

Evaluating Biomass and Carbon Stock Responses to Thinning and Pruning in Mature *Larix principis-rupprechtii* Stands: A Case Study from Northern China

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Abstract

Forestry management operations significantly influence biomass accumulation and carbon sequestration, essential factors for climate change mitigation. The study focuses on the 50-year-age *Larix principis-rupprechtii* Mayr plantations at Saihanba Mechanical Forest Farm, Northern China, assessing how varying intensities of thinning and pruning influence biomass and carbon stocks. The experimental design included 45 plots subjected to 15 treatments having a combination with five thinning (T0:0%, T1:10%, T2: 20%, T3: 30%, T4: 35%) and three pruning intensity levels (P0: 1:2, P1: 1:3, P2: 2:3), with comprehensive assessments of aboveground biomass (AGB), belowground biomass (BGB) and Total Biomass. The statistical significance of differences between treatment groups was assessed using Analysis of Variance (ANOVA). Regression analysis was used to explore the relationships between silvicultural treatment intensities and forest growth responses. This involved fitting linear models to predict forest metrics (dependent variables) from treatment intensities (independent variables). Results indicate an apparent reduction in AGB, BGB, and total biomass with increasing thinning intensity, showing a decrease in AGB and BGB by up to 42.13% and 42.57% compared to the control treatment. The percentage decrease in total biomass from the control treatment, T0P0, to the most intensive treatment, T4P2, is approximately 42.44%. The percentage decrease in total carbon over the same treatments is about 44.18%. The soil organic carbon (SOC) decreased by 35.56% compared to the control treatment. Pruning influences tree structure and health. The findings highlight the complex interactions between forest management practices and carbon dynamics. They underscore the adoption of light, moderate thinning, and light, pruning strategies, which can sustain the forest's carbon sequestration capabilities while maintaining forest health and productivity. This study provides empirical evidence to guide future forest management decisions, emphasizing the critical balance needed to maximize forest health and carbon sequestration potential.

Keywords: Forest management, biomass, carbon stocks, thinning intensity, pruning, *L. principis-rupprechtii*, climate change mitigation, carbon sequestration.

1. Introduction

The main factor of global warming is recognized to be a rapid increase in greenhouse gases, primarily carbon dioxide (CO₂) (Barzagli & Mani, 2019). Therefore, under the Kyoto Protocol and the Paris Agreement, decreasing the amount of CO₂ in the atmosphere is an essential issue for nations; photosynthesis allows trees to sequester carbon (Nunes et al., 2020; Ussiri & Lal, 2017). Forests act as necessary carbon sinks because they are crucial in the terrestrial ecosystems' carbon cycles (Keenan & Williams, 2018; Sha et al., 2022). The Kyoto Protocol's Articles 3.3 and 3.4 recognize the

potential role of forests in reducing climate change. They state that forest carbon sequestration—primarily through reforestation and afforestation—is a crucial method for reducing carbon emissions at the local, regional, national, and even global levels (Dar et al., 2020).

Many nations and areas have committed to achieving carbon neutrality within specific time frames to minimize CO₂ emissions. China committed to achieving carbon neutrality by 2060, and 66 other parties committed to achieving net-zero emissions at the September 2019 United Nations Climate Action Summit (Action, 2020). Since the 1970s, China has implemented extensive afforestation and reforestation projects that protect the ecological environment. China currently holds the top rank in the world for the largest area of plantation forests, with an increase in forest area from 12.7% in early 1970 to 21.6% in 2013; China's forests are responding well to the world's effort to neutralize carbon emissions (Cheng et al., 2023; Vista et al., 2016).

The most common way of manipulating plantation growth among forest management techniques is thinning (Gabira et al., 2023; Ruiz-Peinado et al., 2017). By improving stand vigor and reducing competition among the surviving trees, thinning can increase volume growth for commercial reasons (Vernon et al., 2018). Thus, it can raise the harvest value by making the timber more marketable in size, quantity, and quality (Putz & Romero, 2015). Benefits of thinning include: (1) removing weak, disease- and insect-susceptible, and undesired tree phenotypes can improve forest health by reducing tree mortality (2) Improving stand density can increase pest resistance and stand vigor (3) improving biodiversity by adjusting tree growth to redistribute site components (J.-C. Lin et al., 2018a). Both at the individual tree and stand levels, thinning influences tree growth. Additional research proved that thinning can promote the growth of stands (Alm, 2019; Mäkinen et al., 2021). Thinning also affects respiration and tree biomass loss, which changes the carbon dynamics in forests. Because of the years-long removal of aboveground trees changes how organic matter decomposes in soil (Fekadu Hailu et al., 2021). It creates spaces for the remaining trees, and thinning is a helpful treatment technique to improve the light environment in forests. Past studies on increasing light intensity showed that thinning promotes reproduction (Lu et al., 2018; Matsushita et al., 2022). Cone formation in larch orchards is well correlated with increases in light intensity (Li et al., 2021). However after the thinning, the remaining trees grow bigger and have larger crowns (Dobner et al., 2019; Gonçalves, 2021). Allowing the spaces between crowns to fill up following thinning frequently (Juchheim et al., 2017; Pretzsch, 2014). Forest trees are pruned to produce veneer logs and timber free of knots, which increases the plantation's value. Although pruning can impact growth in both height and diameter, these effects are frequently limited and temporary (Dufour, 2019; Lewark, 2022). Pruning can instantly improve light usage proficiency and even increase photosynthetic rates in the maintained upper canopy because low-intensity pruning eliminates the crown's lowest and relatively inefficient regions (Forrester et al., 2012, 2013). Along with the degree of defoliation, other factors that vary depending on the site include the time of pruning and how stand density reacts to it (Lisboa et al., 2014). Pruning has less of an impact on good sites than on poor sites (Montagu et al., 2003; Viquez & Pérez, 2005).

