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The Short-Term Impact of Logging Intensity on the Stand State of Middle-Aged Masson Pine (*Pinus massoniana* Lamb.) Plantations

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Abstract: By assessing the short-term impact that various logging intensities have on stand state in middle-aged *P. massoniana* plantations, this investigation aimed to establish a theoretical foundation to support the judicious management of *Pinus massoniana* plantations. Five distinct logging intensity categories were delineated (0%, 10%, 20%, 30%, 40%). To construct a robust stand-state evaluation framework, nine representative indicators across the three dimensions of structure, vitality, and diversity were selected. We scrutinized the short-term impacts of logging intensity by employing the unit circle method. The findings revealed that (1) four indicators—stand density, tree health, species composition, and species diversity—exhibited pronounced sensitivity to logging intensity. These four exhibited significant improvements in the short-term post-logging ($p < 0.05$). Conversely, the indicators of species evenness, diameter distribution, height distribution, tree dominance, and stand growth exhibited a more subdued response to logging intensity. These five necessitated an extended period to begin to improve. (2) The comprehensive evaluation values measuring the stand state of middle-aged *P. massoniana* plantations initially ascended but then subsequently descended as logging intensity escalated. The stand-state zenith was pinpointed at an approximate 30% logging intensity. (3) A highly significant linear correlation emerged between the unit circle method results and the principal component analysis results in evaluating stand state ($R^2 = 0.909$, $p < 0.001$), and the unit circle method proved to be more intuitive and responsive. In summation, logging intensity exerted a substantial influence on stand state in middle-aged *P. massoniana* plantations, with moderate logging (circa 30% logging intensity) enhancing stand state the most. The unit circle method proficiently and effectively illuminated the short-term effects of logging intensity on the stand dynamics of middle-aged *P. massoniana* plantations, so it thereby may provide invaluable guidance for the formulation of specific forest management strategies.

Keywords: plantation; logging intensity; stand state; unit circle method; principal component analysis



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1. Introduction

In light of escalating global environmental change and the intensification of human activity, the stewardship of plantation forests has become a particularly paramount issue. Plantation forests particularly are pivotal for mitigating climate change [1], protecting biodiversity [2–4], and providing timber and other forest products [5]. They play an essential role in maintaining ecological balance and fostering sustainable development

through their robust growth. However, contemporary plantation forest management plans often inadequately account for the influence of stand state on forest ecosystem functions, thereby unintentionally exacerbating challenges such as excessive density [6], suboptimal growth [7], monospecific structure [8], and diminished ecological service function [9]. An in-depth examination of the specific impacts of forest management practices on plantation stand states can not only elucidate the dynamic processes underpinning forest ecosystems but also establish a scientific foundation for the sustainable management of plantation forests in the future. In recent years, a multitude of researchers have investigated many methods of assessing stand states within a forest, which has thus resulted in the formulation of various theoretical frameworks and practical guidelines. Nonetheless, practitioners continue to grapple with issues such as the absence of unified evaluation standards, an insufficiently comprehensive consideration of affecting factors, and limited adaptability to diverse regions and forest types. These challenges complicate the potential for the sustainable management and development of plantation forests.

Masson pine (*Pinus massoniana* Lamb.), a staple timber species and a pioneer useful in afforestation [10–12], is highly adaptable, economically significant [13], and extensively distributed throughout southern China [12], making it an integral component of local forestry production and forest ecosystems [14]. However, a prolonged monoculture methodology has led to problems such as homogeneous species composition, high stand density, and low species diversity in *P. massoniana* plantations. These factors further contribute to reduced productivity, degraded soil [15], and heightened susceptibility to pest or disease infestation [16–18]. These issues profoundly affect tree development and reproductive environments, thus posing formidable threats to the sustainable development of plantation lands. Logging intensity, a critical technical component of forest management, exerts a direct influence on the structure, function, and dynamics of *P. massoniana* plantations [19]. Previous studies have demonstrated that different degrees of logging intensity can exert different complex and multifaceted effects on forest ecosystems. Moderate logging can improve a standing environment, bolstering tree regeneration and growth while also sustaining and enhancing ecosystem function [20–23]. Conversely, excessive logging can precipitate habitat destruction, biodiversity loss, and soil erosion. Despite an extensive archive of related research, there remains a significant gap in our understanding of how varying logging intensity specifically affects plantation forests. This knowledge gap is particularly evident given the heterogeneous responses observed across different geographical regions, tree species, developmental stages, and environmental conditions [24–26]. Understanding the growth dynamics of forest stands, including their responses to different logging intensities, is therefore crucial for maintaining ecosystem stability and implementing scientific forest management practices [26–28].

This study targeted middle-aged *P. massoniana* plantations. A stand-state evaluation index system was constructed based on typical indicators of structure, vitality, and diversity. The objective was to systematically assess the impacts of various logging intensities on stand states in *P. massoniana* plantations to unravel the ecological response mechanisms and thus provide a scientific basis for optimizing forest management strategies. Through this investigation, we aspired to gain a profound understanding of the regulatory impacts of logging intensity on forest ecosystems, thereby offering novel theoretical support and practical guidance for enhancing forest quality and promoting its sustainable management.

