

Article

Relationship Between Wood Productivity and Tree-Layer Carbon Sequestration Rate and Their Drivers in *Pinus massoniana* Plantations Under Forest Management

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Abstract

The coordinated enhancement of wood production and carbon sequestration in plantations is increasingly important for sustainable forest management and climate-change mitigation. However, quantitative evidence on how forest management can jointly improve these two functions remains limited. Based on 847 *Pinus massoniana* plantation plots (yielding 1184 consecutive-period observations) from China's 7th–9th National Forest Inventories (covering 2004–2018), we quantified the degree of coordination between wood productivity and tree-layer carbon sequestration rate. Linear mixed-effects models, the piecewise structural equation model, and XGBoost-SHAP analyses were subsequently applied to identify the major drivers and threshold ranges of key stand factors. The results showed that mean carbon sequestration rate and wood productivity were 1.16 Mg/ha/yr and 4.17 m³/ha/yr, respectively. Among the examined management categories, plots with standing-volume harvest intensity < 0.15 (i.e., removing less than 15% of stand volume) showed the highest tree-layer carbon sequestration rate and wood productivity. Overall, wood productivity and tree-layer carbon sequestration rate showed broadly consistent responses across the examined management conditions, suggesting a generally high degree of coordination between the two functions. Stand structural attributes were the primary determinants of the degree of coordination, whereas management factors tended to strengthen this coordination both directly and indirectly through modifications of stand structure. Within the sampled range, a higher degree of coordination was associated with stand DBH values of 7.5–10.6 cm, stand density below 1071 trees/ha, stand age exceeding 29 years, and standing-volume harvest intensity approaching 0.12. These findings provide a quantitative basis for balancing timber production and tree-layer carbon sequestration, and offer practical implications for adaptive management of subtropical plantations under climate-mitigation and timber-supply objectives.

Keywords: *Pinus massoniana* plantation; forest management; carbon sequestration; wood productivity; functional coordination



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1. Introduction

Forests are among the most important carbon pools in terrestrial ecosystems and play a crucial role in regulating the global carbon balance, mitigating greenhouse gas

emissions, and supporting timber supply [1–3]. Accurate estimation of forest biomass and carbon stocks is fundamental for evaluating carbon sequestration potential and supporting climate-change mitigation strategies. Recent studies have further demonstrated that biomass and carbon stock assessments provide critical information for understanding ecosystem functioning and informing sustainable forest management and restoration practices [4,5]. In China, plantations constitute the main component of afforestation, reforestation, and managed forests, and have become a major contributor to the national increase in forest carbon stocks [6]. Under China's carbon-peaking and carbon-neutrality goals, plantation management is expected not only to enhance carbon sequestration but also to maintain a stable wood supply. This challenge has become increasingly important as the gap between domestic wood production and market demand continues to widen. However, traditional plantation management has long focused primarily on maximizing wood production. In many production-oriented plantations, intensive monoculture practices, high planting densities, and short rotation cycles have been widely adopted [7,8]. Although such management can increase wood production in the short term, it may also lead to site degradation, simplified stand structure, declining stand volume, and reduced long-term sustainability [9]. Moreover, many Chinese plantations are dominated by young and middle-aged stands. These forests often exhibit low stand volume, inappropriate stand density, simplified stand structure, and frequent pest outbreaks, all of which can constrain wood productivity and reduce carbon sequestration capacity [8]. Therefore, under the dual pressures of climate-change mitigation and wood security, plantation management needs to shift from a yield-oriented approach toward strategies that simultaneously enhance wood production and carbon sequestration [10]. Consequently, understanding how forest management influences the degree of coordination between these two functions has become a key prerequisite for developing sustainable plantation management strategies under climate-change mitigation objectives.

Carbon sequestration and wood productivity in plantations are influenced by overlapping but distinct drivers. Tree-layer carbon sequestration rate mainly depends on carbon assimilation, biomass accumulation, and carbon allocation, and is affected by stand age, stand density, canopy structure, tree size, site conditions, climate, disturbance, and management practices [9,11]. Wood productivity is regulated by stand developmental stage, site productivity, stand structure, and silvicultural interventions, such as density regulation, harvesting, and replanting. These factors collectively influence resource acquisition, competition intensity, and volume increment [9,11]. Previous studies have shown that optimizing stand density, extending rotation age, and applying rational thinning can reduce competition while maintaining high stand-level wood productivity, potentially promoting greater coordination between wood productivity and carbon sequestration. For example, in subtropical plantations, extending the rotation period from 15 to 20–25 years can increase the combined benefits of wood productivity and carbon sequestration [6]. Rotation ages exceeding 30 years may further maximize the coordination between wood productivity and carbon storage [12]. Therefore, identifying the factors that influence the joint variation of carbon sequestration and wood productivity is essential for developing management strategies that enhance their coordination. The relationship between wood productivity and carbon sequestration is complex and context-dependent. Since both depend on photosynthetic carbon assimilation and biomass, the carbon-pool structure is altered and carbon turnover is accelerated. Consequently, the degree of coordination between the two functions can vary with stand structure, developmental stage, site conditions, and management regime [9,13,14]. Forest management plays a crucial role in shaping this relationship. Practices such as harvesting, thinning, density regulation, replanting, and rotation adjustment can modify stand structure and resource competition, thereby affecting carbon

sequestration and wood productivity both directly and indirectly [11,13,14]. Nevertheless, substantial uncertainty remains regarding how management influences the coordination between wood productivity and carbon sequestration across diverse stand conditions and management regimes [15,16].

Pinus massoniana Lamb. (*P. massoniana*), commonly known as *Masson pine*, is widely planted in subtropical China due to its strong tolerance to drought-prone and nutrient-poor environments. It has long served as a representative species in plantation research. According to the Ninth National Forest Resources Inventory Report [17], the plantation area of *P. massoniana* in China reached 2.5192 million ha, emphasizing its substantial carbon sequestration potential and its importance for national timber production, ecological restoration, and achieving the “dual-carbon” goals [18,19]. Despite extensive studies on wood productivity, carbon sequestration, and their responses to stand structure and management practices, several critical knowledge gaps remain. First, most studies have examined either productivity or carbon sequestration individually, while quantitative assessments of the relationship between these two functions under actual forest management remain limited. Second, prior research often relies on experimental plots or simulation scenarios, limiting the ability to evaluate management effects across large spatial scales and diverse stand conditions. Third, the relative contributions of management practices and stand structural attributes to the relationship between wood productivity and carbon sequestration remain poorly understood, particularly regarding potential threshold responses of key management-related variables. To address these gaps, we analyzed multi-period National Forest Inventory data from 847 fixed plots of *P. massoniana* plantations across southern China. We quantified differences in carbon sequestration rate and wood productivity under different management regimes; evaluated the degree of coordination between the two functions; and identified key drivers using linear mixed-effects model (LMM), piecewise structural equation modeling (pSEM), and XGBoost-SHAP analysis to assess nonlinear responses and threshold intervals. The ultimate aim was to propose management strategies that enhance both wood productivity and tree-layer carbon sequestration rate. Specifically, our objectives were to: (1) examine variations in wood productivity and tree-layer carbon sequestration rate across forest management categories; (2) quantify how the coordination between wood productivity and tree-layer carbon sequestration changes with forest management; and (3) identify key factors influencing this coordination and their potential thresholds.

2. Materials and Methods

2.1. Study Species and General Description

P. massoniana is a native conifer widely distributed in southern China (21°41′–33°56′ N, 102°10′–122°14′ E), covering the northern, middle, and southern subtropical zones. It is the most common pine species in China and a representative conifer of the eastern humid region [18,19]. Administratively, it occurs in 14 provinces (autonomous regions and municipalities), including Zhejiang, Fujian, and Jiangxi (Figure 1). Across its distribution range, mean annual temperature ranges from 8.9 to 27.5 °C, mean annual precipitation ranges from 755 to 2500 mm, and the dominant soils are red and yellow soils [20,21].

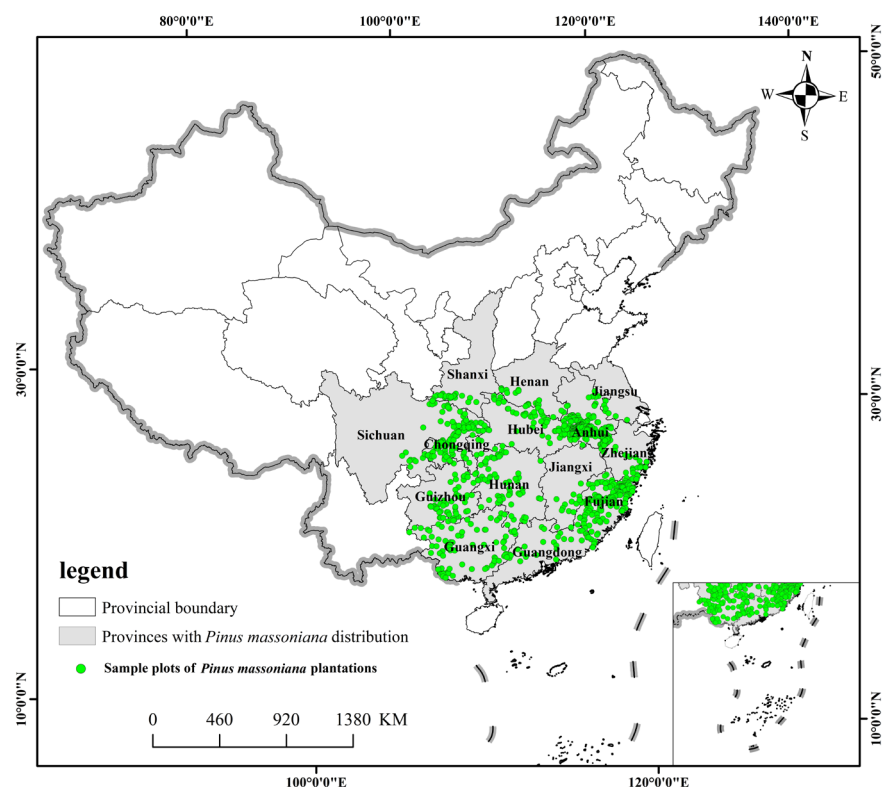


Figure 1. Distribution of sample plots of *P. massoniana* plantations.

