, TH, and SD in the thinning and control plots. (a) Moran’s I coefficient of DBH, tree height, and density of the control plot; (b) Moran’s I coefficient of DBH, tree height, and density of thinning plot. (DBH, TH, and SD are the same as those in Table 3).

3.2.4. Spatial Distribution Pattern of DBH, Tree Height, and Stand Density of Quercus Variabilis Plantation

As shown in Figure 5, the spatial distributions of DBH and stand density in the CP and tree height in the TP had a strip gradient with some patches, while those of the DBH and stand density in the TP and the tree height in the CP had a patch-like gradient. Among them, in the CP, the DBH and tree height increased gradually from northwest to southwest and east, and their high-value area appeared in the east of the study area, while the spatial distribution of the stand density was opposite to those of the DBH and tree height. However, in the TP, DBH increased gradually from southwest to northeast, and its high-value area was in the northeast; tree height decreased gradually from southwest to northwest and southeast, and its high-value area was in the southwest; and stand density increased from northeast to southwest, and its high-value area appeared in the southwest. Hence, the spatial heterogeneity of tree height in the CP and those of DBH and stand density in the TP were relatively large, and their spatial continuity were high on a small scale and had substantial variance.

Further, based on the sharpness of the peaks and the transition degree of each index, the kurtosis of the 3D stereogram of DBH and stand density changed from significant fluctuations to gentle, while that of tree height changed from mild to severe, after thinning (see Figure 6). This result indicated that thinning made the spatial distribution of DBH and stand density uniform with a more negligible overall difference and spatial heterogeneity, while it made the spatial distribution of tree height uneven with a more significant overall difference and spatial heterogeneity.
Figure 5. Two-dimensional map of spatial distribution pattern of DBH, tree height, and stand density in the thinning and control plots. (a) Spatial distribution pattern of DBH, tree height, and stand density of the control plot; (b) spatial distribution pattern of DBH, tree height, and stand density of the thinning plot. (DBH, TH, and SD are the same as those in Table 3).

Figure 6. Three-dimensional map of spatial distribution pattern of DBH, tree height, and stand density in the thinning and control plots. (a) Spatial distribution pattern of DBH, tree height, and stand density of the control plot; (b) spatial distribution pattern of DBH, tree height, and stand density of the thinning plot. (DBH, TH, and SD are the same as those in Table 3).
4. Discussion

Many silvicultural practices such as planting cutover forest lands, vegetation management techniques, and stand thinning have been criticized for creating relatively uniform conditions with forest stands [48]. Pre-commercial thinning, in particular, tends to leave a homogeneous array of trees throughout a treated stand, and this practice contributes to both volume and quality increases in wood fiber on those crop trees selected for superior growth and form during the thinning process [49]. Forest restoration thinning is also a technique that alters the stand structure and ecological succession of understory vegetation. Conventional stand thinning generally leads to positive responses in the biomass of understory vegetation [50–55] and has the potential to increase tree growth [16,56–58] and reduce the competition among trees [59] while generating a gap to increase the diameters of the rest of the trees and the stability of the stand [60]. Due to the forestry characteristics in China, forest restoration thinning could not attain a high timber yield. Hence, it is necessary to analyze the effect of forest restoration thinning on the spatial heterogeneity and structure of the Quercus variabilis plantation in China.

4.1. The Effect of Thinning on the Non-Spatial Structure of Quercus Variabilis Plantation

Forest thinning plays an important role in adjusting tree species composition, reducing stand density, improving forest health, optimizing stand structure, and improving the comprehensive benefits of the stand. Our result indicated that the average DBH and average tree height of the TP were significantly higher than those of the CP. In addition, the variation coefficient and range values of DBH and stand density in the TP were smaller than those in the CP, while the variation coefficient and range values of tree height in the TP were more extensive than those in the CP. This situation showed that the distributions of DBH and stand density in the TP were relatively concentrated and better than those in the CP; while the distribution of tree height in the TP was opposite. In general, the influence of thinning on the tree growth and non-spatial structure of the Quercus variabilis plantation was positive. Our results are consistent with those of previous research [61,62]. Among them, Gradel et al. [59] researched the response of the non-spatial structure of birch and larch stands in North Mongolia to thinning and found that thinning could positively affect the total yield, although the distribution and coefficient of variation in diameter were not greatly changed by thinning. Nguyen et al. [62] studied the influence of thinning intensity on tree growth in a Pinus koraiensis plantation and found that thinning increased tree growth (diameter at breast height and crown size) with the exception of height growth, while the moderately thinning stand had the highest basal area and stock volume at the stand level. Meanwhile, Cabon et al. [61] researched the influence of thinning on tree growth in a Mediterranean evergreen oak coppice, and their result revealed that thinning increased long-term growth at the stem level but decreased the wood biomass at the stand level, while moderate thinning had a sustained beneficial influence on the growth of all stem size classes; by contrast, stronger thinning intensities increased the size asymmetry of competition and their overall effect dropped faster. However, the reason for this situation might be that thinning removed the branched, stunted, or competitive trees around residual trees; decreased the number of neighboring trees around the residual trees; and released a certain amount of nutrition space before adjusting the structure and density of the stand, improving the utilization efficiency of water and light resources, and reducing the proportion of trees with a small DBH and low tree height, resulting in the better growth and development of the remaining trees [63,64]. Due to an excellent correlation between forest growth and stand density, suitable thinning could adjust the stand density, improve the illumination, increase the nutrition of the reserved trees, and effectively promote the growth of trees. Hence, although this research analyzes the impact of thinning from multiple stand features (i.e., DBH, tree height, and stand density), it was necessary to conduct in-depth research on the canopy structure and diversity of the understory plant in the future.
4.2. The Effect of Thinning on the Spatial Heterogeneity of Quercus Variabilis Plantation