The primary source of carbon in the global cycle is biomass from forests. When forests are preserved, they serve as a sink for carbon and a source of when they are burned. (Joshi & Singh, 2020). An increase in forest cover is required to improve carbon sinks and slow down global warming, especially in areas with low forest cover and increasing populations

(Kay et al., 2019). An accurate assessment of carbon sources and sinks is necessary for the growth of the global carbon market (Olivier & Berdowski, 2021). While the fact that trees are carbon sinks, estimating their potential is filled with uncertainty (Yanai et al., 2020). Converting field data of tree height, basal area, and diameter at 1.3 m height (DBH) to biomass is the primary uncertainty (Khan et al., 2020). A vital phase in estimating biomass from field-based measurements is the use of biomass equations. These equations are based on a dimensional analysis called allometry, a functional relationship between tree or forest stand estimating one or more predictable variables like DBH, height, and basal area (Daba & Soromessa, 2019). The distribution of biomass among aboveground components, like leaves, branches, and stems, and below-ground components, such coarse roots, the tissue carbon content of leaves, stems, and roots, the total number of trees, and stand basal area, all affect total forest carbon (Forest et al., 2018; Siddiq et al., 2021). Large basal areas in dense forests store more carbon than young, scattered forests (Lázaro-Lobo et al., 2023).

Because of its strong environmental adaptation and the significance and performance of its wood, Warm temperate subalpine regions are ideal for the growth and spread of larch (*L. principis-rupprechtii* Mayr), one of the primary afforestation tree species in northern China with significant social, economic, and ecological importance. Trees are essential carbon sinks (Giweta, 2020; Krueger et al., 2017; Tebeje, 2020). To study stand structure and function, precise estimates of *Larix principis-rupprechtii* biomass are essential to reach the target of neutralizing global carbon and reducing its peak. Evaluation of its potential for production on the effects of and adaptation to climate change (Dong et al., 2022; Hao et al., 2024; Yuan et al., 2023). We investigated the influence of thinning and pruning intensities on several components of biomass and carbon storage in larch stands at the Saihanba Mechanical Forest Farm in Chengde City, Hebei Province, China. We hypothesized that more intensive thinning and pruning would reduce biomass and carbon stocks in *L. p-r* plantations at varying elevations, aspects, and slopes. Besides that, this study aimed to understand whether elevation, aspect, and slope influence the growth parameters of trees, forest biomass, and carbon stock in the stands managed under different silvicultural intensities.

2. Materials and Methods

2.1. Location and Description of the Study Area

The study area included the Saihanba Mechanical Forest Farm located in Hebei Province, with coordinates (42°02′–42°36′ N and 116°51′–117°39′ E). This site falls within the warm temperate continental monsoon climate zone. The elevation ranges from 1600 to 1800 meters above sea level, with higher terrain in the north compared to the south. The landscape primarily consists of mountains and plateaus. The average annual temperature varies from -43.3°C to 33.4°C, with a mean temperature of -1.2°C. The region experiences an annual evaporation of 1,388 mm and precipitation of 452.2 mm. Common soil types include aeolian sandy soil, meadow soil, brown soil, and grey forest soil. The forest farm covers a total area of 94,000 hectares, with 73,333 hectares dedicated to forest land, of this, 57,333 hectares are artificial forests and 16,000 hectares are natural forests. The forest farm has an impressive average annual growth rate of 9.7%, with a total forest volume of 5.025 million m³ and a forest covering rate of 80%. The primary vegetation includes mixed coniferous and broad-leaved forests, grasslands, meadows, shrub and broad-leaved forests. Dominant tree species are *Larix principis-rupprechtii* Mayr., *Picea asperata* Mast., and *Betula platyphylla* Suk. Key shrub species include *Syringa oblata* Lindl. var. *alba* Rehder, *Rhododendron micranthum* Turcz and *Sambucus williamsii* Hance. The main herbaceous plants are *Menyanthes trifoliata* L. and *Galium verum* L. (Tao et al., 2023; Xu et al., 2022).