2.2. Data Sources and Processing

2.2.1. National Forest Inventory Data

The National Forest Inventory (NFI) data used in this study comprised fixed plots from three consecutive inventory periods: the 7th (2004–2008), 8th (2009–2013), and 9th (2014–2018) inventories. The NFI employs permanent square sample plots with a standard area of 0.0667 ha (approximately 25.82 m × 25.82 m). The dataset included stand-level information, such as geographic coordinates, elevation, aspect, slope position, slope gradient, soil depth, mean diameter at breast height (DBH), mean tree height, and mean stand age; and tree-level information, including measurement type, species code, DBH, harvest type, and individual-tree volume. According to the technical specifications of the National Forest Inventory [22], 847 fixed plots of *P. massoniana* plantations were selected (Figure 1). These plots involved approximately 73,000 trees in the 7th inventory, 79,000 trees in the 8th inventory, and 84,000 trees in the 9th inventory.

To make full use of the repeated measurements from fixed plots, changes between two consecutive inventory periods were treated as the basic analytical unit. Specifically, tree-layer carbon sequestration rate and wood productivity were calculated for each of the 847 fixed plots for the 7th-to-8th and 8th-to-9th inventory intervals. Observations from the two intervals were then pooled into a single analytical dataset. Because of this, the same plot could appear in the analysis more than once across different inventory intervals, resulting in a repeated-measures structure rather than a fully independent cross-sectional dataset.

All stand-level and tree-level variables were compiled in Python 3.8 using the pandas and numpy packages. Indices of species richness, diversity indices, and evenness were calculated using the R package ForestStatTool 0.0.1, developed by the Research Institute of Resource Information Techniques, Chinese Academy of Forestry. Stand density was classified into three categories following the Forest Tending Regulations issued by the State Forestry Administration in 2015 [23]: high (>1500 trees/ha), medium (500–1500 trees/ha), and low (<500 trees/ha). Stand age was categorized into five classes according to the

Technical Regulations for the National Forest Inventory (GB/T 38590-2020): young forest (≤ 10 years), middle-aged forest (11–20 years), near-mature forest (21–30 years), mature forest (31–50 years), and over-mature forest (≥ 51 years).

The occurrence and type of management between two consecutive inventory periods were determined based on individual-tree volume and measurement type. According to the Forest Tending Regulations [23], standing-volume harvest intensity quantified harvesting severity, and standing-volume replanting intensity quantified replanting management intensity. Both indices ranged from 0 to 1, with higher values indicating greater management intensity (see Appendix A for details). Based on previous studies [24,25], standing-volume harvest was classified into three levels: low (<0.15), medium (0.15–0.30), and high (>0.3). These levels were respectively defined as light harvesting (C1), moderate harvesting (C2), and heavy harvesting (C3). Using the changes between two consecutive inventory periods as analytical units, a total of 838 observations were assigned to C1, 175 to C2, and 171 to C3.

2.2.2. Potential Predictor Variables

Biotic and abiotic factors, including human disturbance, site conditions, and climatic variables, jointly affect vegetation growth and development, and alter soil physicochemical properties, which in turn influence forest carbon sequestration and wood productivity [26,27]. Based on previous studies [27,28], we selected 40 potential predictor variables, grouped into five categories: 14 stand attributes, 5 topographic variables, 7 climatic variables, 11 soil properties, and 3 management/disturbance variables (Table 1).

For variables not directly available from the NFI data, we compiled supplementary datasets. The multi-year global terrestrial Human Footprint dataset was used to quantify human disturbance intensity, integrating multiple indicators of anthropogenic activity [29]. Climatic data were obtained from the National Tibetan Plateau Data Center, the Resource and Environment Science and Data Center of the Chinese Academy of Sciences [30], and ClimateAP (v3.10), developed by the Asia-Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet) [31]. Soil property data, including the Chinese soil type map, the Chinese soil texture map, and the China Land Surface Modeling Soil Database, were obtained from the Resource and Environment Science and Data Center [32]. Mean annual NDVI was derived from MOD13A3 data by averaging monthly NDVI values across years. Canopy height was extracted from Google Earth Engine using Sentinel-2 imagery provided by NASA. Except for canopy height, which has a spatial resolution of 10 m, all other geospatial datasets have a 1 km resolution. To ensure spatial consistency, all layers were reprojected to the Gauss–Kruger coordinate system and resampled to a common 30 m grid using nearest-neighbor interpolation in ArcGIS 10.8. This resampling harmonized raster alignment for spatial extraction and did not increase the effective spatial resolution of the original datasets [33].

Table 1. Basic information of independent variable factors.

Indicator Types	Indicator	Indicator Description	Min	Max	Mean
Soil properties	Clay (%)	Clay content	6.57	45.81	25.39
	Silt (%)	Silt content	17.66	63.80	42.34
	Sand (%)	Sand content	6.14	75.77	32.26
	Gravel (%)	Gravel content	0.00	48.73	9.45
	SOM (%)	Soil organic matter	0.66	9.10	2.92
	TN (mg/g)	Total nitrogen	0.04	0.47	0.15
	TK (mg/g)	Total potassium	0.36	3.22	1.69
	TP (mg/g)	Total phosphorus	0.01	0.14	0.05
	AP (mg/kg)	Available phosphorus	1.84	13.00	4.82
	pH	pH	4.22	8.10	5.77
	Depth (cm)	Soil depth	10.00	160.00	59.80

Table 1. Cont.

Indicator Types	Indicator	Indicator Description	Min	Max	Mean
Management and disturbance	Foot	Human Footprint index	2.67	45.69	15.77
	Cut_intensity	Standing-volume harvest intensity	0.00	0.90	0.13
	Plan_intensity	Standing-volume replanting intensity	0.00	0.55	0.01
Topography and geomorphology	Longitude (°E)	Longitude	103.89	121.32	113.27
	Latitude (°N)	Latitude	21.75	33.50	29.08
	DEM (m)	Elevation	18.00	1450.00	405.72
	Slope (°)	Slope gradient	0.00	52.00	21.68
	Aspect	Aspect	-	-	-
Stand factors	DBH (cm)	Mean DBH	7.40	15.92	10.72
	Density (trees/ha)	Stand density	15	3853	1221
	Age (yr)	Stand age	2	60	26
	Crown (%)	Canopy closure	0.00	95.00	60.21
	DBHsd (cm)	Standard deviation of DBH	0.28	7.20	2.07
	DBHcv	Coefficient of variation of DBH	0.03	0.50	0.19
	DBHgini	Gini coefficient of DBH	0.00	0.25	0.11
	Richness (sp.)	Species richness	1	12	3
	GiniSimpson-Div	Gini-Simpson diversity index	0.00	0.77	0.01
	Simpson-Div	Simpson diversity index	1.00	4.39	1.04
	Shannon-Div	Shannon diversity index	0.00	1.66	0.01
	GiniSimpson-Eve	Gini-Simpson evenness index	0.00	1.00	0.01
	Simpson-Eve	Simpson evenness index	0.00	1.00	0.01
	NDVI	Mean annual normalized difference vegetation index	0.35	0.82	0.64
Climate and meteorology	AMT (°C)	Mean annual temperature	12.38	22.97	17.09
	MAP (mm)	Mean annual precipitation	767.80	2188.12	1384.37
	AME (mm)	Annual evaporation	911.18	1799.11	1264.75
	ASH (h)	Annual sunshine duration	1012.62	2181.91	1654.95
	AHM	Annual heat-moisture index	12.19	34.93	20.44
	AAP (hPa)	Mean atmospheric pressure	857.47	1213.16	983.46
	ARH (%)	Relative humidity	69.02	83.20	78.29

2.3. Calculation of Carbon Sequestration Rate

Tree-layer carbon stocks in the inventory plots were estimated using species-specific biomass models and carbon accounting parameters for the major tree species [34]. Specifically, plot-level tree-layer biomass was estimated using species-specific one-variable allometric equations, with individual-tree DBH as the predictor. The estimated biomass was then multiplied by the mean carbon concentration of each species to obtain tree-layer carbon stock [33]. The equation is as follows:

$$C = \frac{\sum_{i=1}^k (cf_1 * a_0 DBH_i^{a_1} + cf_2 * b_0 DBH_i^{b_1})}{S} \quad (1)$$

where C is tree-layer carbon stock per unit area (Mg/ha); k is the number of trees within the plot; a_0 , a_1 , b_0 , and b_1 are species-specific parameters of the aboveground and root biomass equations; cf_1 and cf_2 are the carbon concentration coefficients for the aboveground and root biomass, respectively; and S is the plot area (ha). Species-specific parameter values are given in Table S1.

