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Stability and Spatial Structure of Chinese Pine (*Pinus tabuliformis* Carr.) Plantations in Loess Hilly Region: A Case Study from Huanglong Mountain

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Abstract: In contrast to intensive management practices focused on wood production, plantations designed to safeguard fragile environments prioritize the sustainable fulfillment of ecological functions. To assess the potential for Chinese pine (*Pinus tabuliformis* Carr.) plantations in the Loess Hilly Region to effectively serve their ecological protection role over the long term, we selected nine indices representing biological stability, resistance stability, and functional stability. Employing a novel unit circle method, we evaluated the total stability (sum of the three stability components) of 44 plantation plots in Huanglong Mountain. We also explored the connections between total stability and standing spatial structure parameters to offer insights for promptly enhancing stability through thinning. The findings revealed that 79.5% of Chinese pine plantations exhibited moderate total stability, with 20.5% demonstrating good stability. Most plots displayed a random distribution pattern, moderate size differentiation, low species spatial mixing, and high stand crowding. Among the correlations analyzed, mingling exhibited the highest coefficient, followed by differentiation, while the uniform angle index showed the weakest correlation, and crowding displayed an insignificant correlation. While the presence of good functional stability contributed to the moderate total stability, addressing inadequate biological and resistance stability necessitates thinning measures. This study identifies spatial structure types negatively linked to total stability, offering targeted management insights for enhancing the stability of Chinese pine plantations. The stability assessment methodology and indicators presented in this study can serve as a valuable reference for similar plantations with comparable functions and planting conditions.

Keywords: comprehensive evaluation; unit circle method; nightingale rose diagram; biological stability; resistance stability; functional stability; management suggestions

1. Introduction

The concept of stability encapsulates the holistic capacity of an ecosystem to endure both natural environmental fluctuations and human-induced disturbances. This resilience reflects the ecosystem's ability to sustain its original state and recover from such perturbations [1,2]. Since the introduction of the stability concept, scholars have embarked on a series of theoretical inquiries and empirical investigations into the intricate interplay between diversity and stability [3,4]. The bulk of these studies corroborate a positive connection between diversity and stability, underlining how species diversity augments ecosystem functionalities like productivity by enriching the spectrum of plant adaptive strategies [5,6]. Consequently, this enhanced diversity bolsters the community's ability to withstand and rebound from disturbances, fostering overall ecosystem stability [7]. Nonetheless, dissenting perspectives have been put forth by some scholars [8], contending that stability is governed more by dominant species within a community than sheer species diversity [9]. Beyond species diversity, the stability of forest communities is influenced by various structural attributes such as complexity, stand age, regeneration density, and the presence of large trees [10,11]. Moreover, external environmental factors, including anthropogenic disturbances, also play a role in regulating stability [4].

In the context of the diversity-stability relationship, stability is often gauged through the temporal stability of biomass or productivity, measured by the coefficient of variation in multi-period data [12,13]. Various approaches exist for assessing and evaluating stability, including M. Gordon's method [14,15] and the comprehensive evaluation method [16,17]. The former method hinges on the relative frequency of plant species within a community and the stability of their interactions [14], while the latter entails a thorough assessment of stability through a multi-index framework. These comprehensive evaluation methods encompass diverse calculation techniques like the membership function method based on fuzzy mathematics [17,18], principal component analysis [16], and the unit circle method [19,20].

The unit circle method maps the stability value of an indicator to the square of its standardized value [21]. If the standardized value is 0.5, its mapped stability value is 0.25, while values corresponding to standardized values of 0 and 1 remain 0 and 1, respectively [22]. This non-linear mapping approach underscores the significance of attaining optimal performance in each indicator aspect rather than relying on their interchangeability. Given the method's underlying mechanics and its advantages in visualization, it has become a widely employed tool in comprehensive evaluation [22]. Similarly, it holds promise for infusing fresh vigor into the stability assessment of plantations.

Different research contexts warrant distinct indicators in the comprehensive evaluation method. For natural forests, selected indicators often mirror stand conditions and soil properties, encompassing stand structure, species diversity, and soil physicochemical characteristics, as well as disturbance intensity [17,18]. Conversely, indicators chosen for plantations tend to emphasize ecological functions such as sediment transport rates and protection periods [23]. In a recent study, the scope expanded beyond internal community states to incorporate the impact of external environmental patches on community stability, providing a landscape-level assessment of external disturbances [19]. While various indices exist for assessing stability, the quest for a simple yet effective evaluation system for plantations remains unfulfilled.

While research on the stability of natural forests is abundant, the same cannot be said for plantations. Studying plantation stability necessitates an approach that prioritizes the ecological functions specific to these managed ecosystems rather than merely replicating methods developed for natural forests [24]. Currently, research on the stability of artificial sand-fixation forests is quite comprehensive, featuring detailed descriptions, clear functional definitions, and an evaluation system aligned with sand-fixation properties [23,25]. However, this also underscores the imperative of devising a novel index system to evaluate stability on other types of plantations.

Within the Loess Hilly Region of China, soil erosion stands as a formidable environmental challenge due to factors like loose soil, rugged terrain with steep slopes, uneven rainfall distribution, and limited vegetation cover [26]. To address soil erosion and preserve the ecological balance, Chinese pine (*Pinus tabuliformis* Carr.) has been extensively planted as a native species and vital afforestation component in the Huanglong Mountain of Shaanxi Province for over a century [27]. These Chinese pine plantations primarily serve ecological conservation goals such as soil and water retention and erosion control, refraining from commercial logging activities. However, inconsistent forest community stability has emerged due to insufficient targeted post-afforestation management practices [28].

Among various management measures, thinning stands out as the most common and effective strategy. Yet, prevailing thinning guidelines often focus on cutting intensity and forest health, leading to subjective tree selection [29]. Modern methods based on spatial structure parameters offer a more precise and objective approach to thinning tree selection [30]. The spatial structure of a stand encompasses the spatial arrangement of trees and their attributes, providing a comprehensive reflection of the stand's development process, including regeneration, competition, self-thinning, external disturbances, and the potential for restoration and enhancement through management [31]. Although exploring the connections between stand spatial structures and stability bears profound significance in enhancing plantation stability through targeted thinning, there is still a lack of comprehensive knowledge on the relationships between them.

In response to the aforementioned challenges, we have crafted a novel and accessible, comprehensive evaluation index system designed specifically for assessing the stability of plantations. Within this system, we have deliberately excluded indices that necessitate extensive subsequent experiments, rely on prolonged observation periods, or demand costly measurement procedures. Instead, we have chosen to focus on nine key indices, organized into three distinct components: biological stability, resistance stability, and functional stability. These indices can be readily derived from the data available in the National Forest Inventory (NFI) and sample plots. Our research will leverage the innovative unit circle method to perform a comprehensive assessment of the total stability of plantations, which is the cumulative result of these three stability components. Furthermore, we will conduct correlational analyses to investigate the relationships between stability and its associated indicators with stand spatial structure parameters and their respective types. The ultimate goal of our study is to develop precise management recommendations aimed at enhancing the stability of Chinese pine plantations on Huanglong Mountain. By doing so, we aim to unlock the full potential of these plantations in terms of soil and water conservation, water storage, and erosion control.

2. Materials and Methods

2.1. Site Description

The study area is located in the forest region of Huanglong Mountain, Shaanxi Province, China, spanning geographic coordinates from 109°38′49″ to 110°12′47″ E and 35°28′46″ to 36°02′01″ N (Figure 1). Situated within the transitional zone between temperate sub-humid and semi-arid climates, this region is characterized by hilly and gully terrain within the Loess Plateau. The elevation ranges from 1100 m to 1500 m above sea level, with an average annual precipitation of approximately 611.8 mm and an average annual temperature of around 8.6 °C. The dominant forest communities in this region comprise pine forest, oak forest, birch forest, and pine-oak mixed forest. Among the noteworthy tree species are *Pinus tabuliformis* Carr., *Quercus wutaishanica* Mayr, *Betula platyphylla* Suk., *Populus simonii* Carr., *Malus spectabilis* (Ait.) Borkh., *Pyrus betulifolia* Bunge, *Crataegus cuneata* Siebold & Zucc., and *Acer ginnala* Maxim. Additionally, principal shrub species comprise *Spiraea pubescens* Turcz., *Cotoneaster multiflorus* Bge., and *Lespedeza formosa* (Vog.) Koehne. The herbaceous species are predominantly represented by *Carex Linn* and *Artemisia Linn* [32].