2. Materials and Methods

2.1. Study Area

The study area was situated within the state-owned Guihua Forest Farm, located in Zhijin County, Guizhou Province (26°38′21″–26°39′18″ N, 105°44′55″–105°45′5″ E)

(Figure 1), at an average elevation of 1310 m above sea level. The annual precipitation there ranges from 1200 to 1500 mm, complemented by approximately 1170 h of sunshine per annum. The frost-free period spans from 240 to 290 days, with an annual mean temperature oscillating between 11.6 and 15 °C. This locale falls under the southeastern monsoon climate zone, characterized by a well-developed karst landscape. Prominent geomorphological features include mountains and hills, with notable topographical variations such as peak clusters, trough valleys, and interspersed depressions. The soil parent material predominantly consists of limestone, with calcareous soil, yellow–brown soil, and yellow soil being the primary soil types.

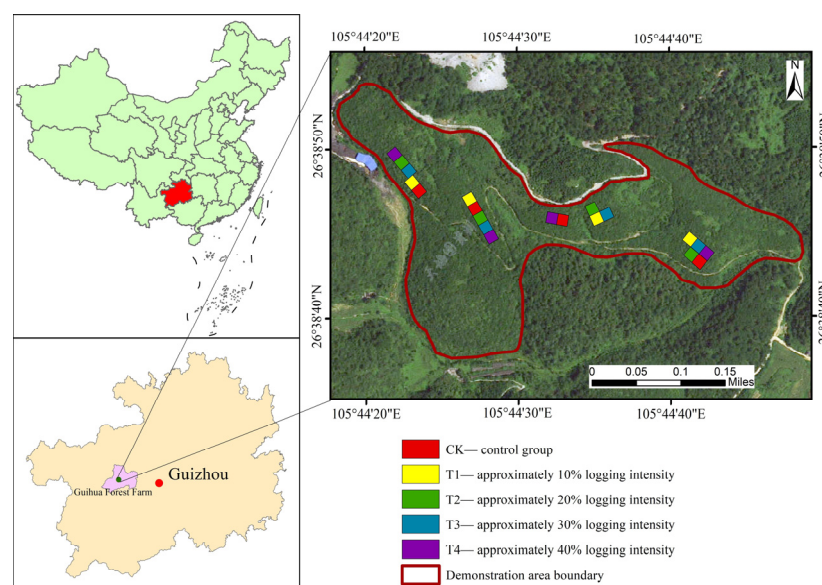


Figure 1. Geographical location of and sample block distribution in the study area.

The forest expanse encompasses 439,490 hectares, an area which is dominated by *P. massoniana* forests. These forests primarily include artificially-established plantations that are extensive and broadly distributed. This forest farm has garnered recognition as one of the “Pilot Forest Farms for the GEF National Forest Project”, “National Long-Term Scientific Experimental Base for *P. massoniana* forest”, and a “Teaching and Research Practice Base for Guizhou University”. It boasts a relatively extensive history in sustainable forest management and has well-established forest management monitoring blocks and ecological service monitoring systems, rendering it an exemplary site for scientific inquiry.

This study specifically focused on the Machang Work Area within the Guihua Forest Farm, where a substantial aggregation of middle-aged *P. massoniana* plantations can be found. These stands were planted in 2004 with an initial spacing of 1.5×1.5 m. Since their establishment, the stands have undergone zero silvicultural interventions and minimal anthropogenic disturbance. However, these middle-aged *P. massoniana* plantations are generally plagued by issues such as excessive stand density, suboptimal stem form, monospecific composition, inadequate regeneration, and low productivity. A crop tree selective thinning operation system was proposed to rectify these issues. This system aims to gradually bring about a mixed-species, uneven-aged, multi-layered forest structure. The overarching objective is to expedite community succession, enhance stand productivity, and facilitate the utilization of large-diameter timber.

2.2. Block Setup and Survey

In April 2021, after a thorough reconnaissance of middle-aged *P. massoniana* plantations, we selected blocks with consistent forest stand states and established a demonstration area

for our close-to-nature management technology experiment. The demonstration area included four sample blocks, each containing five square blocks with an area of 32×32 m each. These corresponded to five different logging intensity treatments: CK (control group), T1 (approximately 10% logging intensity), T2 (approximately 20% logging intensity), T3 (approximately 30% logging intensity), and T4 (approximately 40% logging intensity) (Figure 1). Before logging, all trees within the blocks with a diameter at breast height (DBH) of ≥ 5 cm were individually numbered with a permanent iron tag, and key factors such as DBH (diameter at the breast height), tree height, crown width, and height to the first live branch were measured and recorded. In addition to sampling, an undergrowth vegetation and soil survey was conducted concurrently.

The logging intensity was determined based on the total basal area of each block. The “target tree selection + whole-stand management” operation method was used. Trees that interfered with the growth of the crop trees were removed, as were trees with poor form, weak vitality, or zero cultivation potential. Eleven crop trees were selected within each block. Logging targeted *P. massoniana* individuals mainly, which means that other well-growing and potentially valuable broadleaf species were retained and left to grow. In July 2023, the experimental blocks were re-measured, using the same survey factors as before logging (Table 1).