In this study, the tree-layer carbon sequestration rate was defined as the annualized change in tree-layer carbon stock represented by the change in live-tree carbon stock together with the carbon contained in harvested and dead trees during the inventory interval. Specifically, tree-layer carbon sequestration rate was calculated as the change in live-tree carbon stock between two consecutive inventories, plus the carbon stock contained

in harvested and dead trees during the inventory interval, and divided by the length of the inventory interval (years):

$$\Delta C = \frac{C_{i,2} - C_{i,1} + D}{y} \quad (2)$$

where ΔC is the tree-layer carbon sequestration rate of the plot (Mg/ha/yr); $C_{i,1}$ and $C_{i,2}$ are live-tree carbon stocks measured at the first and second inventories, respectively (Mg/ha); D is the carbon stock contained in harvested and dead trees during the inventory interval, calculated as the sum of the carbon stocks of all harvested and dead trees (Mg/ha); and y is the length of the inventory interval (years).

2.4. Calculation of Wood Productivity

Following previous studies [35], wood productivity was defined as the sum of net increment in stand volume and the harvested volume over a given inventory interval. Accordingly, the term “wood productivity” in this study refers to stand-level wood production potential rather than actual harvested timber yield. This definition reflects the capacity of a stand to generate merchantable wood over time rather than realized timber extraction alone [23,35], and therefore incorporates both harvested timber volume and the net increment in live-tree volume that may become merchantable wood in the future. Based on individual-tree volume and measurement records, live-tree volume and harvested-tree volume were estimated for each inventory period, and plot-level wood productivity was calculated as follows:

$$\Delta P = \frac{\sum_{i,2} V_{i,2} - \sum_{i,1} V_{i,1} + M}{y} \quad (3)$$

where ΔP is stand-level wood production potential (m³/ha/yr); $V_{i,1}$ and $V_{i,2}$ are the live-tree volumes measured at the first and second inventories, respectively (m³/ha); M is the total harvested volume during the inventory interval, calculated as the sum of the volumes of all harvested trees (m³/ha); and y is the length of the inventory interval (years).

2.5. Analysis of Degree of Coordination

Under different stand-structure gradients, simple linear regression was used to characterize the relationship between wood productivity and carbon sequestration rate and to evaluate changes in the degree of coordination between the two functions. Within individual plots, the relative degree of coordination between the two functions was quantified using an approach adapted from ecosystem-service relationship studies. Root mean square deviation (RMSD) was used to quantify the degree of divergence or coordination between wood productivity and tree-layer carbon sequestration rate [36].

$$RMSD = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n (ES_i - ES_{std})^2} \quad (4)$$

where n is the number of ecosystem functions; ES_i is the normalized value of each function i (wood productivity and tree-layer carbon sequestration rate); and ES_{std} is the mean standardized value of the two functions. RMSD theoretically ranges from 0 to 1. Values closer to 1 indicate a greater divergence between the two functions, whereas values closer to 0 indicate a higher degree of coordination. Following previous studies, RMSD values below 0.2 were interpreted as indicating a relatively high degree of coordination between the two functions [37]. Because wood productivity and tree-layer carbon sequestration rate were both derived from stock-change and removal terms, part of the observed association between the two indicators may reflect shared accounting components. Therefore, RMSD-based interpretations were combined with gradient responses and driver analyses to avoid overinterpreting low RMSD values as direct evidence of ecological coordination.

2.6. Statistical and Driver Analyses

Data were organized in Excel 2021 and analyzed and visualized in R 4.5.1. Outliers in tree-layer carbon sequestration rate and wood productivity were identified using Tukey's Fences. The robustness of the results was assessed by comparing analyses before and after outlier removal. After outlier removal and pooling observations from the two inventory intervals, 1184 valid observations were retained for subsequent analyses and modeling. One-way analysis of variance (ANOVA) was used to test whether carbon sequestration rate or wood productivity differed significantly among gradient classes, followed by Tukey's honestly significant difference (HSD) test for pairwise post hoc comparisons among groups [38]. When the assumptions of normality or homogeneity of variance were violated, the Kruskal–Wallis test was used as a non-parametric alternative to compare differences among groups ($p < 0.05$) [39].

LMM were used to test the effects of management intensity, stand attributes, and environmental factors on tree-layer carbon sequestration rate, wood productivity, and RMSD, with plot identity included as a random effect to account for repeated observations from the same fixed plots. Prior to model fitting, soil variables were standardized and reduced using principal component analysis (PCA) [40]. Principal components explaining more than 80% of the cumulative variance were retained, and their scores were used as integrated soil predictors in subsequent analyses. The retained soil principal components were then combined with stand structural, management, topographic, and climatic variables for multicollinearity assessment. Variance inflation factors (VIF) were calculated for all candidate predictors using the 'rdacca.hp' package in R. A conservative threshold of $VIF > 3$ was adopted to identify variables with high multicollinearity, and predictors exceeding this threshold were removed iteratively until all retained predictors had VIF values below 3 [33]. The remaining variables were used in subsequent LMM analyses and pSEM. The pSEM was implemented using the piecewiseSEM package in R to quantify the direct and indirect associations among management intensity, stand structure, environmental factors, and RMSD. In the pSEM framework, stand structural variables were specified as potential mediators linking management and environmental conditions with RMSD, and plot identity was included as a random effect in each component model. Model fit was evaluated using the chi-square test ($\chi^2 > 0.05$), degrees of freedom ($df > 0$), Fisher's C statistic, and the associated p values (> 0.05) [41]. Standardized path coefficients were used to compare the relative importance of direct effects, and indirect and total effects were calculated from the products of standardized path coefficients.

For the XGBoost-SHAP analysis, predictors retained after LMM, pSEM, and multicollinearity screening were used to characterize nonlinear responses and identify potential threshold effects [42]. Soil variables were represented by the three original soil attributes with the highest loadings on the first principal component (PC1), rather than by PCA scores, to facilitate ecological interpretation of nonlinear responses and threshold values [40]. To reduce the risk of overfitting, several regularization and model-validation procedures were implemented. Hyperparameters were optimized using grid-search procedures, including parameters controlling tree complexity (max_depth, min_child_weight, and gamma), learning rate and number of trees, row and column subsampling (subsample and colsample_bytree), and L1/L2 regularization terms (reg_alpha and reg_lambda). Because the dataset contained repeated observations from the same fixed plots across inventory intervals, conventional random partitioning may allow observations from the same plot to be simultaneously assigned to training and validation datasets, potentially inflating predictive performance. Therefore, model evaluation was conducted using five-fold Group-KFold cross-validation, with plot identity (plot ID) specified as the grouping factor. This procedure ensured that all observations originating from the same fixed plot were assigned

to either the training subset or the validation subset within each fold, thereby preventing information leakage arising from repeated observations of the same plot and providing a more conservative and realistic assessment of model generalization performance. Model performance was evaluated using out-of-fold predictions across all validation folds and quantified using the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). SHAP values were calculated for observations in each validation fold and subsequently aggregated across folds to quantify variable importance, characterize nonlinear response patterns, and identify threshold effects. By deriving SHAP values exclusively from validation subsets, interpretation of variable effects was less dependent on model fitting to the training data and more representative of model behavior on previously unseen observations [33].

It should be noted that changes between consecutive inventory periods of fixed plots were treated as the analytical unit. Consequently, some plots contributed observations to more than one inventory interval, resulting in a repeated-observation structure rather than a fully independent cross-sectional dataset. To account for this dependence, plot identity was incorporated as a random effect in the LMM and pSEM analyses, and Group-KFold cross-validation based on plot identity was used in the XGBoost-SHAP analysis. Nevertheless, potential within-plot correlation cannot be entirely excluded and should be considered when interpreting the results. This issue is further discussed in the Discussion as a study limitation.

3. Results

3.1. Variation in Carbon Sequestration Rate and Wood Productivity in *P. massoniana* Plantations

Under managed conditions, the mean tree-layer carbon sequestration rate of *P. massoniana* plantations was 1.16 Mg/ha/yr, with values ranging from 0.03 to 3.41 Mg/ha/yr across plots, whereas mean wood productivity was 4.17 m³/ha/yr, ranging from 0.02 to 12.70 m³/ha/yr. Table 2 summarizes the tree-layer carbon sequestration rate and wood productivity of *P. massoniana* plantations under the three harvesting-intensity categories. Overall, both tree-layer carbon sequestration rate and wood productivity differed significantly among the three management levels, both exhibiting a declining trend with increasing harvesting intensity ($p < 0.001$).