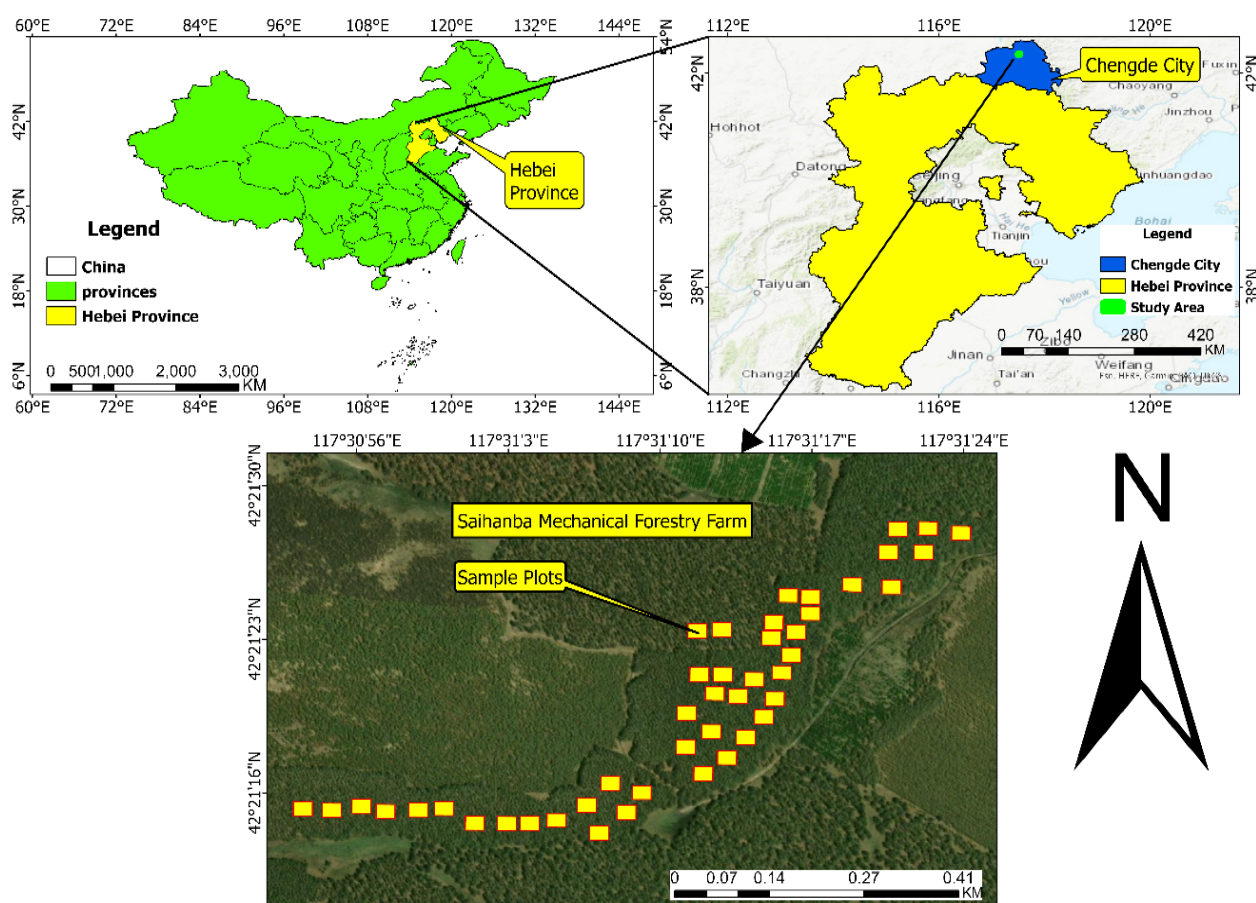


Figure 1. Geographical Distribution of Study Site, Saihanba Mechanical Forest Farm, Chengde City, Hebei Province, China

2.2. Field Sampling

The *Larix principis-rupprechtii* plantation was used for the silvicultural operations (thinning and pruning) experiment in June 2010. All thinning was done selectively before the trial's establishment, removing any smaller or deformed stems. Initially, the *L. principis-rupprechtii* plantation was subjected to different treatments: five thinning intensities (T0 - control thinning, intensity 0%, T1 - light thinning, intensity 10%, T2 - moderate thinning, intensity 20%, T3 - heavy thinning, intensity 30%, T4 - extreme heavy thinning, intensity 35%) and three pruning's Intensities (P0 -

control pruning, intensity (1:2), P1: light pruning, intensity (1:3), P2: high pruning, intensity (2:3)). The purpose of the thinning operation was to selectively thin (based on intensity level) to decrease the number of stems/ha. At the same time, the objective of the pruning operation was to reduce the tree's middle crown branches (based on the level of intensity). In August 2023, after a comprehensive survey of the site, 45 sample plots (20 m × 20 m area of each plot) were set up; in 2023, the forest age was 50 years. The Plantation was subjected to 45 plots with fifteen silvicultural treatments, including five thinning intensities (T0, T1, T2, T3, T4) with the combination of three pruning intensities (P0, P1, P2) (Figure 2).