Table 1. Stand state in study area two years after logging at various intensities.

Item	CK	T1	T2	T3	T4
Mean DBH (cm)	13.5 ± 0.75	14.2 ± 0.99	13.5 ± 1.80	14.3 ± 1.43	14.6 ± 1.43
Mean Height (m)	11.5 ± 0.49	11.4 ± 0.51	10.88 ± 1.49	12.1 ± 2.13	12.4 ± 2.01
Tree density (No. of trees·hm ⁻²)	1651 ± 216	1331 ± 188	1319 ± 195	1028 ± 184	801 ± 159
Canopy cover	0.88 ± 0.025	0.84 ± 0.025	0.79 ± 0.025	0.69 ± 0.025	0.57 ± 0.025
Basal area (m ² ·hm ⁻²)	27.49 ± 3.64	23.93 ± 3.65	21.50 ± 2.82	18.17 ± 1.38	15.15 ± 0.93
Volume (m ³ ·hm ⁻²)	186.1 ± 21.2	159.1 ± 31.6	138.4 ± 26.2	126.9 ± 24.3	106.5 ± 9.8

2.3. Evaluation Index Measuring Forest Stand State

This study established a stand state indicator system based on three fundamental principles: rationality, comprehensiveness, and operational feasibility [29,30]. The rationality principle ensures that the indicators accurately and objectively reflect specific stand attributes so they can demonstrate high precision, sensitivity, comparability, and discriminatory capacity. The comprehensiveness principle guarantees that the system encompasses multiple aspects of stand states. The operational feasibility principle stipulates that all indicators must be clearly defined, with straightforward data collection and calculation methods, which facilitates practical implementation and management decision-making. Guided by these principles and informed by past research on stand-state evaluation [31,32], our method also integrates a stand-state indicator system proposed in previous studies [32,33]. This study developed a framework that assesses stand state through three primary dimensions: structure, vitality, and diversity. Each dimension encompasses three specific indicators, thereby creating a nine-indicator system that enables comprehensive stand-state assessment. The indicators of stand structure were diameter at breast height distribution (*H*), tree height distribution (*V*), and stand density (*K*); the indicators of vitality were stand dominance (*U*), stand growth (*B*), and tree health (*Q*); the indicators of diversity

were tree species composition (Z), tree species diversity (D), and tree species evenness (P). The specific definitions and formulas are shown in Table 2.

Table 2. Indicators and corresponding formulas for evaluating forest stand state.

Item	Stand Characteristics	Indicators	Formula or Definition
Structure	DBH distribution (H)	q value	The DBH of trees is divided into classes with a width of 2 cm, and $N = ke^{-ad}$ is represented by Meyer's negative exponential distribution, where N is the number of trees; e is the base of the natural logarithm; d is the DBH; a is a negative exponential distribution structure constant and k is a constant. $q = e^{ah}$, where h indicates that the diameter step is 2 cm. If the q value falls between 1.2 and 1.7, it means that it is in the reasonable distribution range of different age forest diameters [34].
	Tree height distribution (V)	Gini coefficient	In the equation $H = 1 - \sum (2Q_i - w_i)/n$, where n represents the number of individual trees, W_i represents the proportion of the height of the i -th individual tree to the total tree height, and Q_i represents the cumulative value of W_i [35].
	Stand density (K)	Crowding degree of forest	In the equation $K = \frac{100}{N^{0.5}} / \bar{c}\bar{w}$, where N represents the number of trees per hectare, represents the average crown width. If the value of K falls within the range of 0.6 to 0.8, it indicates a reasonable stand density [36].
Vitality	Stand dominance (U)	Dominant tree species proportion	The proportion of count of dominant canopy trees to count of total trees in a forest.
	Stand growth (B)	Potential density	In the equation $B = \frac{\bar{G}}{G_{max}}$, where $\bar{G}$ represents the cross-sectional area of the forest stand and G_{max} represents the potential maximum cross-sectional area of the forest stand. Here, G_{max} is defined as the product of the average cross-sectional area of the 50% largest individuals in the forest stand and the total tree count [32,37].
	Tree health (Q)	Proportion of healthy trees	The proportion of healthy trees (without pests and diseases, and without deformities such as broken branches, bending, hollow trunks, etc.) to the total number of trees in a forest stand [32,33].
Diversity	Species composition (Z)	Index of tree species composition	In the equation $Z = -\sum_{i=1}^S P_i \ln P_i$, where P_i represents the volume proportion of the i -th tree species, and S represents the number of tree species in the sample block. Note: The composition of tree species is expressed in decimal notation [38].
	Species diversity (D)	Simpson index	In the equation $D = 1 - \sum_{i=1}^S P_i^2$, where P_i represents the proportion of individuals of the i -th tree species, and S represents the number of tree species present in the block [34].
	Species evenness (P)	Pielou index	In the equation $p = -\sum_{i=1}^S P_i \ln P_i / \ln S$, where S represents the number of tree species present in the block [34].