Table 2. Statistics of carbon sequestration rate and wood productivity of *P. massoniana* plantations under different management regimes.

Functional Type	Management Regime	Mean $\pm$ SD	Min	Max	Significance
Tree-layer carbon sequestration rate (Mg/ha/yr)	C1	1.39 $\pm$ 0.71	0.05	3.41	$p < 0.001$
	C2	1.25 $\pm$ 0.69	0.14	3.36	
	C3	0.86 $\pm$ 0.59	0.03	2.68	
Wood productivity (m ³ /ha/yr)	C1	5.66 $\pm$ 2.74	0.09	12.70	$p < 0.001$
	C2	4.22 $\pm$ 2.14	0.08	11.70	
	C3	2.62 $\pm$ 1.92	0.02	12.30	

3.2. Relationship Between Carbon Sequestration Rate and Wood Productivity

Under forest management, RMSD values between tree-layer carbon sequestration rate and wood productivity ranged from 0 to 0.21, and the vast majority of plots had RMSD values below 0.2. This suggests a generally low degree of divergence between the two indicators and a relatively high level of correspondence in their responses. However, the relationship between the two indicators varied across stand structure, suggesting that the relationship was conditional and context-dependent rather than uniform across stand conditions (Figure 2).

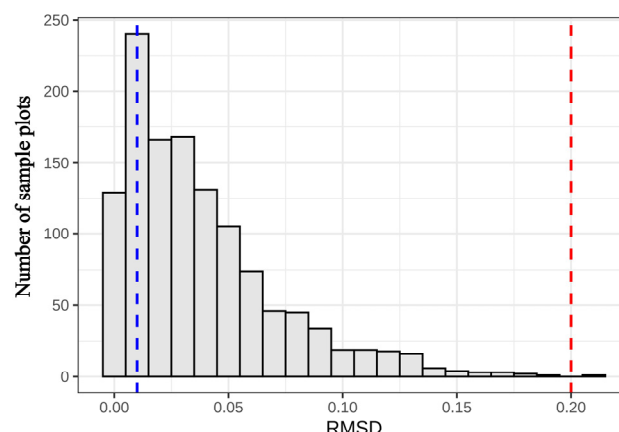


Figure 2. Frequency distribution of RMSD values between tree-layer carbon sequestration rate and wood productivity in *P. massoniana* plantations under forest management.

We further analyzed the relationship between carbon sequestration rate and wood productivity under three harvesting intensities across different gradients. Under light harvesting, both carbon sequestration rate and wood productivity declined with increasing harvest intensity, indicating a synchronous decline rather than contrasting trends (Figure 3a). This pattern suggests that even within the light-harvesting category, increasing harvest intensity may weaken both functions simultaneously. Carbon sequestration rate increased with replanting intensity, whereas wood productivity showed the opposite trend, indicating differing responses of the two indicators to replanting intensity; wood productivity tended to be higher when replanting intensity was below 0.04 (Figure 3b). Across the three stand-density classes, carbon sequestration rate declined with stand age, whereas wood productivity showed an increasing trend within the sampled age range. No clear age-related decline in wood productivity was observed in the available inventory data. Consequently, the two functions showed contrasting responses to stand age. Higher tree-layer carbon sequestration rates were generally observed in low-, medium-, and high-density stands younger than 40, 23, and 31 years, respectively (Figure 3c–e). Across the five age classes, both carbon sequestration rate and wood productivity increased with stand density, indicating broadly similar responses of the two indicators to increasing stand density (Figure 3f–j). Within young, middle-aged, near-mature, and mature stands, densities below 243, 226, 1500, and 2186 trees/ha, respectively (Figure 3f–i).

Under moderate harvesting, carbon sequestration rate declined with increasing stand age across the three stand-density classes, whereas wood productivity showed the opposite trend, indicating contrasting responses of the two indicators (Figure S1a–c). In medium- and high-density stands, higher tree-layer carbon sequestration rates were generally observed at stand ages below 24 and 25 years, respectively (Figure S1b,c). In middle-aged, near-mature, and mature stands, both carbon sequestration rate and wood productivity increased with stand density, indicating broadly similar responses of the two indicators to increasing stand density, wood productivity tended to be higher at densities below 283, 2189, and 1844 trees/ha, respectively (Figure S1d–f). Both indicators declined with increasing harvesting intensity, indicating broadly synchronous declines rather than contrasting responses. The decline in wood productivity was steeper than that in carbon sequestration rate, suggesting that wood productivity was more sensitive to increasing harvest intensity under moderate harvesting (Figure S1g).

Under heavy harvesting, both carbon sequestration rate and wood productivity declined with increasing harvest intensity, indicating synchronous declines in both indicators. However, plots with harvest intensity below 0.5 maintained higher carbon sequestration rates and maintained relatively higher tree-layer carbon sequestration rates (Figure S2a).

Across the three stand-density classes, carbon sequestration rate declined with stand age, whereas wood productivity increased, indicating contrasting responses of the two indicators; higher tree-layer carbon sequestration rates were generally observed in stands younger than 41, 27, and 27 years (Figure S2b–d). Across four age classes (without over-mature stands), both carbon sequestration rate and wood productivity increased with stand density, indicating broadly similar responses of the two indicators to increasing stand density (Figure S2e–h). Among middle-aged and near-mature stands, corresponding to densities below 669 and 1016 trees/ha, respectively, wood productivity tended to be higher (Figure S2f,g).

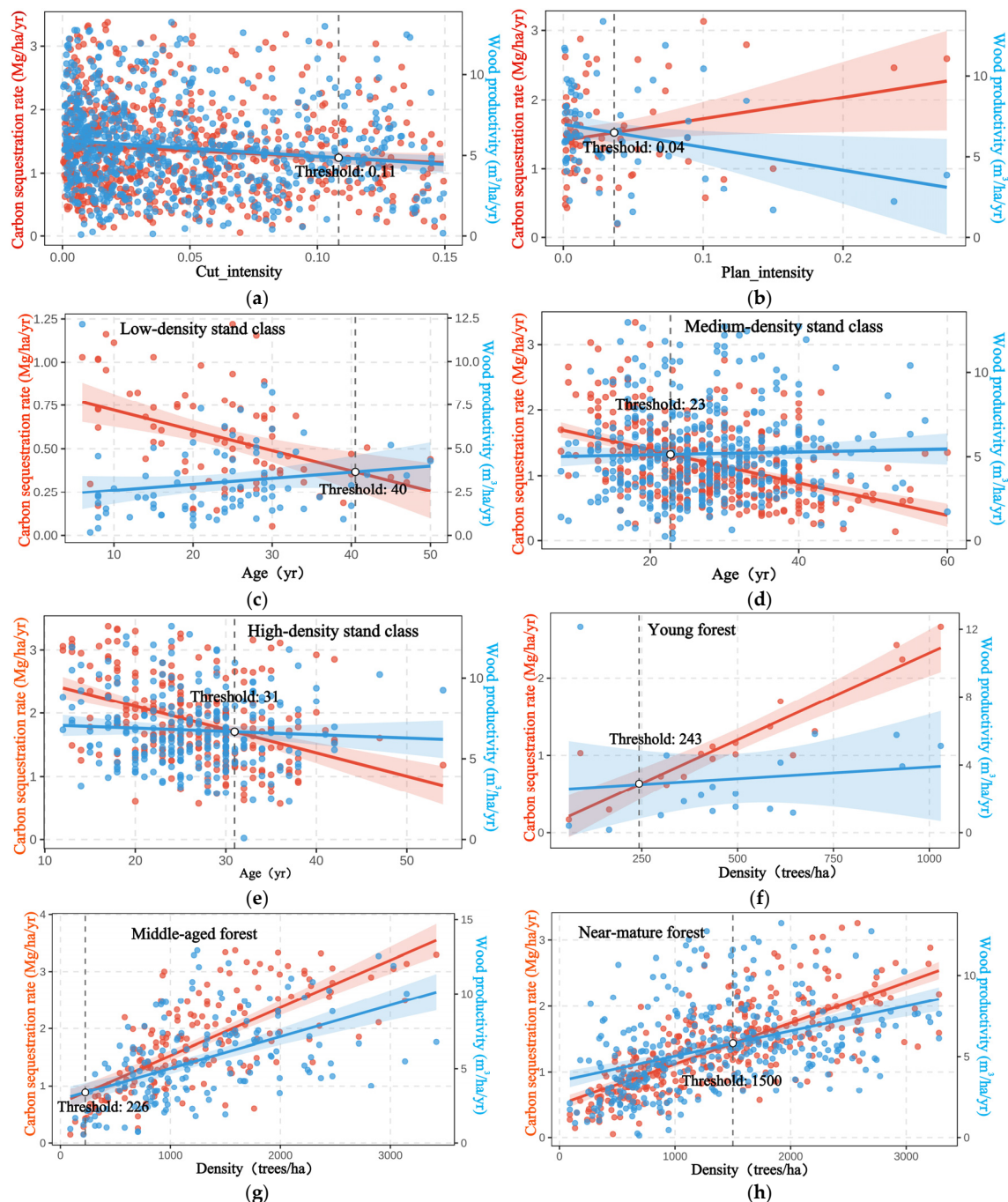


Figure 3. Cont.