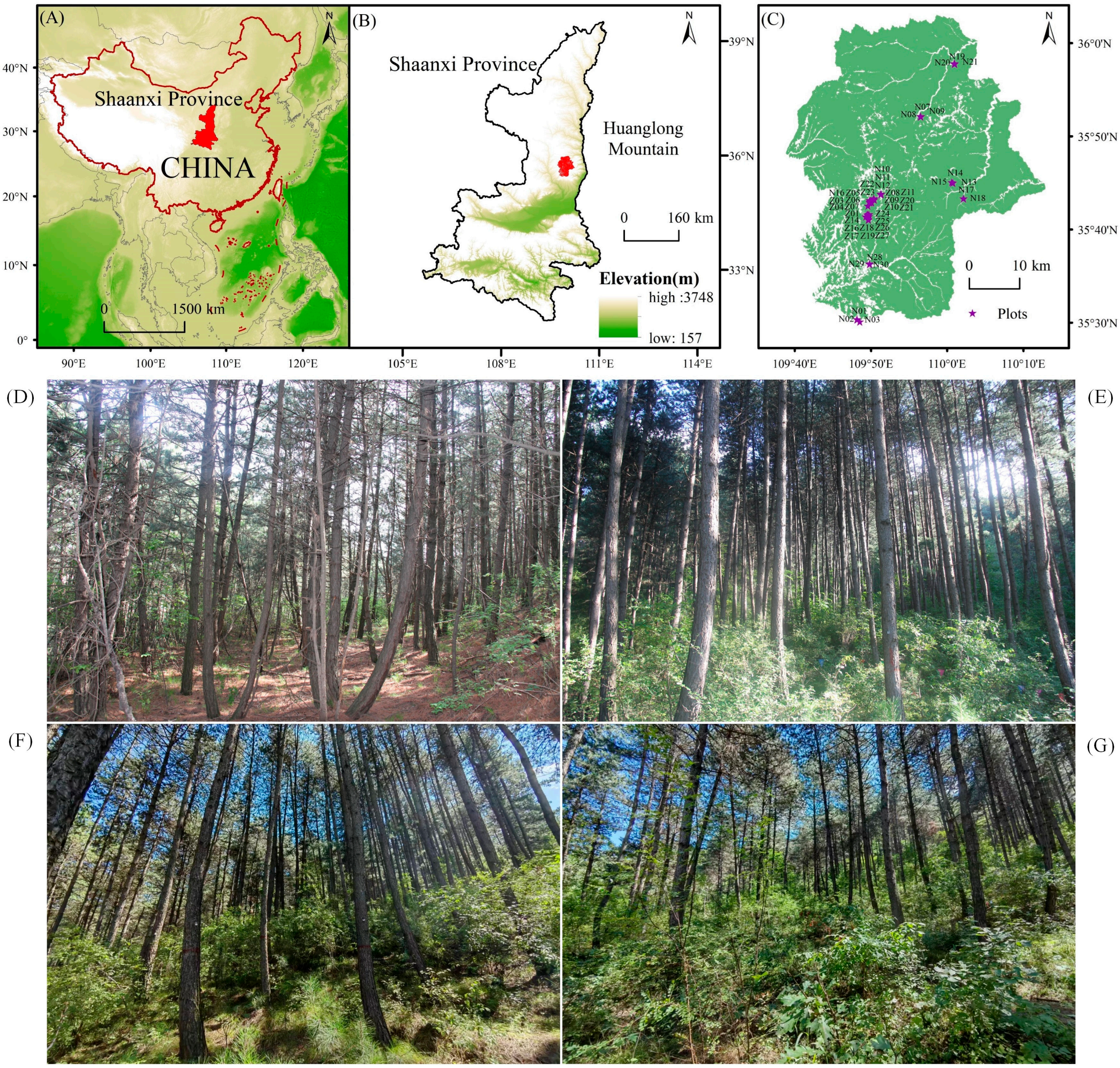

Figure 1. Geographic overview of Shaanxi Province (**A**) and Huanglong Mountain (**B**). Mapping the distribution of Chinese pine plantations in Huanglong Mountain (**C**). Variations in Plantation Characteristics: (**D**) dense plantation with a thicker litter layer and the absence of understory vegetation. (**E**) Plantation with vigorous understory vegetation. (**F**) Plantation with some natural regeneration of *Pinus tabuliformis*. (**G**) Plantation with some natural regeneration of *Quercus wutaishanica*.

The forests in Huanglong Mountain experienced a high intensity of deforestation before the 1960s, while in the four decades since the establishment of the Huanglongshan Forestry Bureau in 1962, significant afforestation efforts have gradually taken place in this region, with Chinese pine plantations playing a vital role in this restoration process [27]. In the reforestation process, saplings of Chinese pine are strategically planted in groups of 2 or 3 within designated planting points (Figure 1D). This meticulous planting strategy ensures that the resultant tree density conforms to the prescribed requirements. Moreover, the arrangement of these planting points follows a geometric pattern resembling an isosceles triangle grid (Figure 2A). It is imperative to emphasize that these Chinese pine plantations have remained insulated from commercial logging activities due to stringent forestry policies. Instead, they have received silvicultural treatments, primarily pruning and the removal of deadwood, to optimize their growth and health [27].

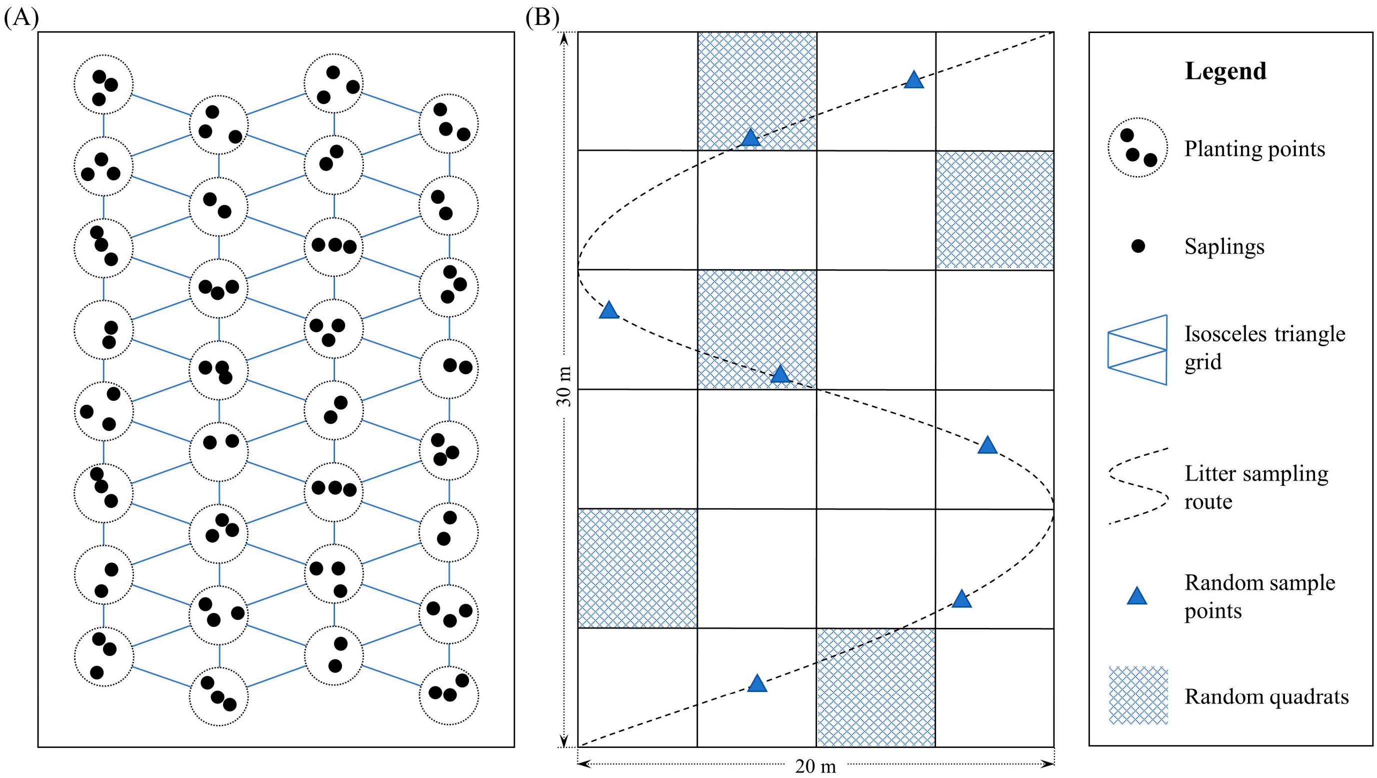

Figure 2. Schematic diagram of afforestation arrangement for Chinese pine plantations (**A**) and survey design in plots (**B**).

2.2. Field Data Collection

Between 2016 and 2018, a total of 44 plots measuring 20 m × 30 m were established within the primary distribution area of Chinese pine plantations across various forest farms under the jurisdiction of the Huanglong Mountain Forestry Bureau (Figure 1C). Each plot was subdivided into 24 subplots measuring 5 m × 5 m. Trees with a diameter greater than 3 cm at breast height were meticulously measured, documenting species, relative positions (x and y coordinates), diameter at breast height (DBH), crown width (in the x and y directions), and health status. Trees that are affected by disease, pests, or stress due to overcrowded canopies, leading them to be on the brink of death or already dead, are considered unhealthy. On the other hand, trees that remain free from disease and pests, are structurally sound with no damage or hollow areas, and can successfully complete their life cycles are considered healthy [21].

All Chinese pine trees are divided into diameter classes based on their DBH at 2 cm intervals. Within each diameter class, half of the trees were selected for height measurement (all trees will be measured if the number of trees is less than five within a diameter class). The heights of other Chinese pine trees were considered equal to the mean height of measured trees within the same diameter class. For stand age determination, 4–5 dominant Chinese pine trees were randomly chosen for growth cone drilling and subsequent examination of tree rings.

Furthermore, 5 out of the 24 subplots were randomly designated as quadrats for surveying the understory vegetation. Records were made of understory vegetation coverage and regenerations with a height $\geq$ 50 cm. Litter thickness was assessed at 7 randomly selected points within each sample plot using an S-type method (Figure 2B).