For the above nine indicators, except for the intermediate indicators of diameter at breast height distribution (H) and stand density (K), a higher value is better than a lower value, with the values ranging from 0 to 1. The two intermediate indicators of diameter at breast height distribution (H) and stand density (K) were standardized using

formula (1) [39] to fit within the same from 0 to 1 range as the other indicators. Again, the larger the value, the better the indicator.

$$f(x) = \begin{cases} 0.1 & X \leq L, X \geq U \\ 0.1 + 0.9(X - L)/(O_1 - L) & L < X < O_1 \\ 1.0 & O_1 \leq X \leq O_2 \\ 0.1 + 0.9(X - O_2)/(U - O_2) & O_2 < X < U \end{cases} \quad (1)$$

In the formula, X represents the observed value of the indicator, $f(X)$ represents the score function value, U represents the upper limit value of the indicator (the U value of diameter at breast height distribution (H) is 2.7, and the U value of stand density is 1.0), L represents the lower limit value of the indicator (the U values of diameter at breast height distribution (H) and stand density (K) are both 0), and O_1 and O_2 represent the optimal values of the indicator (the O_1 and O_2 values of diameter at breast height distribution (H) are 1.2 and 1.7, respectively; the O_1 and O_2 values of stand density (K) are 0.6 and 0.8, respectively).

2.4. Comprehensive Evaluation of Stand State

The unit circle method was used to evaluate the stand states of middle-aged *P. massoniana* plantations under different logging intensities. The calculation formula was as follows [33,40]:

$$\omega = \frac{\sum_{k=1}^m \frac{\pi R_k^2}{m}}{m R^2} = \frac{1}{m} \sum_{k=1}^m R_k^2 \quad (2)$$

In the formula, ω represents the comprehensive evaluation value of forest stand state, m represents the number of forest stand state indicators, and R_k represents the k -th forest stand state indicator.

2.5. Statistical Analysis

All statistical analyses were performed using the R programming language (version: 4.3.1). All datasets were tested for normality using Shapiro–Wilk tests. Analysis of variance was employed to examine the disparities in stand state indicators between blocks and logging measures, and Tukey’s test was used to test for differences in treatment means among different logging intensity levels at $p \leq 0.05$. Furthermore, we employed the unit circle method and principal component analysis (PCA) to elucidate the impact of logging intensities on forest stand state. Linear regressions were conducted between the unit circle method results and the principal component analysis results. Significant differences and effects were established at $p \leq 0.05$.

3. Results

3.1. Impact of Various Logging Intensities on Stand State Indicators in Middle-Aged *P. massoniana* Plantations

Analysis of variance was used to examine the influences of block and logging on the *Masson pine* plantation stand states. According to the results, significant differences were observed among different blocks in stand dominance (U) and in species composition (Z) ($p < 0.05$). Moreover, logging measures significantly impacted stand density (K), tree health (Q), species composition (Z), species diversity (D), species evenness (P), and comprehensive evaluation (ω) ($p < 0.05$). Further analysis unveiled that blocks had a very small impact on the stand state of *Masson pine* plantations. The main difference was caused by the variation in logging intensity (Table 3).

Table 3. Analysis of variance of block and logging on stand state in *Masson pine* plantations.

Indicators	Block		Logging	
	Degree of Freedom	F Ration	Degree of Freedom	F Ration
DBH distribution (<i>H</i>)	3	1.534	4	0.570
Tree height distribution (<i>V</i>)	3	1.569	4	0.854
Stand density (<i>K</i>)	3	0.552	4	1.259×10^{30} ***
Stand dominance (<i>U</i>)	3	6.690 **	4	0.794
Stand growth (<i>B</i>)	3	1.886	4	0.173
Tree health (<i>Q</i>)	3	1.491	4	11.187 ***
Species composition (<i>Z</i>)	3	4.094 *	4	4.539 *
Species diversity (<i>D</i>)	3	3.138	4	3.939 *
Species evenness (<i>P</i>)	3	2.512	4	3.252
Comprehensive evaluation (ω)	3	15.638	4	44.042 ***

Note: * means that there is a significant effect between them ($p < 0.05$); ** means that there is a very significant effect between them ($p < 0.01$); *** means that there is a highly significant effect between them ($p < 0.001$).

In middle-aged *P. massoniana* plantations subjected to various logging intensities (Table 4), four stand state indicators were found to be critical—stand density (*K*), species composition (*Z*), species diversity (*D*), and species evenness (*P*). These four initially exhibited an increase and then subsequently decreased as logging intensity escalated, with the apex values observed at a logging intensity of 30% (T3). Analysis of variance revealed that both stand density (*K*) and species diversity (*D*) were markedly lower in the control blocks (CKs) than in any blocks subjected to logging treatments ($p < 0.05$). The species composition (*Z*) was significantly more pronounced in the T1, T2, and T3 blocks than in the control blocks ($p < 0.05$), whereas the T4 blocks show no significant deviation from the control blocks ($p > 0.05$). Moreover, species evenness (*P*) was substantially higher in the T2 and T3 blocks than in the control blocks ($p < 0.05$). Tree health (*Q*) improved as logging intensity increased, registering significantly and increasingly superior levels in the treatment blocks than in the control blocks ($p < 0.05$). Conversely, tree height distribution (*V*), DBH distribution (*H*), tree dominance (*U*), and stand growth (*B*) differed between the control and treatment blocks, but not significantly ($p > 0.05$).