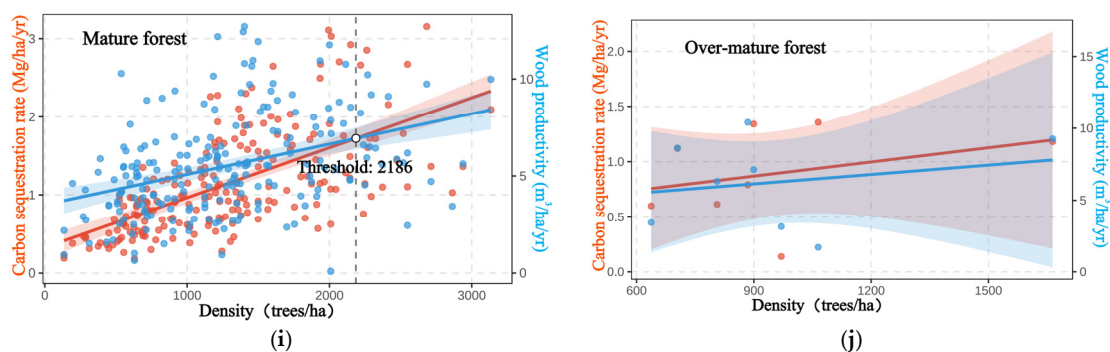


Figure 3. Fitted relationships of tree-layer carbon sequestration rate and wood productivity across different gradients under light harvesting. Panels (a,b) represent differences along the harvest-intensity and replanting-intensity gradients, respectively; panels (c–e) represent age-related differences under low-, medium-, and high-stand-density classes, respectively; and panels (f–j) represent density-related differences in young, middle-aged, near-mature, mature, and over-mature stands, respectively.

3.3. Drivers of the Relationship Between Carbon Sequestration Rate and Wood Productivity

PCA was performed on standardized soil variables. The first six principal components explained 85.9% of the cumulative variance and were retained as composite soil predictors for subsequent multicollinearity assessment and the LMM and pSEM analyses (Tables S2 and S3).

LMM showed that RMSD was primarily associated with stand structural attributes after accounting for repeated observations within plots. The fixed effects explained 55.0% of the variation in RMSD ($R_m^2 = 0.55$), whereas the conditional variation (R_c^2) increased to 0.77 after inclusion of plot identity as a random effect. Among the retained predictors, stand density, mean DBH, DBHcv, stand age, elevation, annual mean temperature, and Soil_PC6 were significantly associated with RMSD. In contrast, harvest intensity did not show a significant main effect on RMSD in the additive model. However, interaction models revealed significant interactions between harvest intensity and stand density, DBH, DBHcv, and elevation, indicating that the influence of harvesting on RMSD varied with stand structural conditions (Tables S4 and S5).

As shown in Figure 4, the simplified pSEM provided an acceptable fit to the data. The model explained 54.8% of the R_m^2 and 76.2% of the R_c^2 in RMSD. Standardized path coefficients indicated that variation in RMSD was primarily associated with stand structural attributes, particularly mean DBH (0.66), stand density (0.46), and DBHcv (0.16). Harvest intensity showed no significant direct association with RMSD but was significantly associated with stand density, mean DBH, and DBHcv, indicating that its association with RMSD was mainly mediated through stand structure. The decomposition of standardized total effects further indicated that DEM had the strongest positive total association with RMSD (0.42), followed by AMT (0.33) and stand age (0.22), whereas harvest intensity showed a negative total association (−0.21). Soil_PC6 exhibited a relatively weak positive total association (0.06), indicating that the integrated soil gradient contributed less to RMSD variation than stand structure, topography, and climate. These results suggest that topographic and climatic conditions were associated with variation in RMSD both directly and indirectly through stand structural attributes, whereas harvest intensity was associated with lower RMSD primarily through indirect pathways involving stand density, mean DBH, and DBHcv.

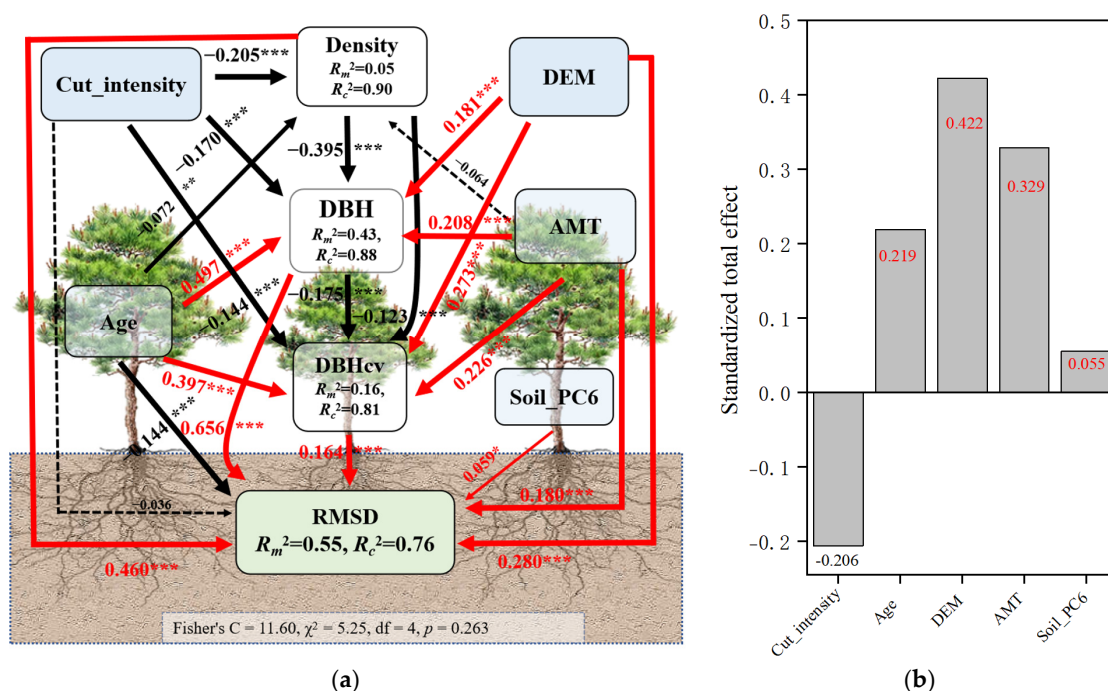


Figure 4. pSEM of the factors affecting RMSD under forest management. (a) shows the path diagram and (b) shows the standardized total effects of exogenous predictors on RMSD. Red and black solid arrows indicate positive and negative relationships, respectively, whereas dashed arrows indicate non-significant relationships. Arrow thickness is proportional to the absolute value of standardized path coefficients; R_m^2 and R_c^2 indicate marginal and conditional explanatory power, respectively; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The XGBoost model captured the nonlinear relationships between RMSD and the predictor variables, achieving R^2 values of 0.98 in the training set and 0.70 across the five GroupKFold cross-validation folds (Figure 5a). For the representative observation shown in Figure 5b, the SHAP decomposition indicated that the combined effects of multiple predictors reduced the model-predicted RMSD from 0.038 to 0.017, indicating a lower predicted RMSD value. Among all the predictors, DBH showed the largest contribution to model-predicted RMSD. This result is consistent with the LMM and pSEM analyses, which identified stand structural attributes as the primary variables associated with RMSD. However, because DBH is directly involved in the estimation of both biomass and stand volume, its high SHAP importance likely reflects a combination of biological effects and shared accounting structure rather than an entirely independent external driver. The SHAP beeswarm and dependence analyses further showed that the magnitude and direction of the DBH effect varied across value ranges, indicating pronounced nonlinear responses. In contrast, topographic, climatic, soil, and replanting variables contributed relatively little to model predictions, with individual contributions generally ranging from 1.62% to 10.07% (Figure 5c; Table 3). Overall, the XGBoost-SHAP results were consistent with the LMM and pSEM analyses, indicating that variation in RMSD under forest management was more strongly associated with stand structural attributes than with individual environmental variables, while additionally revealing nonlinear and threshold-dependent responses that were not fully captured by the linear and path-based modeling approaches.