The tree volumes of Chinese pine and other species were calculated using the two-variable and one-variable tree volume tables of the Huanglongshan region, respectively [33]. Summary statistics for stand variables are presented in Table 1.

Table 1. Summary statistics of stand variables (n = 44).

Variables	Median	Min.	Max.	Mean ± SD
Stand age/years	35	29	45	35 ± 4
Average DBH/cm	13.5	8.9	23.9	14 ± 2.9
Top height/m	13.0	8.1	18.9	12.9 ± 2.4
Stand density/(trees·ha^{-1})	2700	500	4533	2660 ± 1100
Canopy density	0.90	0.75	0.98	0.89 ± 0.05
Stand basal area (Ba)/(m^2·ha^{-1})	35.7	15.6	58.3	35.8 ± 8.6
Stand volume (V)/(m^3·ha^{-1})	234.8	99.3	439.8	239.1 ± 71.6
Elevation/m	1424.5	1114.0	1519.0	1387.4 ± 110.1
Slope gradient/°	18.5	3	40	19.9 ± 7.9
Slope aspect/°	101	0	345	154 ± 125
Litter thickness/cm	4.6	7.3	2.4	4.5 ± 1.4

Note: The slope aspect starts at 0° of north and increases clockwise with a max value of 359°.

2.3. Construction of Stability Comprehensive Evaluation Index System for Chinese Pine Plantations

In this study, indicators were selected from three critical components—biological stability, resistance stability, and functional stability—to evaluate the total stability of Chinese pine plantations, following the approach by Xing et al. [23].

Biological stability emphasizes a plantation's ability to consistently fulfill ecological functions. Structural heterogeneity, reflecting age variation of trees and layering, is captured by variations in tree sizes within a plot [34]. Adequate regeneration is integral to ensuring ecological function and sustainability [21], while the dominance of target species competition reinforces community stability [22].

Resistance stability centers on a plantation's resilience against external disturbances. Tree condition and potential stand risks serve as resistance indicators. The height-to-diameter ratio (slenderness), representing the ratio of tree height to DBH, offers insights into the mechanical stability [35] or static stability [36] of a tree or stand against adverse environmental conditions like wind and snow disasters [37,38]. Common disturbances—such as pests, diseases, and fires—pose potential risks to plantations. Overall tree health mirrors the stand resistance against historical interferences, while species diversity gauges the forest's resilience against potential risks [5].

Functional stability underscores a plantation's role in soil protection and water retention. Enhanced vegetation cover effectively reduces short-term soil erosion resulting from heavy rainfall events [39]. Thus, forest canopy and understory coverage serve as indicators of the plantation's soil conservation and ecological function. Additionally, litter contributes to rain-induced soil erosion reduction, along with slowing surface runoff and soil evaporation [40].

Building on this analysis, the comprehensive evaluation index system for the total stability of Chinese pine plantations comprises 9 indicators. The calculations and standardization methods for each indicator are as follows:

(1) Biological stability

- Structural heterogeneity (SH): calculate the Gini coefficient based on basal area [41]:

$$SH = \frac{\sum_{i=1}^{n} (2i - n - 1)BA_i}{\sum_{i=1}^{n} BA_i(n-1)} \quad (1)$$

where BA_i symbolizes the basal area of the i-th tree within a plot, i signifies the ranking of the basal area of trees in ascending order, and n denotes the number of trees in the plot. When the value of SH falls below 0.2, it indicates minimal variance in tree sizes, while an

SH value surpassing 0.7 suggests a substantial dissimilarity in tree sizes, so the SH were normalized as follows:

$$SH_j = \begin{cases} 0, & SH_j \leq 0.2 \\ (SH_j - 0.2) \times 2, & 0.2 < SH_j < 0.7 \\ 1, & SH_j \geq 0.7 \end{cases} \tag{2}$$

SH_j—Gini coefficient of j-th plot.

- Regeneration potential (*Reg*): the number of saplings (height $\geq$ 50 cm) per hectare was used. Since the number of saplings greater than 2500 trees/ha indicates a successfully naturally regenerated area [22,42], the Reg was normalized as follows:

$$Reg_j = \begin{cases} N_j/2500, & N_j < 2500 \\ 1, & N_j \geq 2500 \end{cases} \tag{3}$$

N_j—number of saplings per hectare in j-th plot.

- Target species competition (*Comp*): is quantified by the dominance of the target species (Chinese pine) [21,22]:

$$Comp = \sqrt{pBA_{sp} \times D_{sp}} = \sqrt{\frac{BA_{sp}}{BA_{plot}} \times \frac{\overline{Rank_{sp}} - 1}{N - 1}} \tag{4}$$

where pBA_{sp} symbolizes the proportion of basal area for the target species; BA_{sp} and BA_{plot} denote the basal area of the target species and the plot; D_{sp} signifies the competition dominance of the target species; $\overline{Rank_{sp}}$ symbolizes the average tree rank of the target species in ascending order based on basal area; and N stands for the number of trees in a plot.

(2) Resistance stability

- The height-to-diameter ratio (*HDR*): *HDR* is calculated based on the mean values of the height-to-diameter ratio of three mean trees in the plot. *HDR* values typically range from 50 to 150, with lower values indicating greater stand stability [38]. The standardization of *HDR* is as follows:

$$HDR_j = \begin{cases} 0, & HDR_j \geq 150 \\ (150 - HDR_j)/100, & 50 < HDR_j < 150 \\ 1, & HDR_j \leq 50 \end{cases} \tag{5}$$

HDR_j—H/D ratio of j-th plot.

- Species diversity (*SD*): using the Simpson diversity index [43]:

$$SD = 1 - \sum\nolimits_1^m p_k = 1 - \sum\nolimits_1^m \frac{n_k}{n} \tag{6}$$

where p_k is the proportion of the k-th species within a plot; m denotes the total species number of the plot; n_k and n are the number of the k-th species and all trees within a plot, respectively.

- Tree health (*TH*): the proportion of healthy trees (without pests or diseases and with good growth) in the stand. A stand is categorized as unhealthy and assigned a value of 0 if over 50% of the trees within the plot exhibit compromised health [21,22]. The standardization of *TH* is as follows:

$$TH_j = \begin{cases} 0, & TH_j < 0.5 \\ (TH_j - 0.5) \times 2, & TH_j \geq 0.5 \end{cases} \tag{7}$$

TH_j—tree health status of j-th plot.

(3) Functional stability

- Shelterwood area (*SA*): the ratio of the crown projection area to the forest land area. When SA falls below 0.4, it denotes a sparsely vegetated stand with inadequate soil protection functionality, warranting an assigned value of 0. Conversely, when *SA* exceeds 0.9, it indicates a stand capable of delivering comprehensive soil protection, meriting an assigned value of 1 [42]. The standardization of *SA* is as follows:

$$SA_j = \begin{cases} 0, & SA_j \le 0.4 \\ (SA_j - 0.4) \times 2, & 0.4 < SA_j < 0.9 \\ 1, & SA_j \ge 0.9 \end{cases} \tag{8}$$

SA_j—shelterwood area of *j*-th plot.

- Understory coverage (*UC*): the total coverage of vegetation in the shrub and herb layer. When *UC* is greater than 0.7, it is considered that the understory vegetation can provide better soil protection functions and is assigned a value of 1 [42]. The standardization of *UC* is as follows:

$$UC_j = \begin{cases} UC_j/0.7, & UC_j < 0.7 \\ 1, & UC_j \ge 0.7 \end{cases} \tag{9}$$

UC_j—understory coverage of *j*-th plot.

- Litter thickness (*LT*): the thickness of both undecomposed and semi-decomposed layers of litter. Since a thickness of 2 cm for *LT* accomplishes 70% of the soil and water conservation functions, it is thus assigned a value of 0.7 [40], while *LT* exceeding 5 cm qualifies as a thicker category, facilitating the complete realization of ecological functions and thus being assigned a value of 1 [42]. A straightforward power function has been formulated on the basis of these two pivotal coordinate points to effectuate the standardization of the *LT* value:

$$LT_j = \begin{cases} 0.5344649 \times (LT_j)^{0.3892596}, & LT_j < 5 \\ 1, & LT_j \ge 5 \end{cases} \tag{10}$$

LT_j—litter thickness of *j*-th plot.

2.4. Comprehensive Evaluation of Stability in Chinese Pine Plantation

The unit circle method [21,22] is employed for comprehensive stability evaluation. First, normalization standardizes all indices to values between 0 and 1, mitigating dimensional and unit influences. A nightingale rose diagram featuring n index petals is then drawn on a unit circle with a radius of 1. The length of each petal corresponds to the value of a specific indicator. The stability value is computed by aggregating the areas of all petals and dividing by the unit circle area (π). The radian of each petal is determined by the index weight, which remains uniform for this study.

Finally, the stability score S_j of each plot is calculated using the following formula:

$$S_j = \frac{\sum_{i=1}^{m} \pi \times {P_{ij}}^2 \times W_i}{\pi} \tag{11}$$

where W_i signifies the weight value of the *i*-th indicator, P_{ij} denotes the value of the *i*-th indicator for the *j*-th plot, and *m* represents the number of evaluation indicators.