Table 4. The impact of logging intensity on stand state indicators of *Masson pine* plantations.

Indicators	CK	T1	T2	T3	T4
DBH distribution (<i>H</i>)	0.219 ± 0.03 a	0.201 ± 0.024 a	0.198 ± 0.009 a	0.222 ± 0.042 a	0.206 ± 0.032 a
Tree height distribution (<i>V</i>)	0.119 ± 0.037 a	0.135 ± 0.025 a	0.117 ± 0.014 a	0.13 ± 0.04 a	0.097 ± 0.044 a
Stand density (<i>K</i>)	0.55 ± 0 c	1 ± 0 a	1 ± 0 a	1 ± 0 a	0.85 ± 0 b
Stand dominance (<i>U</i>)	0.046 ± 0.048 a	0.091 ± 0.173 a	0.028 ± 0.05 a	0.17 ± 0.333 a	0.182 ± 0.348 a
Stand growth (<i>B</i>)	0.639 ± 0.033 a	0.658 ± 0.03 a	0.642 ± 0.023 a	0.641 ± 0.045 a	0.648 ± 0.055 a
Tree health (<i>Q</i>)	0.788 ± 0.038 d	0.868 ± 0.07 c	0.9 ± 0.071 bc	0.96 ± 0.045 ab	1 ± 0 a
Species composition (<i>Z</i>)	0.187 ± 0.122 b	0.422 ± 0.128 a	0.475 ± 0.105 a	0.494 ± 0.211 a	0.401 ± 0.144 ab
Species diversity (<i>D</i>)	0.214 ± 0.144 b	0.452 ± 0.147 a	0.512 ± 0.097 a	0.537 ± 0.218 a	0.455 ± 0.143 a
Species evenness (<i>P</i>)	0.138 ± 0.079 b	0.219 ± 0.061 ab	0.235 ± 0.038 a	0.269 ± 0.072 a	0.224 ± 0.043 ab

Note: Different lowercase letters indicate a significant difference between different logging intensities ($p < 0.05$).

3.2. Comprehensive Evaluation of Stand States in Middle-Aged *P. massoniana* Plantations Using the Unit Circle Method

By employing the unit circle method to evaluate stand states, an integrative assessment could be performed on middle-aged *P. massoniana* plantations under differing logging intensities. The comprehensive evaluation values (ω) oscillated between 0.151 and 0.196 for the control blocks (CKs), between 0.288 and 0.344 for the T1 blocks, between 0.292 and 0.348 for the T2 blocks, between 0.301 and 0.386 for the T3 blocks, and between 0.270 and 0.377 for the T4 blocks. This holistic examination revealed that the stand state initially improved but then subsequently deteriorated as logging intensity increased, with the zenith occurring at a 30% logging intensity (T3). Furthermore, the stand states of all logging treatments (T1–T4) surpassed those of the control blocks, underscoring that moderate logging enhances the

stand state. The 30% logging intensity exerted the most salient positive impact, culminating in the best stand state observed in this study (Figure 2).