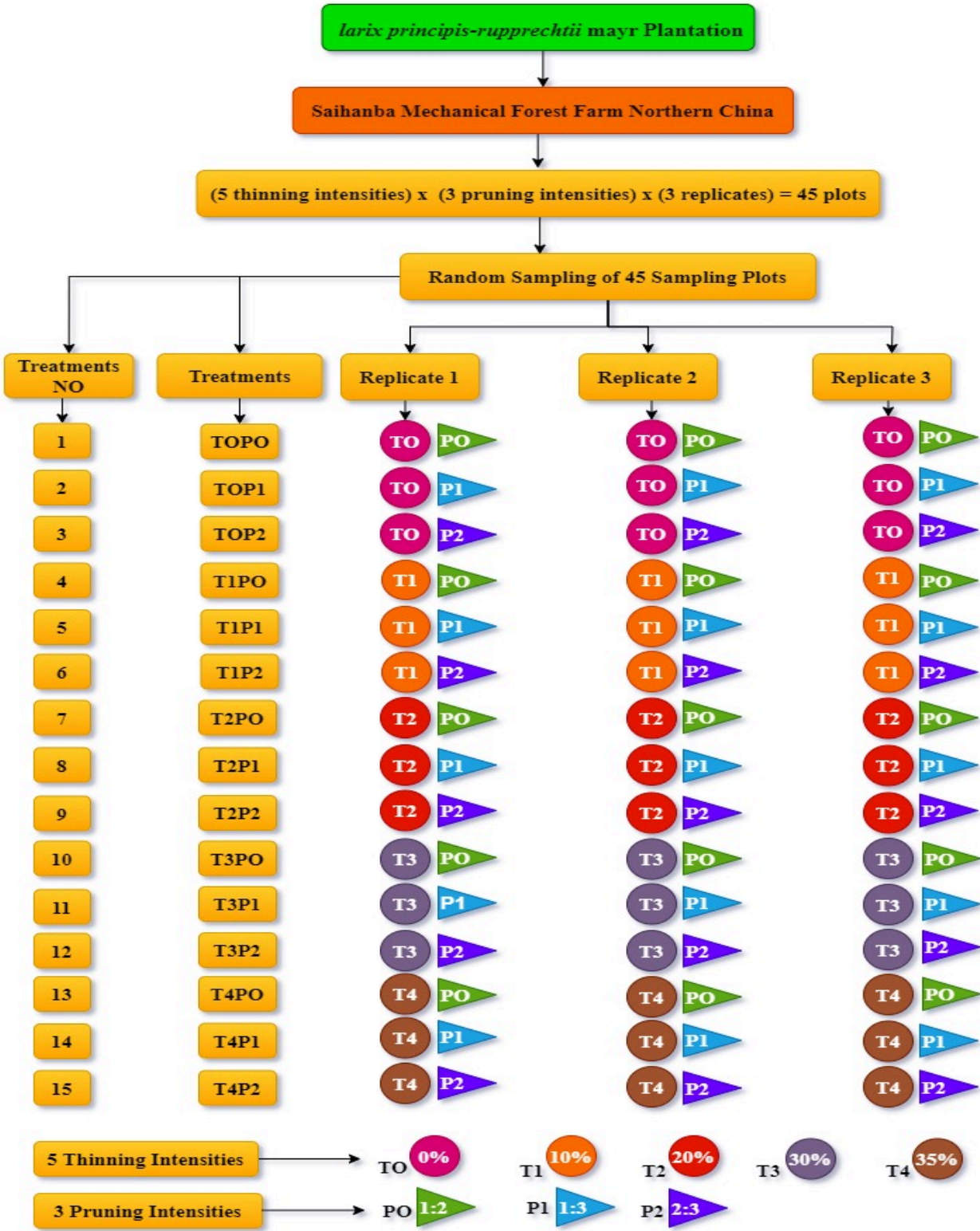


Figure 2. The methodological layout of the sampling plots in Stands of 50-Year-Age of *Larix principis-rupprechtii* Mayr Plantation. The thinning operation was intended to reduce the number of stems/ha by selective thinning (depending upon intensity level), whereas the pruning operation was intended to lower the middle crown branches of the individual tree (depending upon intensity level).

2.3. Data Collection

The coordinates of each tree and plot were recorded using Real-Time Kinematic (RTK). For analysis, we recorded each plot's elevation, aspect, and slope as well as its height (m), stem density (tree/ha), and the diameter at breast height (DBH), which is standard at 1.3 meters above the ground, was measured for each tree using a calibrated diameter tape and caliper at the breast height of the trees. Stem density in each plot was measured by counting the tree number. Tree heights were measured using Reliscope (Song et al., 2021). Soil samples were collected with a soil auger from the upper 20-cm layer to determine SOC (Couwenberg, 2011; Stolbovoy et al., 2005). The collected Soil samples were placed in plastic bags, dried in air, and sent to a laboratory for further analysis. This study's systematic procedure was designed to quantify some key forestry metrics necessary to define the carbon dynamics and the forest ecosystem's structural stability. The first step within the methodology quantifies stem density. Stem density is calculated by physically counting the number of stems in the plot. It accurately calculates the number of trees in a one-hectare area, as shown in (equation 1).

$$\text{Density} \left(\frac{\text{Stems}}{\text{ha}} \right) = \left(\frac{n \times 100000}{\text{Area (m}^2\text{)}} \right) \quad (1)$$

Where n: represents stem number counted in a plot. Area (m²): The area over which the stems are counted, expressed in square meters. 100,000: This factor converts the area from square meters to hectares, as 1 hectare equals 10,000 square meters. The basal area is calculated. It measures the cross-sectional area expended by the trees on the plot. Therefore, it can be determined by the (equation 2).

$$\text{BA} = \left(\frac{\text{DBH}}{200} \right)^2 \times \pi \times \text{Stand Density} \quad (2)$$

Where BA = tree basal area (m²), r = radius (cm)

The tree volume, a crucial parameter for estimating biomass, is then determined from the basal area. It uses the tree height and a predefined volume form factor, through (equation 3).

$$\text{Volume} = \text{Basal area} \times \text{Height} \times \text{Volume form factor (0.48)} \quad (3)$$

Basal Area (BA): This refers to the cross-sectional area of a tree trunk at breast height (usually 1.3 meters above ground level). Height: The tree's height from the ground to its highest point. Volume Form Factor (VFF): This is a constant value that represents the relationship between the actual volume of a tree and its basal area and height. In this case, the VFF is given as 0.48.

To measure total biomass distribution, use allometric equations of all tree elements, such as stem, branches, leaves, and roots. It allows for precise calculations of the distribution of above and below-ground biomass (Zhao et al., 2016; Zhao Kuangji et al., 2016). To estimate the AGC and BGC amount, the obtained AGB and BGB values were multiplied by 0.5, assuming that the total amount of aboveground and belowground biomass had a 50% carbon content (Aye et al., 2022; Eshetu & Hailu, 2020). The amount of organic carbon in the soil was determined by applying an external heating and oxidation technique with potassium dichromate-concentrated sulfuric acid. (equation 4).

$$\text{Soil organic carbon (g/kg)} = \frac{5c(V_0 - V) \times 3 \times 1.1}{mV_0} \quad (4)$$

Here, c represents the concentration of the 1/6 potassium dichromate solution, 0.8 mol/L. The number 5 indicates the volume, in milliliters, of the potassium dichromate solution added. V₀ is the volume of ferrous sulfate used in the

blank titration, also measured in milliliters. V denotes the volume of ferrous sulfate used in the sample titration, in milliliters. The value 3 corresponds to $1/4$ of the molar mass of a carbon atom, expressed in grams per mole. Factor 1.1 is the oxidation correction coefficient. Finally, m is the mass of the soil sample, measured in grams. Three replicates of soil samples were used in this experiment.

2.4. Statistical Analysis

The analysis was performed using the Shapiro-Wilk test for normality and Levene's test for homogeneity of variances. Initially, we conducted descriptive statistics to summarize and describe the essential characteristics of our data. We computed all forest metrics' mean and standard deviation for every treatment, such as DBH, tree height, and stem density. We conducted inferential statistics using two-way ANOVA to test whether the differences between the treatments were significant. The significance of all parameters was obtained from Tukey HSD posthoc tests. This method was critical in testing the null hypothesis of no significant difference among the groups' means. We reported ANOVA results with F-values and their corresponding P-values to investigate whether variations in forest metrics such as basal area, volume, and biomass were affected by treatment.

Moreover, a regression analysis was performed to predict forest metrics based on the different estimates. These linear regression models predict the dependent variables using independent variables. Regression coefficients, P-value, and the R-squared value are used to quantify the proportion of variance in forest metrics attributable to treatment effects and explain the variability.