A stability value of 0 corresponds to a rose diagram area of 0, reflecting minimum stability. Conversely, with all indices at 1, the rose diagram becomes a full unit circle with an area of π, signifying maximum stability. This study categorizes total stability—along with its biological, resistance, and functional components—into four levels: poor stability, moderate stability, good stability, and excellent stability. Thresholds are set at 30%, 50%, and 70% of the maximum stability value.

2.5. Assessment of Spatial Structures in Chinese Pine Plantations

We employ four spatial structure indices from an individual-based method [31,44] to assess the spatial structure of Chinese pine plantations. These indices encompass:

(1) Uniform angle index (W):

$$W_i = \frac{1}{n}\sum\nolimits_{j=1}^{n} z_{ij}, z_{ij} = \begin{cases} 1, & \text{if } \alpha_j \text{ is smaller than } \alpha_0 \\ 0, & \text{otherwise} \end{cases} \quad (12)$$

where α_j stands for the j-th small angle form by two neighbors and i-th reference tree, and the standard angle α_0 equal to $360°/(n-1)$. n is the neighbor's number of a reference tree and was set to 4.

(2) Differentiation (T):

$$T_i = \frac{1}{n}\sum\nolimits_{j=1}^{n} 1 - \frac{\min(D_i, D_j)}{\max(D_i, D_j)} \quad (13)$$

where D_j and D_i denote the DBH of j-th neighbor and reference tree i, respectively.

(3) Mingling (M):

$$M_i = \frac{1}{n}\sum\nolimits_{j=1}^{n} v_{ij}, v_{ij} = \begin{cases} 1, & \text{if } sp_j \text{ is differnent from } sp_i \\ 0, & \text{otherwise} \end{cases} \quad (14)$$

where sp_j and sp_i denote the species of j-th neighbor and reference tree i, respectively.

(4) Crowding (C):

$$C_i = \frac{1}{n}\sum\nolimits_{j=1}^{n} y_{ij}, y_{ij} = \begin{cases} 1, & \text{if } c_j + c_i \text{ is larger than } dist_{ij} \\ 0, & \text{otherwise} \end{cases} \quad (15)$$

where c_j and c_i stand for the crown radius of the j-th neighbor and reference tree i, respectively. The $dist_{ij}$ denotes the distance between the j-th neighbor and the reference tree i.

The Uniform Angle Index, Mingling, and Crowding indices each encompass five predefined potential values: 0, 0.25, 0.5, 0.75, and 1. For the sake of comprehensive analysis, the differentiation values were stratified into five intervals: [0, 0.2], (0.2, 0.4], (0.4, 0.6], (0.6, 0.8], and (0.8, 1], corresponding to the assignment of the aforementioned five values.

The aforementioned formulas yield the spatial structure of each individual tree, while the stand spatial structure equates to the mean value of the spatial structure of all individual trees. In particular, the mean values of the uniform angle index between 0.475 and 0.517 indicate that the spatial distribution pattern of trees is random; less than 0.475 or more than 0.517 are classified as regular or clumped distribution, respectively [45]. A translation method is applied to correct edge effects [46].

2.6. Analysis of Patterns and Interrelations of Stability and Spatial Structure Indicators

The distribution patterns of the 9 stability indices and the 4 spatial structure indices were individually subjected to analysis. The correlations between the stability indices, stand age, density, and the 4 spatial structure indices were investigated utilizing the Pearson correlation coefficient. By computing the proportions for 5 types within each spatial structure index, subsequent analyses were conducted to examine their correlations with the stability value. These deliberations collectively provide insights to inform targeted management optimizations aimed at enhancing the stability of Chinese pine plantations.

The correlation coefficient and its probability values of significance are both computed by the corr.test function of package psychology [47]. All statistical analyses were performed using R software v4.1.3 [48].

3. Results

3.1. Distributions of Stability and Stability Indicators

The array of 44 nightingale rose diagrams vividly elucidates the differences in stability index values (represented by petal lengths) and stability values (reflected through petal areas) across the plantation plots (Figure 3). Notable distribution variations among stability indices are observed, with some indices exhibiting highly concentrated distributions. For instance, shelterwood area (*SA*) and litter thickness (*LT*) are predominantly clustered around 1.0, while target species competition (*Comp*) is concentrated near 0.7 (Figure 4). Structural heterogeneity (*SH*), height-to-diameter ratio (*HDR*), and understory coverage (*UC*) follow a normal distribution pattern, with concentrations at intermediate values. Indices such as regeneration potential (*Reg*) and species diversity (*SD*) have a more extensive spread towards lower values. Tree health (*TH*) portrays a more uniform distribution across the entire spectrum of values.

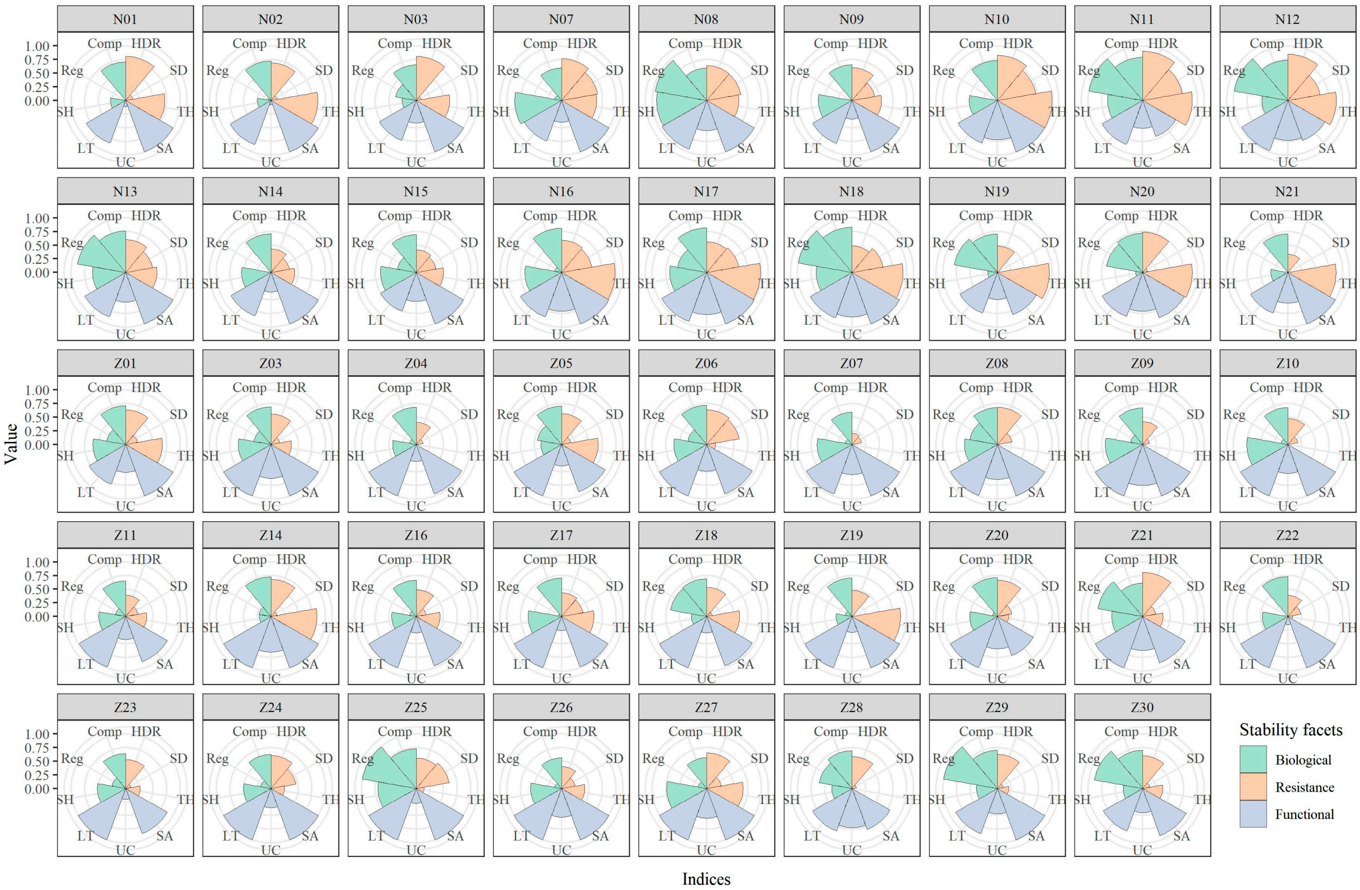

Figure 3. Nightingale rose diagrams of 44 plantation plots. *SH*—structural heterogeneity; *Reg*—regeneration potential; *Comp*—target species competition; *HDR*—height-to-diameter ratio; *SD*—species diversity; *TH*—tree health; *SA*—shelterwood area; *UC*—understory coverage; *LT*—litter thickness.

Stability value distributions reveal the following trends: concerning biological stability, the majority of plots exhibit poor stability, followed by moderate stability, while fewer plots demonstrate excellent and good stability. This pattern is similarly observed for resistance stability. In contrast, functional stability displays most plots with good stability, followed by excellent stability, and a smaller number with moderate and poor stability. In terms of total stability, considering these three facets, approximately 79.5% of plots demonstrate moderate stability, 20.5% exhibit good stability, and none fall into the categories of poor or excellent stability (Table 2).