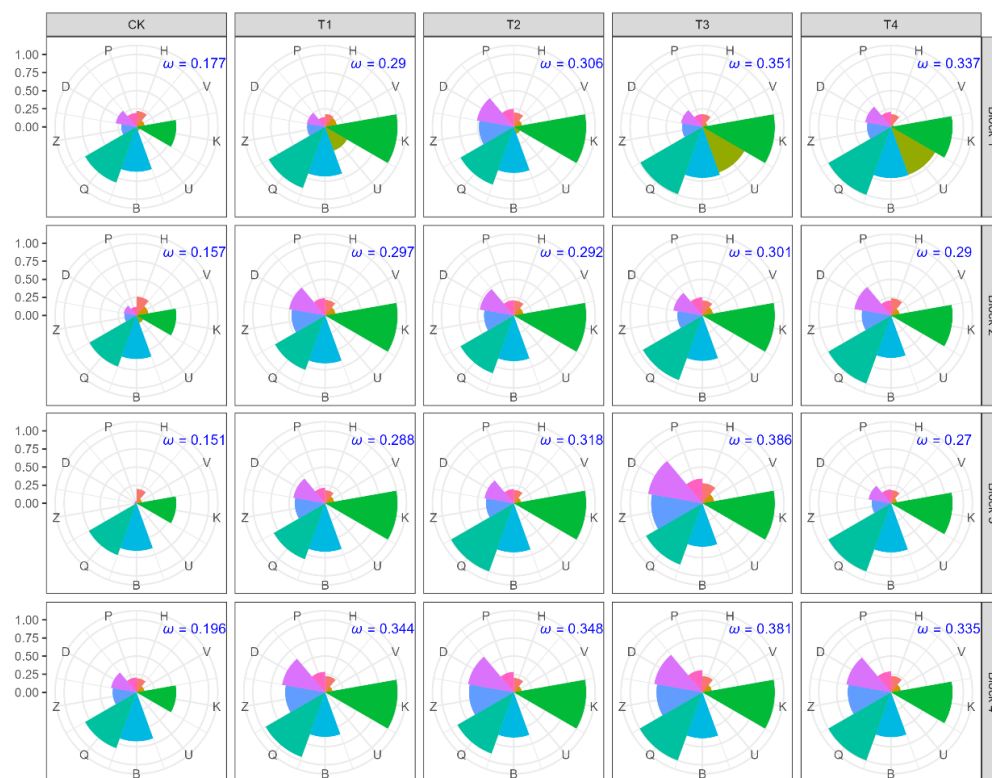


Figure 2. Unit circle method stand-state evaluation of *Masson pine* mid-aged plantations. The differently colored sectors represent various stand state indicators. The area of the sector that is colored in represents the magnitude of each stand state indicator value, with a larger area signifying a better indicator. The symbol ω in the upper right corner represents the value of the comprehensive evaluation of each forest stand state.

3.3. Stand-State Evaluation of Middle-Aged *P. massoniana* Plantations Using Principal Component Analysis

Principal component analysis (PCA) was conducted on stand state indicators of stands in middle-aged *P. massoniana* plantations that had been subjected to various logging intensities (Table 4; Figure 2). The sample data successfully passed the KMO and Bartlett's sphericity tests, affirming their suitability for PCA. The first two principal components accounted for a cumulative contribution rate of 87.546% and were thus selected for comprehensive evaluation. The first principal component's variance contribution rate was 56.677%, with high loadings on species diversity (*D*), species composition (*Z*), and species evenness (*P*), the three diversity attributes. Consequently, the first principal component can represent diversity status in comprehensive evaluations. The second principal component's variance contribution rate was 30.869%, with high loadings on tree dominance (*U*), stand density (*K*), tree health (*Q*), stand growth (*B*), DBH distribution (*H*), and tree height distribution (*V*), which were the vitality and structural characteristics. Thus, the second principal component can represent growth status in comprehensive evaluations. Notably, significant disparities existed between the control blocks (CKs) and the logging blocks (T1, T2, T3, T4), which illustrates that logging markedly improved the stand state of middle-aged *P. massoniana* plantations. However, the stand states were mostly similar across different logging intensities, suggesting that the few observable differences were not strikingly pronounced (Figure 3a).

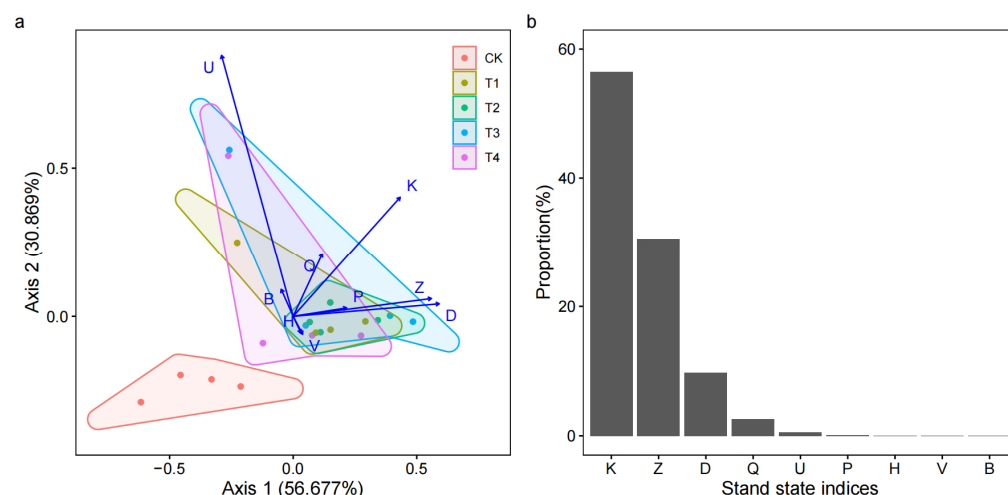


Figure 3. Principal component analysis-based stand-state evaluation of *Masson pine* mid-aged plantations. (a) Based on the principal component analysis, the load values of stand state indicators; Different colored boxes represent different logging intensity sample areas; (b) based on the principal component analysis, the ranking of stand state indicator weights.

Based on the principal component analysis, the ranking of trait weights is (Figure 3b) stand density (K, 56.411%) > species composition (Z, 30.543%) > species diversity (D, 9.744%) > tree health (Q, 2.591%) > stand dominance (U, 0.556%) > species evenness (P, 0.091%) > diameter distribution (H, 0.050%) > height distribution (V, 0.011%) > stand vigor (B, 0.003%). The four indicators of stand density (K, 56.411%), species composition (Z, 30.543%), species diversity (D, 9.744%), and tree health (Q, 2.591%) account for 87.146% of the weight, and each indicator has a weight greater than 1%, making them key indicators for characterizing the stand state of middle-aged *Masson pine* forests. In addition, there were no significant differences in the comprehensive evaluation of the stand state of mid-aged *Masson pine* forests under various logging intensities (T1, T2, T3, T4), but all were significantly greater than in the control blocks CK (Table 5).

Table 5. Stand-state evaluation of mid-aged *Masson pine* plantations using the unit circle method and principal component analysis.