This analysis used RStudio 4.3.2 and several essential libraries to handle data, create visualizations, and perform statistical analyses. The ggplot2 library makes detailed and customizable plots easier to visualize data. With dplyr, could efficiently manipulate and prepare the data for analysis. For statistical comparisons, used the multcomp library to perform multiple comparisons and multcompView to visualize the results. To present multiple plots together, relied on gridExtra and cowplot. These tools helped arrange and align the plots, ensuring they were clear and visually appealing. Additionally, the grid library provided the flexibility to fine-tune and customize the plots of graphical elements. Together, these libraries made data analysis and visual presentations clear and professional.

3. Results

3.1. Treatments-Wise Stand Metrics

The control treatment, T0P0, had (942 ± 30 trees/ha); the most severe Treatment, T4P2, had (483 ± 22 trees/ha). Hence, tree density decreased with increasing treatment intensities. DBH and height values show an increase in individual tree growth; with higher intensity treatments, T4P2 has the highest average DBH (26.25 ± 0.18 cm) and height values (19.45 ± 0.53 m). Basal area and volume equally fluctuated with treatment. The T0P0 treatment exhibited the lowest basal area (0.47 ± 0.03 m²) and volume (8.50 ± 0.42 m³), respectively. In contrast, the highest values were recorded in the T3P2 treatment, with a basal area of (0.57 ± 0.03 m²) and a volume of (11.82 ± 0.89 m³) (table 1).

Table 1. Treatments-Wise Stand Metrics ($\pm$ SE)

3.2. Treatment-Wise Analysis of Total Biomass and Total Carbon

Different treatments had varying levels of AGB, BGB, T. Biomass, AGC, BGC, and T. carbon, with a decrease in these parameters as the Forest management treatment intensities increased. Thus, in the control treatment (T0P0), the AGB was 9.78 Mg/ha and BGB was 3.50 Mg/ha. Additionally, the total biomass amounted to 13.29 Mg/ha, and the total carbon content was 6.70 Mg/ha, all of which were higher compared to the other treatments. When compared the T4P2 treatment, which had the highest level of treatment intensity, had the lowest levels of AGB (5.65 Mg/ha), BGB (2.01 Mg/ha), as well as total biomass (7.65 Mg/ha) and total carbon was at (3.74/ Mg/ha). Soil carbon content also showed variability, with the highest recorded in the control treatment, T0P0 (160.32 g/kg/t), and the lowest in the T4P2 treatment (103.33 g/kg/t).

Treatments	Density (trees/ha)	Mean DBH (cm)	Mean Height (m)	Basal area (m ² /ha)	Volume (m ³ /ha)
T0P0	942 ± 30	23.43 ± 0.42	18.84 ± 0.33	0.47 ± 0.03	8.50 ± 0.42
T0P1	858 ± 8	25.33 ± 0.4	19.22 ± 0.1	0.52 ± 0.02	10.14 ± 0.28
T0P2	808 ± 36	24.65 ± 0.66	19.06 ± 0.01	0.49 ± 0.02	9.43 ± 0.47
T1P0	808 ± 65	25.12 ± 0.84	18.79 ± 0.85	0.51 ± 0.03	9.71 ± 1.05
T1P1	758 ± 60	25.10 ± 0.34	18.46 ± 0.50	0.50 ± 0.01	9.34 ± 0.49
T1P2	725 ± 29	24.93 ± 0.29	19.01 ± 0.13	0.50 ± 0.01	9.60 ± 0.19
T2P0	700 ± 52	25.91 ± 0.21	19.00 ± 0.64	0.54 ± 0.01	10.34 ± 0.36
T2P1	667 ± 22	24.37 ± 0.72	20.09 ± 0.14	0.50 ± 0.02	10.19 ± 0.53
T2P2	658 ± 17	25.20 ± 0.43	19.19 ± 0.13	0.51 ± 0.02	9.89 ± 0.41
T3P0	625 ± 14	26.00 ± 1.00	19.90 ± 0.35	0.54 ± 0.04	10.94 ± 0.93
T3P1	542 ± 42	26.50 ± 1.36	20.03 ± 0.42	0.56 ± 0.06	11.36 ± 1.33
T3P2	525 ± 25	26.69 ± 0.62	20.22 ± 0.61	0.57 ± 0.03	11.82 ± 0.89
T4P0	558 ± 44	26.07 ± 0.59	20.24 ± 0.36	0.54 ± 0.03	11.14 ± 0.79
T4P1	492 ± 8	25.96 ± 1.07	19.84 ± 0.90	0.54 ± 0.04	10.91 ± 1.38
T4P2	483 ± 22	26.25 ± 0.18	19.45 ± 0.53	0.55 ± 0.06	10.83 ± 0.37
Total	10149				154.14

The findings demonstrate forest management operations' significant impact on biomass production and carbon sequestration. Moreover, the decrease in biomass and carbon stock was observed with an increased Silvicultural operation intensity (table 2).

3.2.1. Annual Loss of Total Biomass and Total Carbon

The result showed a progressive decline in various biomass and carbon stocks from (2010 to 2023). The annual decrease in AGB was estimated at 0.25 Mg/ha while BGB showed a consistent annual reduction of 0.095 Mg/ha. These findings collectively indicate a consistent downward trend in total biomass, with an average annual decrease of total biomass of 0.35 Mg/ha. Similarly, analyses of carbon content demonstrated an annual decline in both AGC and BGC by 0.13 Mg/ha) and 0.049 Mg/ha, contributing to an overall yearly decrease in total carbon of 0.18 Mg/ha. Soil carbon content showed a more annual decrease of 2.15 g/kg/t. These results highlight the ecological severe impact of ongoing environmental pressures. The decline in biomass and carbon stocks means that the ecosystem's ability to capture and store

carbon is weakening, which could degrade the effects of climate change. Additionally, the loss of biomass affects biodiversity, soil health, and the overall resilience of the forest. These findings emphasize the urgent need for strategies to protect and improve ecosystem health and increase carbon sequestration. Addressing these declines through adaptive forest management practices is crucial to maintaining ecological balance and supporting efforts to mitigate climate change.