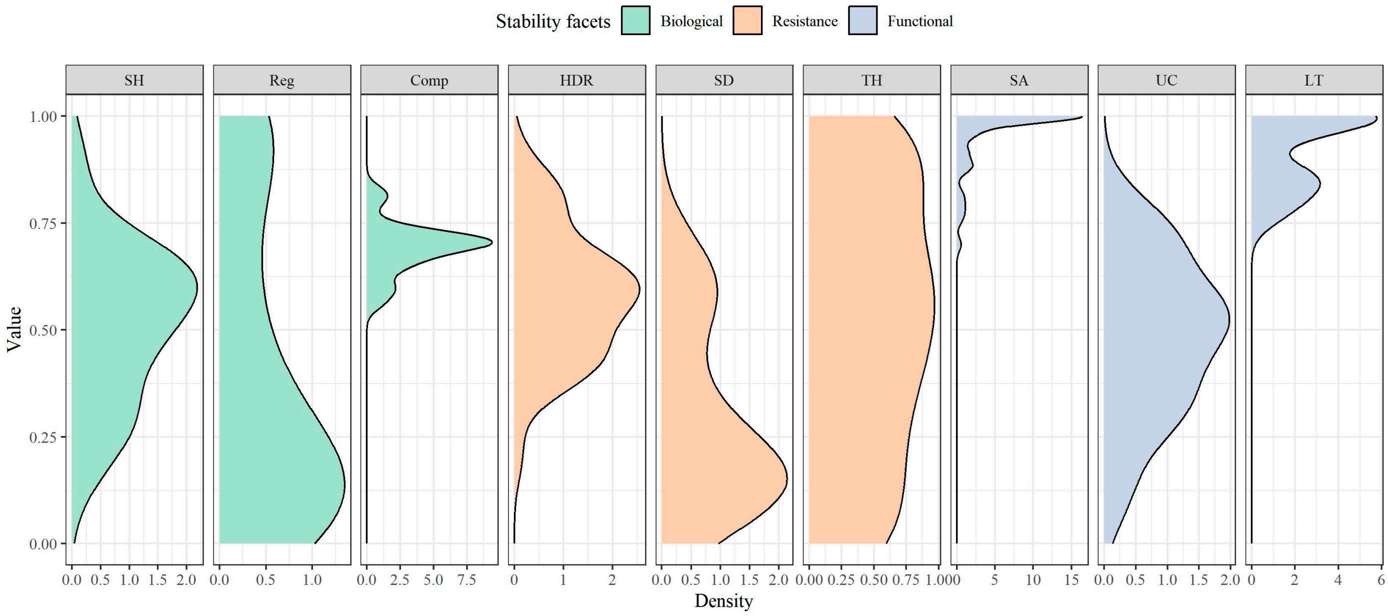

Figure 4. Distribution patterns of nine stability indices. *SH*—structural heterogeneity; *Reg*—regeneration potential; *Comp*—target species competition; *HDR*—height-to-diameter ratio; *SD*—species diversity; *TH*—tree health; *SA*—shelterwood area; *UC*—understory coverage; *LT*—litter thickness.

Table 2. Distribution of stability status.

Stability Status	Excellent	Good	Moderate	Poor
Biological stability	2 (4.5%)	5 (11.4%)	16 (36.4%)	21 (47.7%)
Resistance stability	2 (4.5%)	3 (6.8%)	13 (29.5%)	26 (59.1%)
Functional stability	16 (36.4%)	27 (61.4%)	1 (2.3%)	0 (0%)
Total stability	0 (0%)	9 (20.5%)	35 (79.5%)	0 (0%)

3.2. Distributions of Spatial Structure Indicators

The mean value distributions of the four spatial structure indices within Chinese pine plantation plots reveal distinct patterns. Specifically, the mean values of the uniform angle index and crowding cluster around 0.5 and 0.95, respectively. Similarly, the mean values of the differentiation concentrate at around 0.35, albeit with a broader spread. The mean values of the mingling predominantly concentrate at lower ranges, with several plots having intermediate to higher mean values (Figure 5).

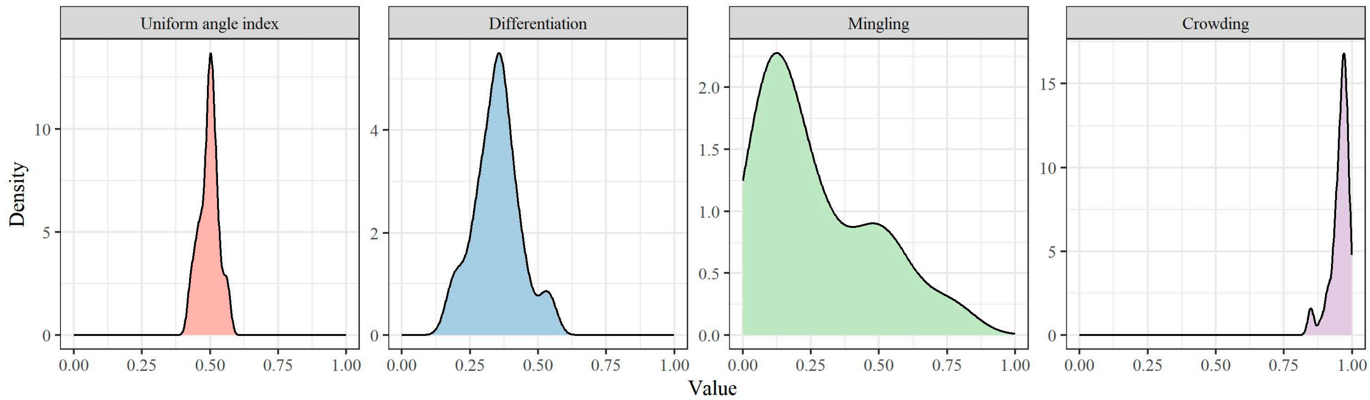

Figure 5. Distribution patterns of the mean values of four spatial structure indices.

With the exception of the "M = 0" type in Mingling, the proportions of the other five types across all spatial structure indices are largely concentrated within a narrow range. When arranging in accordance with the proportions of the distribution peak for each type, uniform angle index prioritizes "W = 0.5" > "W = 0.25" > "W = 0.75" > "W = 1" > "W = 0". Similarly, differentiation follows the order "T = 0.25" > "T = 0.5" > "T = 0" > "T = 0.75" > "T = 1". Mingling is distributed as "M = 0" > "M = 0.25" > "M = 0.5" > "M = 0.75" > "M = 1", while crowding exhibits "C = 1" > "C = 0.75" > "C = 0.5" > "C = 0.25" > "C = 0" (Figure 6).

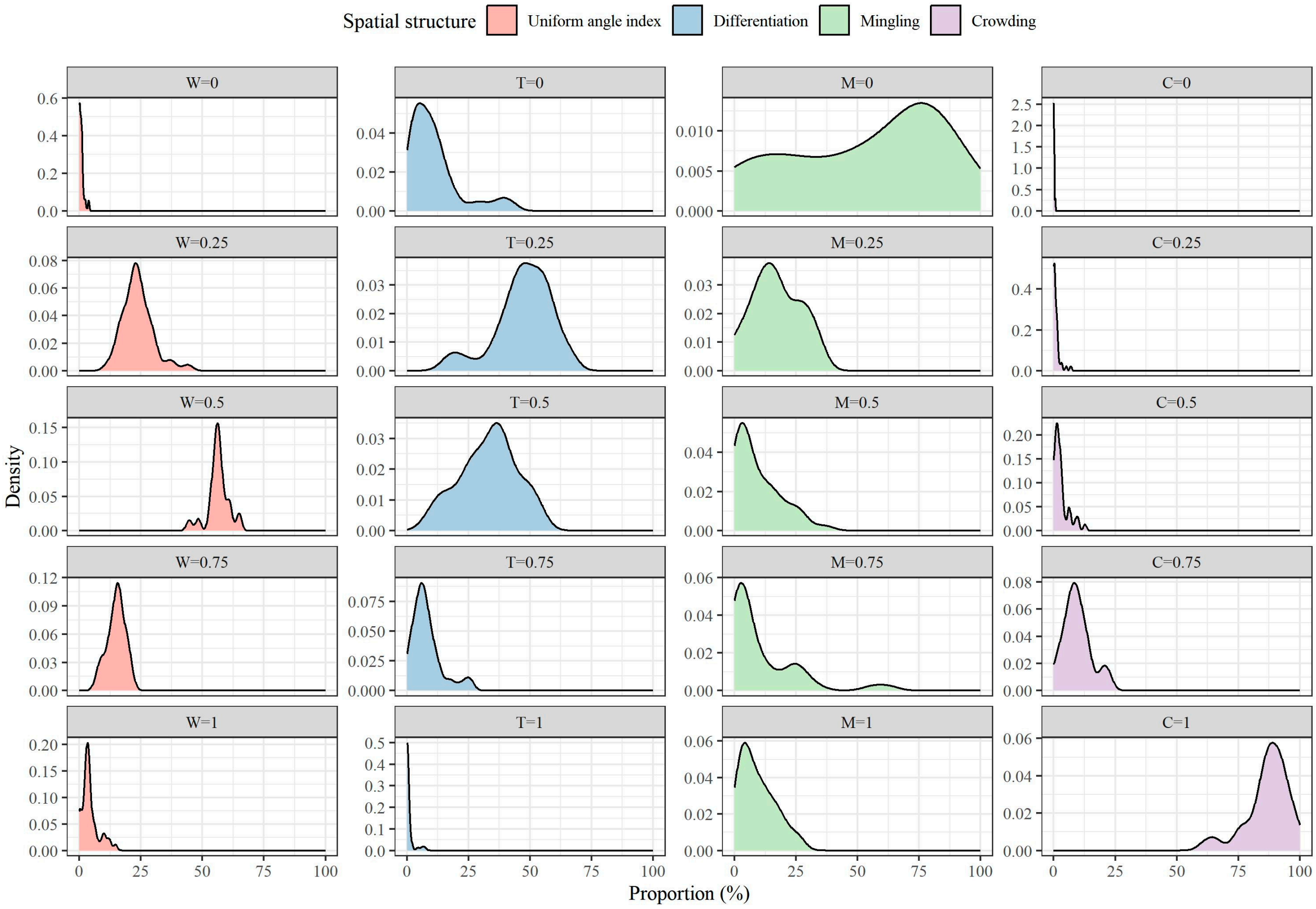

Figure 6. Distribution patterns of proportions of each type in four spatial structure indices. W—uniform angle index; T—differentiation; M—mingling; C—crowding.