Method	CK	T1	T2	T3	T4
Unit circle method	0.170 ± 0.020 c	0.305 ± 0.026 b	0.316 ± 0.024 ab	0.355 ± 0.039 a	0.308 ± 0.033 b
Principal component analysis	0.194 ± 0.149 b	0.695 ± 0.124 a	0.749 ± 0.101 a	0.810 ± 0.184 a	0.648 ± 0.134 a

Note: Different lowercase letters indicate a significant difference between different logging intensities ($p < 0.05$).

3.4. Comparative Analysis of Stand-State Evaluations Using the Unit Circle Method Versus Principal Component Analysis

The evaluative outcomes derived from the unit circle method and principal component analysis exhibit a highly significant linear correlation ($R^2 = 0.909$, $p < 0.001$) (Figure 4), which attests to the high consistency of overall trends across both methods. Nevertheless, multiple comparative analyses revealed that the unit circle method demonstrated a relatively higher sensitivity, thus enabling a more precise differentiation of subtle distinctions among the various logging treatments (Figure 4).

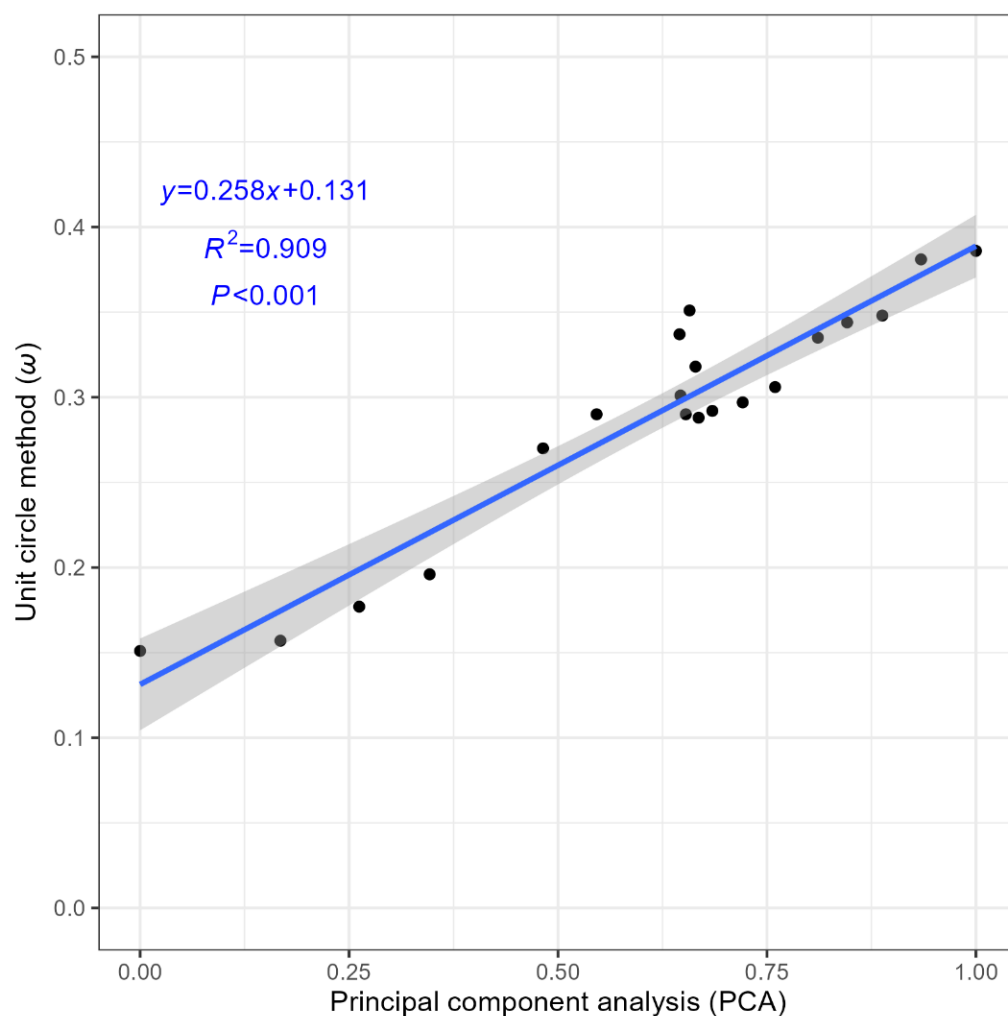


Figure 4. Correlation analysis of unit circle method versus principal component analysis stand-state evaluation results.

4. Discussion

A comparative analysis of stand states under varying logging intensities, using the unit circle method, elucidates that selective logging can significantly improve stand state in middle-aged *P. massoniana* stands characterized by excessive density and high canopy closure. Notably, a logging intensity approximating 30% was observed to yield the most optimal stand state. Logging can alleviate inter-tree competition by liberating growth and nutrient space, thereby fostering tree growth [41–43]. A judicious logging intensity thus exerts beneficial effects on forest structural optimization [44] by fine-tuning the forest structure to its optimal state through the removal of a specific number of trees, thus maximizing ecological function [45,46]. Chang et al. discerned that moderate logging (30.4% logging intensity) had the most pronounced impact on the stand state of *P. taiwanensis* plantations, enhancing spatial structure and stability [47]. Logging can engender new ecological niches within forest communities, mitigate competitive intensity among trees, promote ecological succession, and augment forest health [24]. Consequently, logging, as a scientific and efficacious forest management technique, diverges from traditional clear-cutting; its essence lies in retaining superior species and robust, vigorous trees, thereby maintaining forest productivity and stability through rational structural adjustments. Only healthy and stable forest ecosystems can fully utilize their ecological, social, and economic functions [48].