Table 2. Treatment-Wise Total Biomass and Total Carbon ($\pm$ SE)

Treatments	AGB (Mg/ha)	BGB (Mg/ha)	T. Biomass (Mg/ha)	AGC (Mg/ha)	BGC (Mg/ha)	T. Carbon (Mg/ha)	Soil Carbon (g/kg)/t
T0P0	9.78 $\pm$ 0.28	3.50 $\pm$ 0.11	13.29	4.94 $\pm$ 0.10	1.77 $\pm$ 0.04	6.70	160.32 $\pm$ 1.56
T0P1	9.55 $\pm$ 0.10	3.37 $\pm$ 0.03	12.92	4.78 $\pm$ 0.05	1.68 $\pm$ 0.02	6.46	131.21 $\pm$ 6.61
T0P2	8.81 $\pm$ 0.23	3.12 $\pm$ 0.10	11.94	4.41 $\pm$ 0.11	1.56 $\pm$ 0.05	5.97	125.95 $\pm$ 6.65
T1P0	8.88 $\pm$ 0.71	3.14 $\pm$ 0.25	12.02	4.44 $\pm$ 0.35	1.57 $\pm$ 0.12	6.01	152.73 $\pm$ 0.93
T1P1	8.31 $\pm$ 0.57	2.94 $\pm$ 0.21	11.25	4.15 $\pm$ 0.29	1.47 $\pm$ 0.10	5.63	125.83 $\pm$ 4.07
T1P2	8.15 $\pm$ 0.28	2.88 $\pm$ 0.10	11.04	4.03 $\pm$ 0.10	1.43 $\pm$ 0.04	5.46	121.10 $\pm$ 4.16
T2P0	7.91 $\pm$ 0.63	2.78 $\pm$ 0.22	10.69	3.96 $\pm$ 0.32	1.39 $\pm$ 0.11	5.34	145.03 $\pm$ 7.39
T2P1	7.47 $\pm$ 0.20	2.63 $\pm$ 0.07	10.10	3.73 $\pm$ 0.10	1.31 $\pm$ 0.04	5.05	119.70 $\pm$ 0.62
T2P2	7.32 $\pm$ 0.28	2.58 $\pm$ 0.09	9.91	3.66 $\pm$ 0.14	1.29 $\pm$ 0.05	4.95	114.05 $\pm$ 2.86
T3P0	7.16 $\pm$ 0.04	2.51 $\pm$ 0.02	9.67	3.58 $\pm$ 0.02	1.25 $\pm$ 0.01	4.83	135.91 $\pm$ 14.34
T3P1	6.32 $\pm$ 0.52	2.20 $\pm$ 0.18	8.52	3.16 $\pm$ 0.26	1.10 $\pm$ 0.09	4.26	115.41 $\pm$ 9.78
T3P2	6.14 $\pm$ 0.23	2.14 $\pm$ 0.08	8.28	3.07 $\pm$ 0.12	1.07 $\pm$ 0.04	4.14	108.73 $\pm$ 7.67
T4P0	6.48 $\pm$ 0.62	2.26 $\pm$ 0.21	8.75	3.24 $\pm$ 0.31	1.13 $\pm$ 0.10	4.37	132.31 $\pm$ 9.37
T4P1	5.64 $\pm$ 0.30	1.97 $\pm$ 0.09	7.61	2.82 $\pm$ 0.15	0.99 $\pm$ 0.04	3.80	109.01 $\pm$ 3.47
T4P2	5.65 $\pm$ 0.29	2.01 $\pm$ 0.06	7.65	2.77 $\pm$ 0.13	0.97 $\pm$ 0.05	3.74	103.33 $\pm$ 3.01
Total	113.57	40.03	153.64	56.74	19.98	76.71	1900.62

3.3. ANOVA Comparison of Thinning and Pruning Effects on Stand Metrics

The ANOVA was employed to assess the effects of thinning and pruning treatments on several key forest parameters such as DBH, Height, Basal Area, Volume, and Density. The results showed that thinning significantly influences all five parameters, whereas pruning only significantly affects tree density.

In the DBH variable, thinning showed a significant effect with an ($F = 4.693$, $P < 0.05$), indicating that thinning treatments significantly affected DBH. Conversely, pruning did not significantly affect DBH ($F = 0.183$, $P > 0.05$), suggesting that pruning does not contribute to changes in DBH. Regarding tree height, thinning again demonstrated a significant impact with an ($F = 5.896$, $P < 0.05$). This suggests that thinning treatments impact tree height. In contrast, pruning did not have a statistically significant effect on height ($F = 0.289$, $P > 0.05$). In terms of basal area, thinning showed a highly significant impact with an ($F = 7.637$, $P < 0.01$), indicating that thinning increases the basal area. Pruning did not significantly impact the basal area ($F = 0.164$, $P > 0.05$). The volume parameter also showed significant improvement due to thinning, with an ($F = 10.255$, $P < 0.01$), highlighting that thinning significantly impacts tree volume. Pruning did not considerably affect volume ($F = 0.408$, $P > 0.05$). For tree density, both thinning and pruning had significant effects. Thinning displayed a highly significant impact with an ($F = 197.90$, $P < 0.001$), indicating a strong effect on reducing tree density. Pruning also significantly affected density, although to a lesser extent, with an ($F = 31.25$,

P < 0.001) (table 3).