3.3. Correlation Analysis of Stand Structure with Stability

The relationships between certain stand structure indicators and stability metrics exhibit considerable similarity (Table 3). For instance, stand age and stand density display notable correlations with target species competition, species diversity, tree health, and understory coverage, respectively. Notably, differentiation and mingling manifest significant correlations with structural heterogeneity, species diversity, and understory coverage. Moreover, stand density, mingling, and crowding exhibit significant correlations with the height-to-diameter ratio. The uniform angle index demonstrates significant correlations with target species competition and tree health. However, there is no significant correlation between any stand structure indicators and regeneration potential, shelterwood area, or litter thickness.

Table 3. Matrix of the Pearson correlation coefficient.

Indicators/Stabilities	Stand Age	Stand Density	Uniform Angle Index	Differentiation	Mingling	Crowding
Structural heterogeneity				0.81 ***	0.6 ***	
Regeneration potential						
Target species competition	0.42 **	−0.36 *	−0.39 **			
Height-to-diameter ratio		−0.65 ***			0.38 *	−0.47 **
Species diversity	0.43 **	−0.45 **		0.76 ***	0.98 ***	
Tree health	0.52 ***	−0.66 ***	−0.66 ***			
Shelterwood area						
Understory coverage	0.45 **	−0.3 *		0.4 **	0.32 *	
Litter thickness						
Biological stability				0.55 ***	0.57 ***	
Resistance stability	0.55 ***	−0.83 ***	−0.6 ***		0.63 ***	
Functional stability				0.35 *		
Total stability	0.56 ***	−0.66 ***	−0.35 *	0.57 ***	0.74 ***	

Notes: Significance levels are denoted as ***, **, and * to indicate probability values of correlation coefficients smaller than 0.001, 0.01, and 0.05, respectively. Correlation coefficients that are not statistically significant are omitted from the matrix.

Regarding relationships between stand structure indicators and stability values, significant correlations emerge between stand age, density, uniform angle index, and mingling with resistance stability and total stability (Table 3). Furthermore, only differentiation and mingling are significantly correlated with biological stability, while only differentiation is significantly correlated with functional stability. However, crowding exhibits no significant correlation with any stability values.

The correlations between spatial structure types and stability values reveal further insights (Figure 7). Uniform angle index type "W = 0.25" negatively correlates with resistance stability and total stability, while type "W = 0.75" positively correlates with both. Differentiation type "T = 0.25" negatively correlates with most stability values, while "T = 0.75" and "T = 1" types display positive correlations with all stability values. Mingling type "M = 0" negatively correlates with biological stability, resistance stability, and total stability, whereas "M = 0.5", "M = 0.75", and "M = 1" types show positive correlations with these three stability values. Crowding types "C = 0.75" and "C = 1" positively and negatively correlate with resistance stability, respectively.

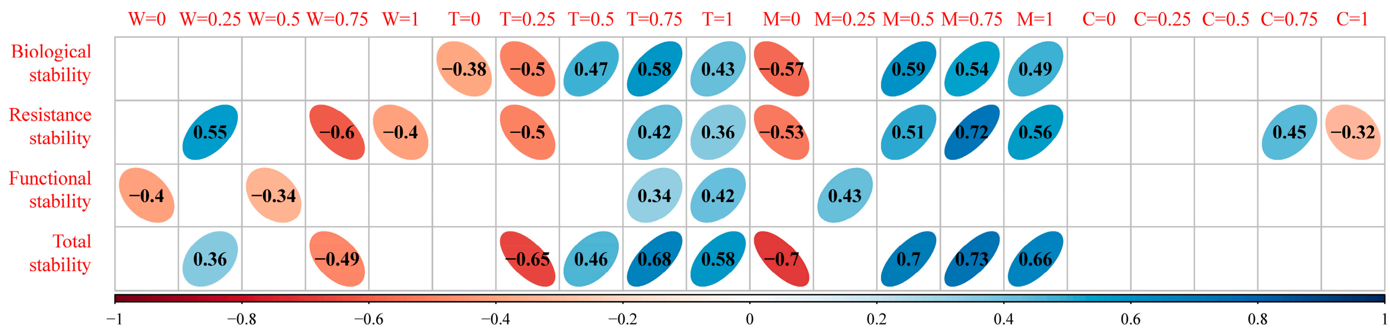

Figure 7. Pearson correlation coefficient matrix of each type proportion in four spatial structure indices with stability values. Insignificant correlations are not shown in the matrix. W—uniform angle index; T—differentiation; M—mingling; C—crowding.

4. Discussion

4.1. Comprehensive Evaluation of the Stability of Chinese Pine Plantation

The comprehensive evaluation method employed to assess the stability of plantations in this study exhibits distinctive characteristics, characterized by a non-linear relationship between the indicator value and the stability value. The selection of these indicators was carefully considered, aiming for ease of acquisition.

The unit circle method applied in this evaluation is noteworthy due to its unique property where the area of the nightingale rose diagram is determined by the squared radius of indicators (indicator sizes). Medium-sized indicators only contribute to low stability values. Consequently, this approach effectively emphasizes the full play of indicator attributes.

Moreover, the stability evaluation indicators utilized in this research can be obtained directly from field surveys, requiring no additional experimental indicators such as soil attributes. These indicators are also easily accessible through National Forest Inventory (NFI) data, allowing for comprehensive stability research at a landscape scale. For studies focused on plantations in different regions, the inclusion, replacement, or weighting of stability indicators can be tailored to the specific research objectives.

While this study categorizes nine indicators into three distinct stability characteristics, it is important to note that these indicators do not solely reflect the stability characteristic they are assigned to. Some indicators may impact multiple stability aspects or even exhibit contradictory effects. In such cases, the indicator is attributed to its most influential attribute. The influence on other stability aspects is captured by employing more suitable indicators.

Litter thickness demonstrates a complex impact on total stability. Firstly, the litter layer plays a vital role in forest soil and water conservation, effectively mitigating soil erosion, runoff, and soil water evaporation [40]. This function aligns with achieving functional stability. However, a thicker litter layer might hinder seed implantation, germination, and regeneration, thereby affecting biological stability [49]. Moreover, excessive litter accumulation could elevate the risk of fire, affecting resistance stability. In this study, we believed the function of soil and water conservation provided by the litter layer outweighs the negative impacts on regeneration and fire risk, thus categorizing it as a functional stability index. However, the potential negative consequences should be considered in forest management strategies.

Species diversity contributes to total stability by offering diverse ecological niches and enhancing community resilience to disturbances [5,6]. Additionally, mixed litter resulting from diverse species can expedite litter decomposition and enhance soil nutrient replenishment. The ecological function of mixed litter in soil consolidation and water conservation surpasses that of single coniferous litter. Diverse species, especially broad-leaved trees, create more space for regeneration and understory vegetation growth, enhancing both biological and functional stability [50]. However, we consider the most significant role of diversity to be its ability to resist disturbance, thus categorizing it as a resistance stability index.

4.2. Stability and Spatial Structure of Chinese Pine Plantations

Most of the Chinese pine plantations (almost 80%) in Huanglong Mountain exhibit moderate total stability, while the remainder display good total stability (Table 2). This pattern diverges from the common notion that plantations generally have poor stability [51]. This shift is attributed to the inclusion of a functional stability index. As Chinese pine plantations are usually densely planted, their canopy easily closes, and pine needles decompose slowly, resulting in a thicker litter layer, resulting in a predominantly good or even excellent functional stability (Table 2). Conversely, biological and resistance stability tend to be poor and moderate (both above 85%, Table 2) due to low regeneration potential and species diversity (Figure 4).

Chinese pine plantations typically display low differentiation, minimal mingling, and high crowding (Figure 5), aligning with the conventional understanding of plantations [52,53]. However, uniform angle index mean values cluster around 0.5, with approximately half of the plots demonstrating random distribution and even 23% classified as clumped distribution. These outcomes stem from the way Chinese pine plantations are established. To ensure Chinese pine survival, saplings are planted in clusters of about 3 at a certain density [27]. As a result, the initial distribution pattern is clumped, with high stand density and crowding. This limits space for other tree species, leading to low mingling values. With the growth, only 1 or 2 saplings may survive within the same cluster due to intense asymmetric competition, leading to a preliminary differentiation of tree size and the shifting of the distribution pattern towards random distribution. Some plantations may have undergone thinning to allow one healthy tree per cluster, leading to a typical uniform distribution pattern [27].