Spatial heterogeneity is the variability and complexity of the system or system attributes in space and is the main reason for the formation of spatial patterns. At present, the research on spatial patterns mainly used the crown width, crown height, tree height, DBH, and stand coverage as regionalized variables to analyze the spatial pattern of stands [65]. This study changed the previous spatial distribution pattern analysis methods, such as the distance method, angular scale, and coefficient of variation of the Voronoi method, and used the semi-variance function analysis and Kriging interpolation method to analyze the spatial heterogeneity. Our results showed that the variation range of the DBH, tree height, and stand density of the thinning and control plots were all greater than 10 m, and the sampling distance met the research requirements. The tree height, DBH, and stand density in the thinning and control plots had a strong autocorrelation. The variation ranges and the spatial autocorrelation distances of DBH and stand density in the thinning plot were all lower than those in the control plot. Meanwhile, the variation range and the spatial autocorrelation distance of tree height in the thinning plot were larger than those in the control plot. Compared with the control plot, the spatial distributions of DBH and stand density in the thinning plot fluctuated less and changed gentler; their spatial continuity was not high but their spatial variation was more significant. Meanwhile, the spatial distribution of tree height in the thinning plot was highly fluctuating, with a strong spatial dependence, simple spatial distribution, and strip gradient distribution. The reason might be that forest thinning decreases the number of competitors around the remaining trees; changes the allocation of habitat resources, especially the allocation of light resources in vertical space; and then adjusts the horizontal and vertical distribution of trees in the stand to make stand structure more stable, letting the forest environment become more suitable for plant growth and development, improving the canopy structure and light environment to make the shrubs and grass grow better, accelerating litter decomposition, increasing the soil nutrient and forest growth space, and then obtaining profit for plant growth and development. However, the slope position, topography, intraspecific competition, and other factors would lead to an uneven distribution of tree height after thinning. This reason is supported by some previous studies [65–67]. Among them, Liu et al. [65] studied the spatial heterogeneity of urban street trees in Harbin, China, and found that interspecific and intraspecific competition would affect the spatial heterogeneity of tree height and DBH. A large number of studies showed that the DBH and height of trees were influenced by soil factors. Li et al. [67] studied the spatial heterogeneity of the DBH growth of Korean pine and revealed that terrain factors could explain the spatial distribution of its DBH growth, to a certain extent. Meanwhile, Samra et al. [66] thought that the growth of tree height had some relationship with the soil environment by studying the spatial dependence between soil alkalinity and tree growth. Exploring the spatial heterogeneity of the DBH, tree height, and stand density of plantations in the thinning and control plots could further elucidate the influence of thinning on stand structure by geostatistical methods and provide a basis for reasonable thinning. However, slope position, soil, and human disturbance all had a certain effect on DBH, tree height, and stand density under different thinning intensities. Hence, it is necessary to further study the spatial heterogeneity of DBH, tree height, and stand density under different thinning intensities.

4.3. The Suggestion of Forest Restoration Thinning in the Semi-Arid Area

Forestry surveys have revealed that the allometric relationships among tree height, canopy area, and breast height diameter are mainly driven by light limitations [68]. However, in open forests such as semi-arid forests, the light resource is generally not a limiting factor for tree growth [69]. In semi-arid areas, there are rich radiation and heat resources but insufficient water resources, thus seriously affecting the survival, growth, and management of afforestation. Some researchers have considered that the semiarid climate conditions limit the height growth of trees [70] and generate an overall deficiency in moisture, which considerably influences the elevational forest distribution and may even control the upper
forest limit [71–73]. Human-driven forest thinning is of primary importance for sustainable water resource management in semi-arid basins [74,75]. In China, the semi-arid area accounts for 22% of the total land area. Hence, based on the effect of thinning on the spatial heterogeneity of DBH, tree height, and stand density in *Quercus variabilis* plantations, forest restoration thinning in semi-arid areas is the suggested target tree management method taking into account soil and water conservation and confirming the disturbance trees around the remaining trees. Then, the competitive trees or the trees that are not conducive to the reconstruction of the stand structure around the remaining trees are selectively removed, but not the deep-rooted tree species, maintaining the water resources environment in the region. Meanwhile, the intensity of this restoration thinning should be moderate to adjust the stand structure and maintain the ecological function of the forest in the semi-arid area to meet the forest-adaptive management requirements.

5. Conclusions

The influence of forest thinning on the stand structure and spatial heterogeneity of a *Quercus variabilis* plantation was explored by geostatistical methods. Forest thinning could improve the distribution of the DBH and stand density and increase the effect of structural factors on the spatial heterogeneity of the DBH, tree height, and stand density. In addition, forest thinning could reduce the stereoscopic distribution fluctuation in DBH and stand density, reduce the fluctuation change, reduce their spatial continuity, and enhance the significance of their spatial difference. However, forest thinning makes the stereoscopic distribution fluctuation of tree height change severely, improves its spatial dependence, and simplifies its spatial distribution, which shows a banded gradient distribution. Forest thinning improves the allocation of light resources in the stand, promotes tree growth, and enriches the spatial heterogeneity of stand features. For the suggested forest management in the semi-arid area, moderate restoration thinning which utilizes the target tree management method considering soil and water conservation is recommended. Hence, this research will provide a reference for exploring the spatial variation and heterogeneity of stand attributes and formulating forest-adaptive management measures in semi-arid areas.


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