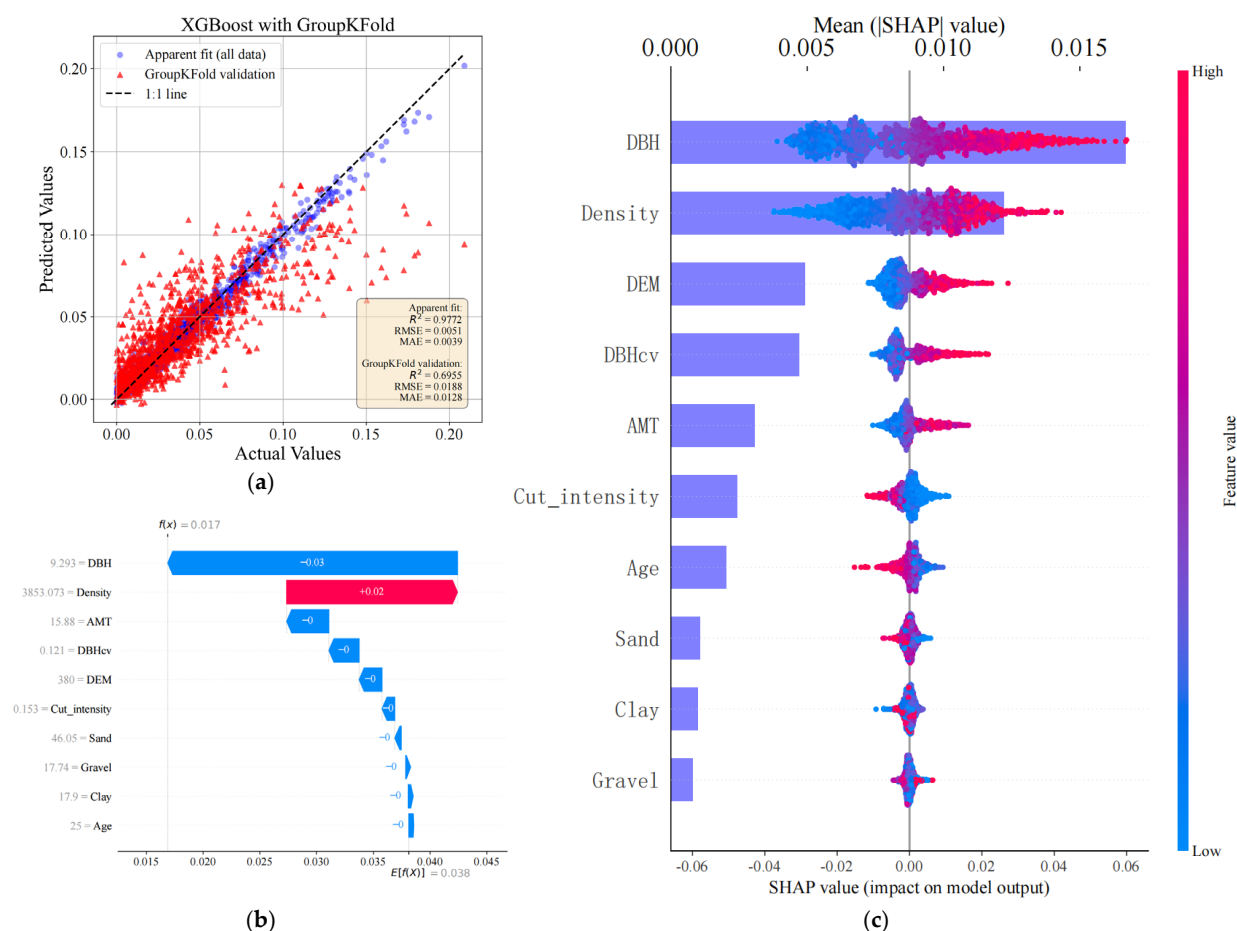


Figure 5. XGBoost-SHAP analysis of the drivers of RMSD between tree-layer carbon sequestration rate and wood productivity in *P. massoniana* plantations under forest management. Panel (a) shows model performance in the training and validation datasets; panel (b) shows SHAP-based local explanation; and panel (c) shows the relative contribution of each predictor.

Table 3. Relative contributions of predictors to RMSD under forest management based on SHAP values.

Driving Factor	Mean_SHAP	Relative Contribution (%)	Reorder
DBH	0.17×10^{-1}	34.09	1
Density	0.12×10^{-1}	24.96	2
DEM	0.05×10^{-1}	10.07	3
DBHcv	0.47×10^{-2}	9.62	4
AMT	0.31×10^{-2}	6.26	5
Cut_intensity	0.24×10^{-2}	4.99	6
Age	2.04×10^{-3}	4.16	7
Sand	1.08×10^{-3}	2.21	8
Clay	0.99×10^{-3}	2.02	9
Gravel	0.79×10^{-3}	1.62	10

SHAP-based partial dependence analysis revealed nonlinear responses and potential threshold ranges of the key predictors associated with variation in RMSD (Figure 6). Stand age, stand density, DBHcv, and standing-volume harvest intensity exhibited clear threshold-dependent responses, whereas DBH showed a more complex interval response. SHAP values became positive when stand density exceeded 1071 trees/ha and DBHcv exceeded 0.20, indicating that values above these thresholds tended to increase the model-predicted RMSD. In contrast, SHAP values remained negative when stand DBH ranged from 7.5 to 10.6 cm, suggesting that this DBH interval was associated with lower predicted RMSD.

values. Stand age around 29 years and standing-volume harvest intensity around 0.12 represented turning points at which SHAP values shifted from positive to negative, indicating that these ranges were associated with lower predicted RMSD within the sampled data. These threshold ranges should therefore be interpreted as model-identified sensitive intervals associated with lower predicted RMSD values, rather than as absolute ecological thresholds or values that necessarily maximize either tree-layer carbon sequestration rate or wood productivity alone.

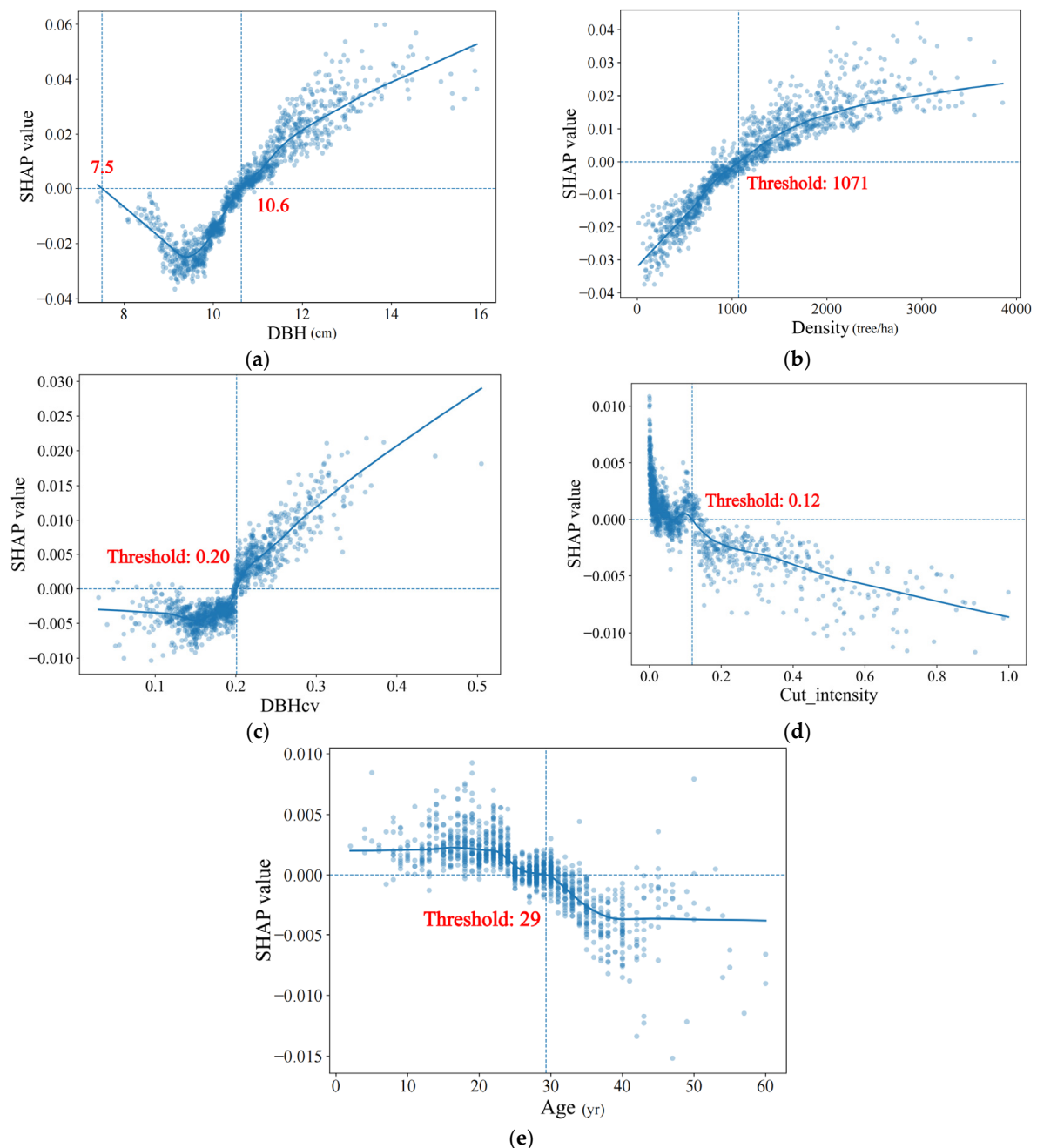


Figure 6. Partial dependence and SHAP-based threshold responses of major predictors affecting the coordination between wood productivity and tree-layer carbon sequestration rate under forest management. Panels (a–e) show the nonlinear responses and potential thresholds between DBH, stand density, DBHcv, Cut intensity, and stand age, respectively, and RMSD.