4.3. Important Stand Structure Indicators Correlated with Stability of Chinese Pine Plantations

Our findings indicate that stand age and density significantly correlate with total stability and most stability indicators (Table 3). The plantation's developmental process aligns with community succession, promoting stability. Previous research by Pan et al. [54] on Masson pine (*Pinus massoniana* Lamb.) plantations at various ages in Guangxi province indicated improved stability as stands matured. Similarly, Ma et al. [55] found that oak mixed forest communities' stability progressed from instability to stability throughout succession stages. Stand density shows significant correlations with several stability indicators due to its impact on understory vegetation emergence, regeneration, and structural heterogeneity [56,57]. Consequently, stand density is a pivotal indicator for enhancing total stability.

Limited research has explored the spatial structure-stability relationship. Yang et al. [58] reported positive correlations between mingling, uniform angle index, and competition index with stability and negative correlations with differentiation. Our findings support these relationships and further highlight a positive correlation between Differentiation and stability, while crowding shows no significant correlation with stability (Table 3).

Mingling's relevance to stability stems not only from its relationship with species diversity but also from the fact that it indicates there are other tree species in the stand. These reserved species can improve structural heterogeneity through better regeneration [32], reducing the height-to-diameter ratio for increased resistance, and providing space and resources for understory vegetation survival [59] (Table 3). Clumped distribution can compromise Chinese pine health by slowing growth and decreasing competition dominance (Table 3). The positive correlation of size differentiation with stability primarily arises from its synchronization with species mixing [60]. Diverse species encourage size differentiation, while the complex environment post-differentiation allows more species survival [61]. We did not find a direct correlation between crowding and stability, possibly due to all plantations being densely packed, leaving insufficient scope to demonstrate the relationship.

4.4. Management Suggestions for Chinese Pine Plantations in Huanglong Mountain

Understanding the spatial structure-stability relationship offers management insights to enhance total stability in Chinese pine plantations. Firstly, thinning intensity should be determined based on actual stand density and the retention densities of different age stages in accordance with "Technical regulations for management plantation forest of *Pinus tabuliformis*" [51,62]. Secondly, unhealthy trees and excess trees in a cluster should be given priority within the designated intensity. Finally, if the retained trees still exceed the standard, thinning should prioritize trees with the following spatial structure types: Uniform angle index "$W = 0.75$", Differentiation "$T = 0.25$", and Mingling "$M = 0$". The more these types are concentrated in the same tree, the higher the thinning priority of these trees.

Other measures also warrant consideration: (1) The generally thick litter layer in Chinese pine plantations impedes natural regeneration and heightens fire risks, which can be addressed through controlled fire interventions. (2) Protect existing broad-leaved species during afforestation's early stages and undertake artificial replanting in understory openings. This echoes the "planting coniferous trees while preserving broad-leaved trees" approach proposed during red pine (*Pinus koraiensis* Sieb. et Zucc.) plantation establishment in Northeast China's forest regions [63]. (3) Minimize disturbances post-management to enhance forest community total stability during self-development and succession.

5. Conclusions

In this study, we conducted an assessment of the stability of Chinese pine plantations in Huanglong Mountain using a set of nine indices representing biological, resistance, and functional stability. Our findings revealed that 79.5% of the Chinese pine plantations exhibited moderate total stability, while 20.5% demonstrated good total stability. These results indicate substantial potential for improvement through targeted management strategies. The predominant distribution pattern in these plantations is random, with moderate size differentiation and low species spatial mixing, while the stand crowding is notably high.

The types of mingling, differentiation, and uniform angle index, which exhibited negative correlations with total stability, can provide valuable guidance for precision thinning operations under controlled thinning intensities. While our study highlights that the total stability of Chinese pine plantations is not particularly unfavorable due to their commendable performance in functional stability, efforts should be focused on enhancing biological stability and resistance stability. The stability assessment methodology and indicators presented in this study can serve as a valuable reference for similar plantations with comparable functions and planting conditions.

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References

1. Yu, G.R.; Wang, Y.S.; Yang, Y. Discussion on ecological principles and technical approaches for improving the quality and stability of ecosystem. *Chin. J. Appl. Ecol.* **2023**, *34*, 1–10.
2. MacArthur, R. Fluctuations of animal populations and a measure of community stability. *Ecology* **1955**, *36*, 533–536. [CrossRef]
3. Tilman, D.; Downing, J.A. Biodiversity and stability in grasslands. *Nature* **1994**, *367*, 363–365. [CrossRef]
4. Ives, A.R.; Carpenter, S.R. Stability and diversity of ecosystems. *Science* **2007**, *317*, 58–62. [CrossRef]
5. Isbell, F.; Calcagno, V.; Hector, A.; Connolly, J.; Harpole, W.S.; Reich, P.B.; Scherer-Lorenzen, M.; Schmid, B.; Tilman, D.; Van Ruijven, J. High plant diversity is needed to maintain ecosystem services. *Nature* **2011**, *477*, 199–202. [CrossRef]
6. Schnabel, F.; Liu, X.; Kunz, M.; Barry, K.E.; Bongers, F.J.; Bruelheide, H.; Fichtner, A.; Härdtle, W.; Li, S.; Pfaff, C.-T.; et al. Species richness stabilizes productivity via asynchrony and drought-tolerance diversity in a large-scale tree biodiversity experiment. *Sci. Adv.* **2021**, *7*, eabk1643. [CrossRef]
7. Van Ruijven, J.; Berendse, F. Diversity enhances community recovery, but not resistance, after drought. *J. Ecol.* **2010**, *98*, 81–86. [CrossRef]
8. May, R.M. Will a large complex system be stable? *Nature* **1972**, *238*, 413–414. [CrossRef]
9. Sasaki, T.; Lauenroth, W.K. Dominant species, rather than diversity, regulates temporal stability of plant communities. *Oecologia* **2011**, *166*, 761–768. [CrossRef]
10. Paquette, A.; Messier, C. The effect of biodiversity on tree productivity: From temperate to boreal forests. *Glob. Ecol. Biogeogr.* **2011**, *20*, 170–180. [CrossRef]
11. Dolezal, J.; Fibich, P.; Altman, J.; Leps, J.; Uemura, S.; Takahashi, K.; Hara, T. Determinants of ecosystem stability in a diverse temperate forest. *Oikos* **2020**, *129*, 1692–1703. [CrossRef]
12. Schnabel, F.; Schwarz, J.A.; Dănescu, A.; Fichtner, A.; Nock, C.A.; Bauhus, J.; Potvin, C. Drivers of productivity and its temporal stability in a tropical tree diversity experiment. *Glob. Chang. Biol.* **2019**, *25*, 4257–4272. [CrossRef] [PubMed]