This study assessed the ramifications of logging intensity on stand states in middle-aged *P. massoniana* plantations by employing the unit circle method alongside principal component analysis. The findings revealed that the parameters of stand density, tree health, species composition, and species diversity were most responsive to logging. Two years after the logging event, these indicators exhibited the most improvement. This improvement can be chiefly attributed to the excision of tightly packed, underperforming trees devoid of future cultivation potential, as well as those afflicted by pests and diseases [49]. Furthermore, the predominantly single-species nature and high degree of monospecificity in mid-aged *P. massoniana* plantations highlights that the logging process successfully removed *P. massoniana* while bypassing other thriving broad-leaved tree species. Thereby, to some extent, this altered the species composition and stand density of the *P. massoniana* plantations while bolstering the health and vigor of any remaining trees. Logging can promote stand composition and vertical structural characteristics while potentially accelerating natural regeneration [50,51], optimizing stand structure, and increasing the growth rate of residual trees when inferior trees are removed [52]. Diameter distribution, height distribution, tree dominance, stand growth, and species evenness all showed relatively poor responsiveness to logging; however, short-term logging efforts have always struggled to enhance these latter indicators. This shortcoming may be attributed to the brevity of the logging period, which is not long enough to allow for substantial changes in tree diameter and height growth. Moreover, the responses of trees and stands to logging can vary temporally [53,54], with uneven size and growth distribution changes manifesting differently at varying logging intervals [53,55]. Previous research has demonstrated that there is a temporal lag in tree and stand growth responses to logging disturbance. For example, no significant changes in growth patterns have been observed during the initial post-logging period (approximately two years) [56,57]. In a notable study, Zeng et al. investigated how growth in *P. massoniana* plantations responded to varying logging intensities in southwestern Guangxi. Their analysis of tree height and diameter growth data across different post-logging intervals revealed no significant changes within the first one to three years following logging [19]. As such, with relatively short logging intervals and limited long-term monitoring data being the norm, our current understanding of tree growth patterns throughout the post-logging recovery period remains incomplete. Further research is needed to assess potential significant changes in various stand-level indicators during an extended recovery process. Thus, prolonged observation and more nuanced management strategies might be needed to improve the indicators that showed poor responsiveness in this study.

The unit circle method, which was utilized in this study to evaluate stand states, enabled a scientific assessment that mirrors actual stand states and provided robust guidance for formulating specific forest management measures. Compared to other traditional evaluation methods, the unit circle method boasts at least three advantages: (1) it is a more scientific evaluation system involving typical indicators of structure, vitality, and diversity. These indicators have a unified value range, thereby rendering the biological significance of the results easier to interpret. (2) It offers a more intuitive data presentation, with the unit circle result presentation method markedly enhancing the comprehension and acceptance of comprehensive stand-state evaluation information. (3) It results in more precise evaluation results; our study demonstrates that the unit circle method and principal component analysis both yield highly congruent overall stand-state evaluation results, but that the unit circle method is more sensitive to logging treatments due to its geometric properties, making it easier for this method to detect trend shifts post-data transformation. In the unit circle method, each sector indepen-

dently represents a separate evaluation index, which facilitates contrasting how each index contributes to the overall evaluation result. Together, the sectors offer a summary of the overall stand performance [32]. Additionally, the geometric transformation process of the unit circle method effectively diminishes noise interference and augments data resolution. Although principal component analysis excels in dimensionality reduction and data simplification, it relies excessively on certain principal components during different treatment contrast analyses, and this results in its insufficient sensitivity to subtle differences [58,59]. Therefore, in scenarios demanding high-precision differentiation of disparate treatment effects, the unit circle method is more advantageous because it delivers more accurate stand-state evaluation results and can strongly indicate forest quality enhancement.

5. Conclusions

Comprehending the impact of logging on stand structure and condition is vital for managing forest resources scientifically. The results of this study underscore that moderate logging intensity substantially influences stand state in mid-aged *P. massoniana* plantation stands with excessive density and high canopy closure. The unit circle method scientifically and effectively reflects the short-term impact of logging intensity on mid-aged *P. massoniana* plantation stand states and strongly indicates forest quality enhancement. This method holds potential for widespread adoption across various forestry production practices as well as for guiding forest management activities. Furthermore, our short-term research demonstrates that implementing an appropriate logging intensity effectively optimizes stand structure and maintains ecosystem stability. However, logging operations can also negatively impact forests, such as through soil compaction or nutrient loss. Thus, it is always necessary to conduct continuous monitoring and ongoing research to clarify the comprehensive impacts of logging on the forest ecosystem.

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