4. Discussion

4.1. Management-Driven Changes in Tree-Layer Carbon Sequestration Rate and Wood Productivity

Forest management was associated with variation in tree-layer carbon sequestration rate and wood productivity primarily through its associations with controllable stand and management attributes, particularly standing-volume harvest intensity, standing-volume replanting intensity, stand density, canopy closure, and diameter structure. Replanting intensity was also associated with variation in the degree of coordination between wood productivity and carbon sequestration, but its effect should be interpreted cautiously because replanting was unevenly distributed and relatively low in frequency across the sampled plots. In this study, tree-layer carbon sequestration rate generally decreased with increasing standing-volume harvest intensity but increased with increasing standing-volume replanting intensity, suggesting that variation in tree-layer carbon sequestration rate in managed *P. massoniana* plantations may depend on whether post-harvest structural recovery can compensate for biomass removal. Harvesting directly removes aboveground biomass carbon and standing volume, but it may also reduce competition, improve light availability, and stimulate the growth of residual trees and regeneration during the recovery phase [43,44]. Accordingly, the observed association between harvesting and tree-layer carbon sequestration rate may vary with harvest intensity and the rate of post-harvest structural recovery. This interpretation is consistent with previous studies reporting that harvest intensity is closely associated with variation in forest carbon stocks and fluxes and that the effects of thinning or harvesting are often expressed as a dynamic process of short-term carbon loss followed by recovery [43–45]. Recent work on middle-aged *P. massoniana* plantations also showed that overall stand condition first improved and then declined with increasing logging intensity, with the highest stand-state value occurring at approximately 30% logging intensity [46]. Light harvesting may reduce competition among residual trees and improve resource availability, thereby promoting compensatory growth while maintaining a relatively large proportion of standing biomass. In contrast, intensive harvesting substantially reduces canopy continuity and standing carbon pools, potentially resulting in declines in tree-layer carbon sequestration rate that exceed the compensatory growth capacity of residual trees.

Our results further suggest that management practices combining biomass removal with structural supplementation were associated with higher tree-layer carbon sequestration rates than biomass removal alone. Among the examined management categories, plots with standing-volume harvest intensity below 0.15 exhibited the highest mean tree-layer carbon sequestration rate. A plausible explanation is that low-intensity biomass removal, when accompanied by sufficient replanting, may help maintain canopy occupancy and accelerate stand recovery. Replanting may enhance tree-layer carbon accumulation by replenishing stem number, occupying canopy gaps, improving regeneration quality, and shortening the period of reduced carbon uptake following disturbance [16,47]. Previous studies have also emphasized that reforestation or regeneration following harvesting can support both wood production and long-term carbon sequestration, provided that stand recovery is rapid enough to offset the initial carbon loss [48].

Wood productivity exhibited a related but distinct response to management interventions. In this study, wood productivity generally decreased with increasing standing-volume harvest intensity but increased with replanting intensity. The highest wood productivity was observed in plots with replanting but no harvesting, whereas high harvest intensity significantly reduced productivity. This pattern suggests that the reduction in stand density and growing stock associated with harvesting may decrease volume increment at the stand scale, even if individual residual trees show compensatory growth. Once

harvest intensity exceeds the recovery capacity of the stand, increased individual-tree growth cannot fully offset the reduction in stem number, canopy continuity, and stand volume [49]. Conversely, replanting can restore occupied growing space, maintain canopy closure, and improve stand structural continuity, thereby supporting sustained wood production [16,47].

These findings suggest that effective plantation management may depend not only on whether harvesting or replanting is implemented, but also on how stand structure is regulated within an appropriate range. Stand density and diameter structure are particularly important because they jointly determine resource occupation, competition intensity, and volume increment. Previous studies on *P. massoniana* plantations have reported that extending the rotation age from 15 to 20–25 years, together with reducing planting density from 3000 to 2000 trees/ha, significantly enhanced the combined benefits of wood production and carbon sequestration [12]. Therefore, the present results suggest that management strategies intended to enhance tree-layer carbon sequestration rate and wood productivity may benefit from maintaining appropriate stand density trajectories, avoiding excessive biomass removal, and using replanting to facilitate structural recovery following disturbance [50].

4.2. Controllable Determinants and Site Constraints of the Relationship

Before discussing the ecological implications of the results, it should be noted that the relationship quantified by RMSD in this study reflects the degree of consistency in the responses of wood productivity and tree-layer carbon sequestration rate rather than a strict ecological functional divergence between two completely independent ecosystem functions. Because both indicators are derived from stand growth dynamics and partly share stock-change and removal-related accounting components, low RMSD values should be interpreted as indicating a higher degree of correspondence in their responses. Variation in RMSD was more strongly associated with controllable stand and management factors than with local environmental factors alone. In this study, stand density, DBH, and standing-volume harvest intensity were the most management-relevant factors shaping RMSD. These factors are likely associated with variation in the two indicators through their effects on resource competition, canopy light interception, biomass accumulation, and stand recovery. When stand density is too low, growing space is not fully occupied, limiting both volume increment and carbon uptake. However, when density becomes too high, competition for light, water, and nutrients increases, which may reduce individual-tree growth and weaken the synchrony between carbon sequestration and wood productivity [50–52]. This density-dependent mechanism may help explain why RMSD increased along the stand-density gradient, reflecting changes in the degree of correspondence between wood productivity and tree-layer carbon sequestration rate.

DBH and diameter structure were also strongly associated with variation in RMSD. DBH reflects both stand developmental stage and the cumulative outcome of density regulation, competition, and management history. In the present study, DBH exhibited a complex interval-dependent response, indicating that the same increase in tree size may have different implications for carbon sequestration and wood productivity at different developmental stages. At appropriate DBH ranges, tree growth can contribute simultaneously to volume increment and biomass carbon accumulation, thereby contributing to lower RMSD values. However, when stands become overstocked or enter later developmental stages, increased maintenance costs and intensified resource limitation may reduce the correspondence between carbon accumulation and volume increment, resulting in higher RMSD values at specific developmental stages [51,52]. Recent studies on *P. massoniana* plantations have likewise reported that stand structural attributes, particularly

DBH distribution and stand density, are closely associated with ecosystem carbon storage, further supporting the importance of these manageable structural indicators in plantation management aimed at enhancing carbon sequestration [53].

The lower RMSD values observed with increasing stand density may reflect greater stand-level biomass accumulation and canopy photosynthetic capacity. However, once density exceeds the optimal range, increasing competition for resources may gradually weaken the correspondence between the two indicators. Younger and middle-aged stands generally exhibit high growth vigor and carbon assimilation rates, whereas older stands allocate a larger proportion of assimilated carbon to maintenance respiration and structural tissues. This shift in carbon allocation may contribute to the observed age-dependent functional divergence patterns. Standing-volume harvest intensity and replanting intensity may influence RMSD primarily through their effects on stand density and diameter structure. Harvesting has a dual effect: it reduces standing biomass and canopy occupation in the short term, but it can release residual trees from competition when intensity remains within the recovery capacity of the stand [43–45]. Replanting has a compensatory effect by rebuilding stem number, occupying open growing space, and shortening the low-growth recovery period after disturbance [16,47]. Therefore, lower RMSD values are more likely to occur when harvest intensity remains within the recovery capacity of the stand and replanting intensity is sufficient to support structural recovery. In contrast, high harvest intensity without adequate structural rebuilding may simultaneously reduce tree-layer carbon sequestration rate and unit-area wood productivity, thereby increasing divergence between the two indicators and contributing to higher RMSD values.

Local environmental factors, including soil, topography, and climate, primarily function as background constraints rather than direct management targets. These factors shape the potential productivity and recovery capacity of a site, but they are difficult to regulate directly in plantation management. For example, soil depth may constrain rooting volume and long-term water and nutrient availability, whereas soil nutrient availability may influence growth responses to management. However, soil carbon and nutrient responses to thinning are often heterogeneous and may vary with thinning intensity, recovery stage, forest type, and temporal scale [54,55]. A meta-analysis showed that thinning did not significantly change total soil carbon, soil organic carbon, or microbial biomass carbon overall, although it increased soil temperature and soil respiration, especially during the early recovery stage [55]. Therefore, compared with local environmental variables, stand density, diameter structure, harvest intensity, and replanting intensity are more actionable targets for developing practical management.

4.3. Mechanisms and Strategies for the Coordinated Enhancement of Wood Productivity and Carbon Sequestration Rate

Under forest management, tree-layer carbon sequestration rate and wood productivity in *P. massoniana* plantations were generally characterized by low RMSD values, indicating limited divergence and a relatively high degree of correspondence between the two indicators, although greater divergence between the two indicators was still observed under certain stand conditions. Importantly, a lower RMSD should not be interpreted as evidence that both functions were simultaneously maximized. In some management gradients, lower RMSD values reflected synchronous declines in tree-layer carbon sequestration rate and wood productivity, rather than true co-enhancement. The generally low RMSD values suggest that, under most management scenarios, increases in wood productivity did not come at the expense of a pronounced decline in carbon sequestration; rather, the two indicators tended to exhibit broadly similar directional responses. This is broadly consistent with previous findings showing that wood production and carbon sequestration are not inherently antagonistic. The critical issue may therefore be not whether management is

implemented, but whether it regulates stand structure in a manner that maintains efficient resource utilization within the stand [3,56].