13. Morin, X.; Fahse, L.; De Mazancourt, C.; Scherer-Lorenzen, M.; Bugmann, H. Temporal stability in forest productivity increases with tree diversity due to asynchrony in species dynamics. *Ecol. Lett.* **2014**, *17*, 1526–1535. [CrossRef] [PubMed]
14. Wu, T.T.; Zhang, K.; Yang, X.B.; Li, D.H.; Liu, Z.J.; Li, Y.L.; Long, C. Community structure and stability of Pinus kwangtungensis forest in Hainan Province. *Acta Ecol. Sin.* **2017**, *37*, 156–164. [CrossRef]
15. Jin, S.-S.; Zhang, Y.-Y.; Zhou, M.-L.; Dong, X.-M.; Chang, C.-H.; Wang, T.; Yan, D.-F. Interspecific Association and Community Stability of Tree Species in Natural Secondary Forests at Different Altitude Gradients in the Southern Taihang Mountains. *Forests* **2022**, *13*, 373. [CrossRef]
16. Zang, M.X.; Wang, D.X.; Peng, S.L.; Huang, Y.K.; Zhang, G.G. Stability of pine and oak mixed forest communities in Qinling Mountains. *Acta Ecol. Sin.* **2015**, *35*, 2564–2573.
17. Guo, Q.Q.; Zhang, W.H.; Cao, X.P. Construction of forest community stability evaluation system model based on fuzzy comprehensive evaluation: A case study of major forest communities in Huanglongshan. *Sci. Silvae Sin.* **2009**, *45*, 19–24.
18. Song, Q.L.; Dong, X.B. Comprehensive evaluation of community stability of different types of low-quality forests in the Daxinganling Mountains. *Sci. Silvae Sin.* **2014**, *50*, 10–17.
19. Liu, W.Z.; Yuan, Y.C.; Zhang, L.J.; Zhao, Z.H. Stability evaluation of *Pinus tabulaeformis* forest based on stand internal state and neighborhood environment. *Sci. Silvae Sin.* **2021**, *57*, 76–86.
20. Deng, H.; Shen, L.; Yang, J.; Mo, X. Stand Stability of Pure and Mixed-Eucalyptus Forests of Different Tree Species in a Typhoon-Prone Area. *Forests* **2021**, *12*, 458. [CrossRef]
21. Hui, G.; Zhang, G.; Zhao, Z.; Hu, Y.; Liu, W.; Zhang, S.; Bai, C. A New Rule of π Value of Natural Mixed Forest Optimal Stand State. *Sci. Silvae Sin.* **2016**, *52*, 1–8.
22. Zhang, G.; Hui, G.; Zhang, G.; Hu, Y.; Zhao, Z. A Novel Comprehensive Evaluation Method of Forest State Based on Unit Circle. *Forests* **2018**, *10*, 5. [CrossRef]
23. Xing, C.W.; Huang, X.R.; Li, Y.L.; Ma, Z.W.; Fu, X.Y. Ecological stability of sand-fixed plantations in Huangyangtan. *Sci. Silvae Sin.* **2014**, *50*, 101–108.
24. Feng, Y.Z. Concept and criteria of stability for managed ecosystem. *Chin. J. Ecol.* **2002**, *21*, 58–60.
25. Zeng, D.H.; Jang, F.Q. Stability of mongolian pine plantations on sand land. *Chin. J. Appl. Ecol.* **1996**, *7*, 337–343.
26. Wang, L.L. *The Study of Community Stability of Main Type Plantation in the Northern Shaanxi Loess Area*; Beijing Forestry University: Beijing, China, 2013.
27. Huo, A.P.; Zhang, F.L.; Tian, G.Z. Brief discussion on the present situation and improvement measures of artificial afforestation in Huanglongshan forestry bureau. *Shaanxi For. Sci. Technol.* **2003**, *31*, 63–66.
28. Dang, P.; Gao, Y.; Liu, J.; Yu, S.; Zhao, Z. Effects of thinning intensity on understory vegetation and soil microbial communities of a mature Chinese pine plantation in the Loess Plateau. *Sci. Total Environ.* **2018**, *630*, 171–180. [CrossRef]
29. Pukkala, T.; Lähde, E.; Laiho, O. Which trees should be removed in thinning treatments? *For. Ecosyst.* **2015**, *2*, 32. [CrossRef]
30. Li, Y.; Ye, S.; Hui, G.; Hu, Y.; Zhao, Z. Spatial structure of timber harvested according to structure-based forest management. *For. Ecol. Manag.* **2014**, *322*, 106–116. [CrossRef]
31. Pommerening, A. Approaches to quantifying forest structures. *Forestry* **2002**, *75*, 305–324. [CrossRef]
32. Wang, D.L.; Li, W.Z.; Cao, T.; Wang, Q.; Wang, G.R. Spatial pattern of Quercus wutaishanica in the natural secondary forest of Huanglong Mountain. *Acta Ecol. Sin.* **2016**, *36*, 2677–2685.
33. Forest Management Research Office. *Appendix Tables of Tree Measurement*; Northwest Forestry College: Yangling, China, 1982.
34. Poorter, L.; Craven, D.; Jakovac, C.C.; van der Sande, M.T.; Amissah, L.; Bongers, F.; Chazdon, R.L.; Farrior, C.E.; Kambach, S.; Meave, J.A. Multidimensional tropical forest recovery. *Science* **2021**, *374*, 1370–1376. [CrossRef]
35. Dušek, D.; Novák, J.; Černý, J. The Mechanical Stability of Pure Norway Spruce Stands along an Altitudinal Gradient in the Czech Republic. *Forests* **2023**, *14*, 1558. [CrossRef]
36. Konôpka, B.; Konôpka, J. Static stability of forest stands in the seventh altitudinal vegetation zone in Slovakia. *J. For. Sci.* **2003**, *49*, 474–481. [CrossRef]
37. Zhang, X.; Wang, H.; Chhin, S.; Zhang, J. Effects of competition, age and climate on tree slenderness of Chinese fir plantations in southern China. *For. Ecol. Manag.* **2020**, *458*, 117815. [CrossRef]
38. Pretzsch, H. Forest dynamics, growth and yield. In *Forest Dynamics, Growth and Yield*; Springer: Berlin/Heidelberg, Germany, 2009.
39. Zhang, G.H.; Liao, Y.M. A summary of impact of vegetation coverage on soil and water conservation benefit. *Res. Soil Water Conserv.* **1996**, *3*, 104–110.
40. Wu, Q.; Zhao, H.; Liu, X.; Han, B. Evaluation on Role of Forest Litter to Water Source Conservation and Soil and Water Conservation. *J. Soil Water Conserv.* **1998**, *4*, 23–28.
41. Gini, C. Measurement of inequality of incomes. *Econ. J.* **1921**, *31*, 124–125. [CrossRef]
42. *GB/T 26424-2010*; Technical Regulations for Inventory for Forest Management Planning and Design. National Forestry and Grassland Administration: Beijing, China, 2010.
43. Simpson, E.H. Measurement of Diversity. *Nature* **1949**, *163*, 688. [CrossRef]
44. Pommerening, A.; Grabarnik, P. *Individual-Based Methods in Forest Ecology and Management*; Springer Nature: Basel, Switzerland, 2019.
45. Hui, G.; Zhang, G.; Zhao, Z.; Yang, A. Methods of Forest Structure Research: A Review. *Curr. For. Rep.* **2019**, *5*, 142–154. [CrossRef]
46. Pommerening, A.; Stoyan, D. Edge-correction needs in estimating indices of spatial forest structure. *Can. J. For. Res.* **2006**, *36*, 1723–1739. [CrossRef]

47. Revelle, W. *Psych: Procedures for Personality and Psychological Research*; R Package Version 2.2.9; Northwestern University: Evanston, IL, USA, 2022.
48. R Core Team. *R: A Language and Environment for Statistical Computing*; Version 4.1.3; R Core Team: Vienna, Austria, 2022.
49. Wang, H.; Wang, Q. Properties of Man-Planted Forest for water and soil conservation. *Yellow River* **2002**, *24*, 34–36.
50. Shen, H.; Jiang, F.Q.; Du, X.J.; Lu, T.G. Evaluation on soil anti-erodibility of soil and water conservation forest. *Chin. J. Appl. Ecol.* **2000**, *11*, 345–348.
51. Sheng, W. The Relationship between Biological Stability and Sustainable Management of Plantation. *World For. Res.* **2001**, *14*, 14–21.
52. Mason, W.L.; Connolly, T.; Pommerening, A.; Edwards, C. Spatial structure of semi-natural and plantation stands of Scots pine (*Pinus sylvestris* L.) in northern Scotland. *Forestry* **2007**, *80*, 567–586. [CrossRef]
53. Zhang, L.; Feng, H.; Du, M.; Wang, Y.; Lai, G.; Guo, J. Dynamic Effects of Structure-Based Forest Management on Stand Spatial Structure in a Platycladus orientalis Plantation. *Forests* **2022**, *13*, 852. [CrossRef]
54. Pan, D.; Zhang, H.P.; Pan, G. Community dynamics and stability of different aged Pinus massoniana plantations in southern Guangxi. *Chin. J. Ecol.* **2016**, *35*, 1481–1490.
55. Ma, H.G.; Li, R.X.; Yuan, F.Y.; Shi, L.Y.; Guan, Q.W. Stability of *Platycladus orientalis* mixed forest communities at different successional stages. *Chin. J. Ecol.* **2013**, *32*, 558–562.
56. Ali, A.; Dai, D.; Akhtar, K.; Teng, M.; Yan, Z.; Urbina-Cardona, N.; Mullerova, J.; Zhou, Z. Response of understory vegetation, tree regeneration, and soil quality to manipulated stand density in a Pinus massoniana plantation. *Glob. Ecol. Conserv.* **2019**, *20*, e00775. [CrossRef]
57. Sun, K.; Sun, H.; Lu, G.; Fang, L.; Wan, Z.; Tan, Z. Study on the effects of stand density management of Chinese fir plantation in Northern China. *Front. Plant Sci.* **2023**, *14*, 1130299. [CrossRef] [PubMed]
58. Yang, R.; Zhao, P.; Li, W.; Wang, B.; Zhou, Y. Research on relationship between stability and spatial structure of Chinese pine plantation based on rule of π value. *J. Cent. South Univ. For. Technol.* **2020**, *40*, 95–103.
59. Pretzsch, H.; Poschenrieder, W.; Uhl, E.; Brazaitis, G.; Makrickiene, E.; Calama, R. Silvicultural prescriptions for mixed-species forest stands. A European review and perspective. *Eur. J. For. Res.* **2021**, *140*, 1267–1294. [CrossRef]
60. Wang, H.; Huang, S.; Zhang, S.; Peng, H.; Cao, K. Localized neighborhood species mingling is correlated with individual tree size inequality in natural forests in South China. *Ann. For. Sci.* **2021**, *78*, 102. [CrossRef]
61. Zhou, C.; Ding, Y.; Zang, R. Assessing the recovery in species, size and location diversities of a lowland tropical rainforest after shifting cultivation by multiple indices at stand and neighborhood scales. *J. Environ. Manag.* **2023**, *341*, 118089. [CrossRef]
62. National Forestry and Grassland Administration. *Technical Regulations for the Management of Pinus Tabulaeformis Plantations (LY/T 2971-2018)*; National Forestry and Grassland Administration: Beijing, China, 2018.
63. Chen, D.K.; Zhou, X.F.; Ding, B.Y.; Hu, Z.C.; Zhu, N.; Zhao, H.X.; Ju, Y.G.; Jin, Y.Y. Research on natural secondary forests in Heilongjiang province (I): Management approaches for broadening of needles and planting. *J. Northeast For. Univ.* **1984**, *12*, 1–12.