Table 3. ANOVA Comparison of Thinning and Pruning Effects on Stand Metrics

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

3.4. ANOVA Comparison of Thinning and Pruning Effects on Total Biomass

In the case of AGB, thinning treatments resulted in a highly significant, as indicated by an (F = 190.99, P < 0.001). This underscores the significant effect of thinning on AGB. Pruning also significantly impacted AGB, though to a lesser

Parameters	Treatment	df	Sum sq	Mean Sq	F value	P value	Significance
DBH	Thinning	4	7.545	1.8862	4.693	0.0303	*
	Pruning	2	0.147	0.0734	0.183	0.8365	
	Residuals		3.215	0.4019			
Height	Thinning	4	3.498	0.8744	5.896	0.0164	*
	Pruning	2	0.086	0.0429	0.289	0.7563	
	Residuals	8	1.186	0.1483			
Basal Area	Thinning	4	0.009911	0.0024778	7.637	0.00774	**
	Pruning	2	0.000106	0.0000531	0.164	0.85172	
	Residuals	8	0.002596	0.0003245			
Volume	Thinning	4	9.182	2.2955	10.255	0.00308	**
	Pruning	2	0.182	0.0912	0.408	0.67832	
	Residuals	8	1.791	0.2238			
Density	Thinning	4	254704	63676	197.90	0.0000000497	***
	Pruning	2	20111	10056	31.25	0.000166	***
	Residuals	8	2574	322			

extent, with an (F = 29.46, P < 0.001). For BGB, the results were similar, with thinning showing a highly significant effect (F = 202.8, P < 0.001), suggesting a significant impact on BGB due to thinning treatment. Pruning also significantly impacted BGB, with an (F = 29.7, P < 0.001), although the effect was less than that of thinning. Total Biomass was significantly affected by thinning, with an (F = 196.79, P < 0.001), indicating that thinning treatments lead to a considerable impact on total biomass. Pruning also significantly influenced total Biomass, as evidenced by an (F = 29.94, P < 0.001). While pruning's impact was significant, it was comparatively less than that of thinning.

In conclusion, the ANOVA results highlight the significant effects of both thinning and pruning on forest biomass parameters, with thinning having a more extensive impact across AGB, BGB, and Total Biomass. These findings underscore the critical role of thinning in forest management practices. Although pruning contributes significantly to biomass, its effects are relatively less noticeable (table 4).

Table 4. ANOVA Comparison of Thinning and Pruning Effects on Total Biomass

Parameters	Treatment	DF	Sum sq	Mean Sq	F value	P Value	Significance
AGB	Thinning	4	23.505	5.876	190.99	0.0000000572	***
	Pruning	2	1.813	0.906	29.46	0.000204	***

	Residuals	8	0.246	0.031			
BGB	Thinning	4	3.1113	0.7778	202.8	0.0000000451	***
	Pruning	2	0.2279	0.1139	29.7	0.000198	***
	Residuals	8	0.0307	0.0038			
Total Biomass	Thinning	4	43.72	10.929	196.79	5.08e-08	***
	Pruning	2	3.33	1.663	29.94	0.000193	***
	Residuals	8	0.44	0.056			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

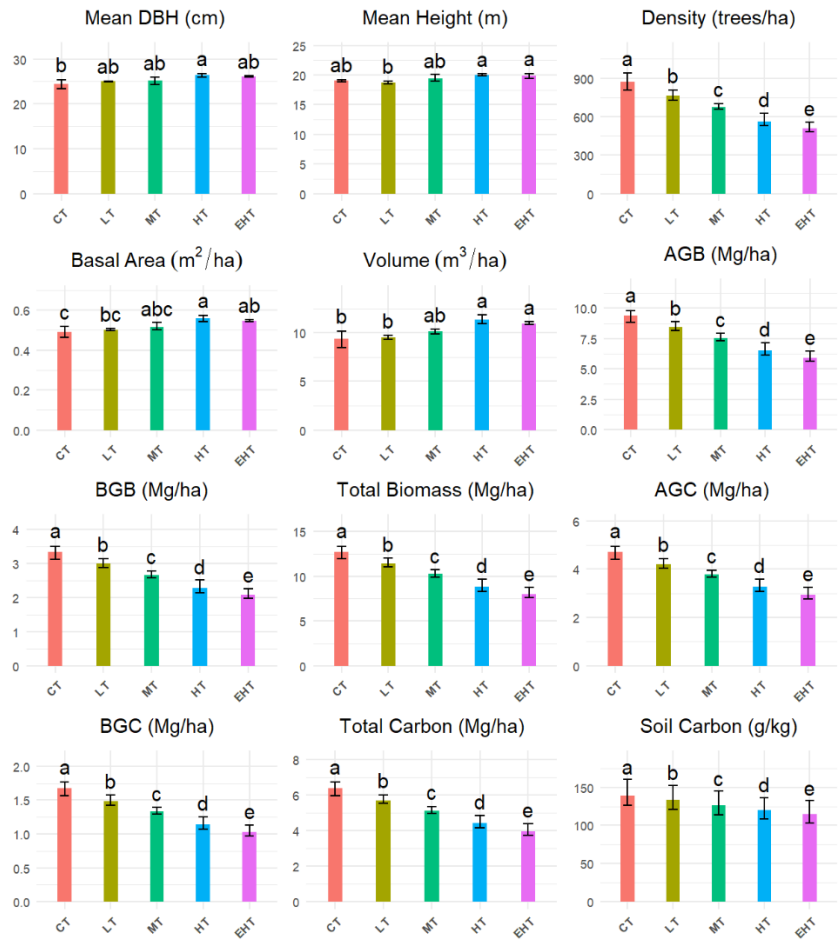
3.5. ANOVA Comparison of Thinning and Pruning Effects on Total Carbon

The ANOVA was performed to evaluate the effects of thinning and pruning on AGC, BGC, Total Carbon, and SOC within forest stands. The results indicate that thinning and pruning significantly impact these carbon pools, with thinning generally showing a more extensive effect. Thinning significantly affects AGC ($F = 222.75$, $P < 0.001$) and BGC ($F = 250.90$, $P < 0.001$), reflecting a significant impact on carbon storage of above and below-ground carbon. Pruning also had an important but comparatively lesser effect on AGC ($F = 37.83$, $P < 0.001$) and BGC ($F = 41.31$, $P < 0.001$). For Total Carbon, thinning demonstrated a highly significant influence ($F = 232.26$, $P < 0.001$), while pruning also significantly contributed ($F = 39.12$, $P < 0.001$), although to a lesser degree. SOC was greatly affected by both treatments, with pruning showing a powerful effect ($F = 421.70$, $P < 0.001$) compared to thinning ($F = 90.92$, $P < 0.001$). These findings underscore the importance of thinning in enhancing overall carbon sequestration in forest ecosystems, while also highlighting the significant role of pruning in increasing soil organic carbon. The minimal residual variability across all parameters further validates the strength of the treatments' effects. This study suggests that strategic implementation of thinning and pruning can optimize carbon storage and contribute to effective forest management practices to mitigate climate change (table 5).