In *P. massoniana* plantations, low-intensity harvesting may release residual trees from competition, whereas subsequent replanting may facilitate structural recovery. Together, these processes may partly offset carbon losses and productivity declines caused by harvesting, thereby helping maintain lower RMSD values and a higher degree of correspondence between the two indicators. Previous studies have shown that the effects of thinning regimes on carbon accumulation and stand-volume growth depend on the stand structure formed after thinning, and that moderate thinning under relatively high canopy closure can balance carbon sequestration and wood production [57]. Consistent with these studies, our results suggest that effective management depends less on increasing harvest intensity and more on promoting structural optimization through light harvesting and appropriate replanting. Further analysis showed that stand structure was most strongly associated with variation in RMSD. The LMM and pSEM results consistently indicated that stand structural variables, particularly stand density, mean DBH, and DBHcv, exerted the strongest direct effects on RMSD. The XGBoost-SHAP analysis further supported the importance of stand structural attributes, with DBH, stand density, and DBHcv contributing more to model predictions than most individual environmental and management variables. Previous work has shown that stand structural factors are more directly associated with current productivity in *P. massoniana* and that reducing competition intensity and improving stand composition can substantially increase tree-layer carbon storage [16,58]. In addition to those findings, our results suggest that excessive stand density may increase RMSD values and reduce the correspondence between wood productivity and tree-layer carbon sequestration rate, whereas maintaining DBH within an appropriate intermediate range and promoting a more balanced diameter structure may be associated with lower RMSD values.

The threshold effects identified in this study further suggest that lower RMSD values do not depend on continuously increasing any single factor, but rather on maintaining the stand within an appropriate structural range. When stand density, canopy closure, and NDVI exceeded certain levels, RMSD values tended to increase, whereas DBH showed a more complex interval-dependent response. Particular ranges of stand age, stand density, DBH, and low-intensity harvesting were more conducive to reducing RMSD and maintaining lower RMSD values and a higher degree of correspondence between the two indicators. These results suggest that plantation management should not simply pursue high density, high canopy closure, or high harvesting intensity, but should instead adopt threshold-based management tailored to age class, density level, and harvest intensity. Studies in *Cunninghamia lanceolata* plantations have likewise shown that optimizing age structure and harvest timing can simultaneously increase carbon storage and wood production [9]. Overall, management strategies intended to maintain both tree-layer carbon sequestration rate and wood productivity should be centered on stand structural optimization, with controlled low-intensity harvesting, replanting-based recovery, and threshold-based regulation serving as the main management pathways. For *P. massoniana* plantations, future practices should prioritize light harvesting, appropriate replanting, and rational control of stand density and canopy closure, combined with differentiated regulation across stand developmental stages, to avoid increases in RMSD associated with excessive harvesting and structural imbalance. This approach may enhance the combined benefits of wood production and carbon sequestration while providing an operational basis for adaptive plantation management under China's "dual-carbon" goals.

4.4. Limitations and Future Perspectives

This study used changes between two consecutive inventory periods of fixed plots as the basic analytical unit. Consequently, observations originating from the same plot could appear in multiple inventory intervals, resulting in a repeated-observation structure. To reduce potential bias arising from within-plot dependence, plot identity was incorporated as a random effect in the LMM and pSEM analyses, and GroupKFold cross-validation based on plot identity was used in the XGBoost-SHAP analysis. Nevertheless, the temporal resolution of the National Forest Inventory data remains relatively coarse and may limit the detection of short-term responses to management interventions. Therefore, the observed relationships should be interpreted primarily as long-term patterns and associations rather than strict causal effects.

Moreover, the climate and soil variables used in this study were derived from regional datasets with a spatial resolution of 1 km and subsequently linked to National Forest Inventory plots. Although these datasets provide consistent environmental information at large spatial scales, they may not fully capture fine-scale heterogeneity in microclimate, soil properties, and site conditions surrounding individual plots. This spatial-scale mismatch may introduce uncertainty into the estimation of environmental effects and may partly explain the relatively weak associations of climate and soil variables observed in the pSEM results. Future studies integrating higher-resolution environmental datasets with field-based measurements would improve the characterization of local site conditions and reduce uncertainty associated with spatial-scale mismatches.

In addition, this study focused on tree-layer carbon sequestration rate and did not explicitly incorporate other key components of the forest carbon balance, including litter, soil carbon pools, deadwood, and harvested wood products. Although tree-layer carbon is the most responsive component to management interventions, excluding these pools may underestimate the overall climate-mitigation potential of plantation ecosystems. Future studies integrating ecosystem-level carbon dynamics would provide a more comprehensive evaluation of forest management effects on carbon sequestration. The relationship between wood productivity and tree-layer carbon sequestration rate was quantified using the RMSD metric derived from standardized values of both functions. While RMSD provides an intuitive measure of functional imbalance, the two functions partly share stock-change components in their calculations. This shared accounting may amplify the apparent positive association and thus influence the estimated degree of functional coordination. Accordingly, RMSD should be considered primarily as an indicator of the degree of coordination between the two functions rather than as a direct measure of ecological functional divergence. Similarly, both the pSEM pathways involving RMSD and the observed low-imbalance or potentially coordinated relationship should be interpreted with caution, because part of the observed association may arise from methodological dependence rather than purely ecological mechanisms. Future studies should aim to separately quantify biomass carbon increment, harvested wood carbon, deadwood carbon transfer, and harvested timber yield to better evaluate whether the observed functional coordination reflects true ecological coordination or shared accounting components.

Finally, although the XGBoost-SHAP framework demonstrated satisfactory predictive performance and effectively identified key drivers and threshold responses, the robustness and generality of the identified thresholds require further validation using independent datasets, longer monitoring periods, and a broader range of plantation types. Such efforts would improve confidence in the proposed management recommendations and support the broader application of threshold-based management approaches across plantation ecosystems.

5. Conclusions

Using fixed-plot data from three consecutive National Forest Inventory periods, this study quantified variation in tree-layer carbon sequestration rate and wood productivity, the degree of coordination between these two functions, in *P. massoniana* plantations under forest management. The results showed that the two functions generally exhibited low RMSD values, indicating a high degree of coordination. However, this relationship was conditional, varying across stand developmental stages and management regimes. Stand structure was the dominant driver of variation, while management practices influenced the strength of coordination primarily through their effects on stand density and diameter structure. Key drivers displayed clear threshold responses, suggesting that coordinated enhancement of wood productivity and carbon sequestration depends on maintaining stands within favorable structural and management ranges rather than continuously increasing any single factor. Specifically, low harvesting intensity, combined with appropriate ranges of stand density, DBH, and stand age, was most conducive to reducing RMSD and maintaining strong coordination with low functional divergence. Although these findings should be interpreted with caution due to the repeated-observation structure of the inventory dataset and the limitations of RMSD-based metrics, the identified drivers and thresholds provide quantitative guidance for balancing timber production and carbon sequestration. Overall, these results support the development of adaptive forest management strategies that aim to simultaneously enhance wood productivity and carbon sink function.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f17070765/s1>.

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Appendix A. Definition and Classification of Harvest and Replanting Intensity Levels

Data Processing Procedure

Using the volume and tally type of each tree recorded in the individual-tree database, we identified whether forest management had occurred in each plot between two consecutive National Forest Inventory periods and classified the corresponding management type. Tree-layer carbon stocks were then estimated separately for live standing trees, harvested trees, standing dead trees, and replanted trees in each plot and inventory period. According to the Forest Tending Regulations issued by the National Forestry and Grassland Administration of China (GB/T 15781–2015), standing-volume harvest intensity was used

to characterize the harvesting intensity of plantation management and was calculated as follows (Equation (A1)).

$$\text{Cut_intensity} = V/M \quad (\text{A1})$$

In this equation, Cut_intensity denotes the standing-volume harvest intensity of a given plot; V denotes the total volume of all harvested trees within the plot (m^3); and M denotes the total stand volume before harvesting within the plot (m^3). The theoretical value of standing-volume harvest intensity ranges from 0 to 1, with higher values indicating greater harvesting intensity. Based on previous studies [24,25], standing-volume harvest intensity was divided into three classes: high (>0.30), medium ($0.15\text{--}0.30$), and low (<0.15).

Similarly, by referring to the calculation method of standing-volume harvest intensity, standing-volume replanting intensity was used to characterize the intensity of replanting management in plantations and was calculated as follows (Equation (A2)).

$$\text{Plan_intensity} = M_1/M_2 \quad (\text{A2})$$

In this equation, Plan_intensity represents the standing-volume replanting intensity of the plot; M_1 is the sum of the volume of all replanted trees within the plot (m^3); and M_2 is the total stand volume after replanting within the plot (m^3). The theoretical range of standing-volume replanting intensity is 0–1, with values closer to 1 indicating higher replanting intensity. Referring to the classification method for standing-volume harvest intensity, standing-volume replanting intensity was classified into three levels: high (>0.30), medium ($0.15\text{--}0.30$), and low (<0.15).

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