Table 5. ANOVA Comparison of Thinning and Pruning Effects on Total Carbon

Parameters	Treatment	df	Sum sq	Mean Sq	F value	P value	Significance
AGC	Thinning	4	5.999	1.4998	222.75	0.0000000311	***
	Pruning	2	0.509	0.2547	37.83	0.0000836039	***
	Residuals	8	0.054	0.0067			
BGC	Thinning	4	0.8033	0.20084	250.90	0.0000000194	***
	Pruning	2	0.0661	0.03307	41.31	0.0000607317	***
	Residuals	8	0.0064	0.00080			
Total Carbon	Thinning	4	11.193	2.7983	232.26	2.64e-08	***
	Pruning	2	0.943	0.4713	39.12	7.41e-05	***
	Residuals	8	0.096	0.0120			
SOC	Thinning	4	1146.8	286.7	90.92	0.0000010549	***
	Pruning	2	2659.6	1329.8	421.70	0.0000000078	***
	Residuals	8	25.2	3.2			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1



Thinning Intensities

Figure 3. Stand characteristics of thinning intensities in Stands of 50-Year-Age of *Larix principis-rupprechtii* Mayr Plantation. Difference letters over bars are significantly different by Tukey HSD post-hoc tests test ($p = 0.05$). (CT; control thinning, LT; light thinning, MT; moderate thinning, HT; heavy thinning, EHT: extreme heavy thinning).

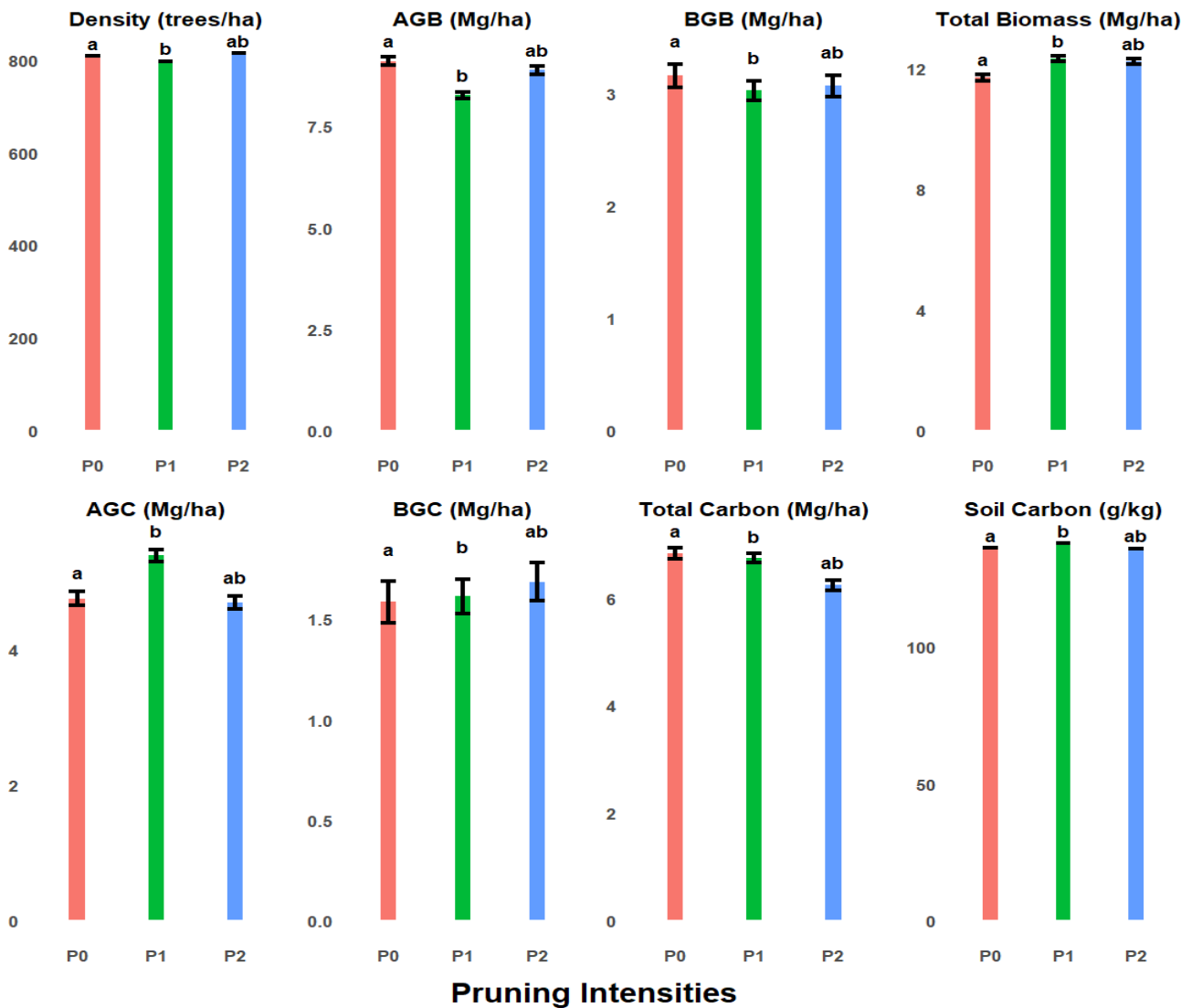


Figure 4. Stand characteristics of Pruning intensities in Stands of 50-Year-Age of *Larix principis-rupprechtii* Mayr Plantation. Difference letters over bars are significantly different by Tukey HSD post-hoc tests test ($p = 0.05$). (P0; control pruning, P1; Light pruning, P2; High pruning).

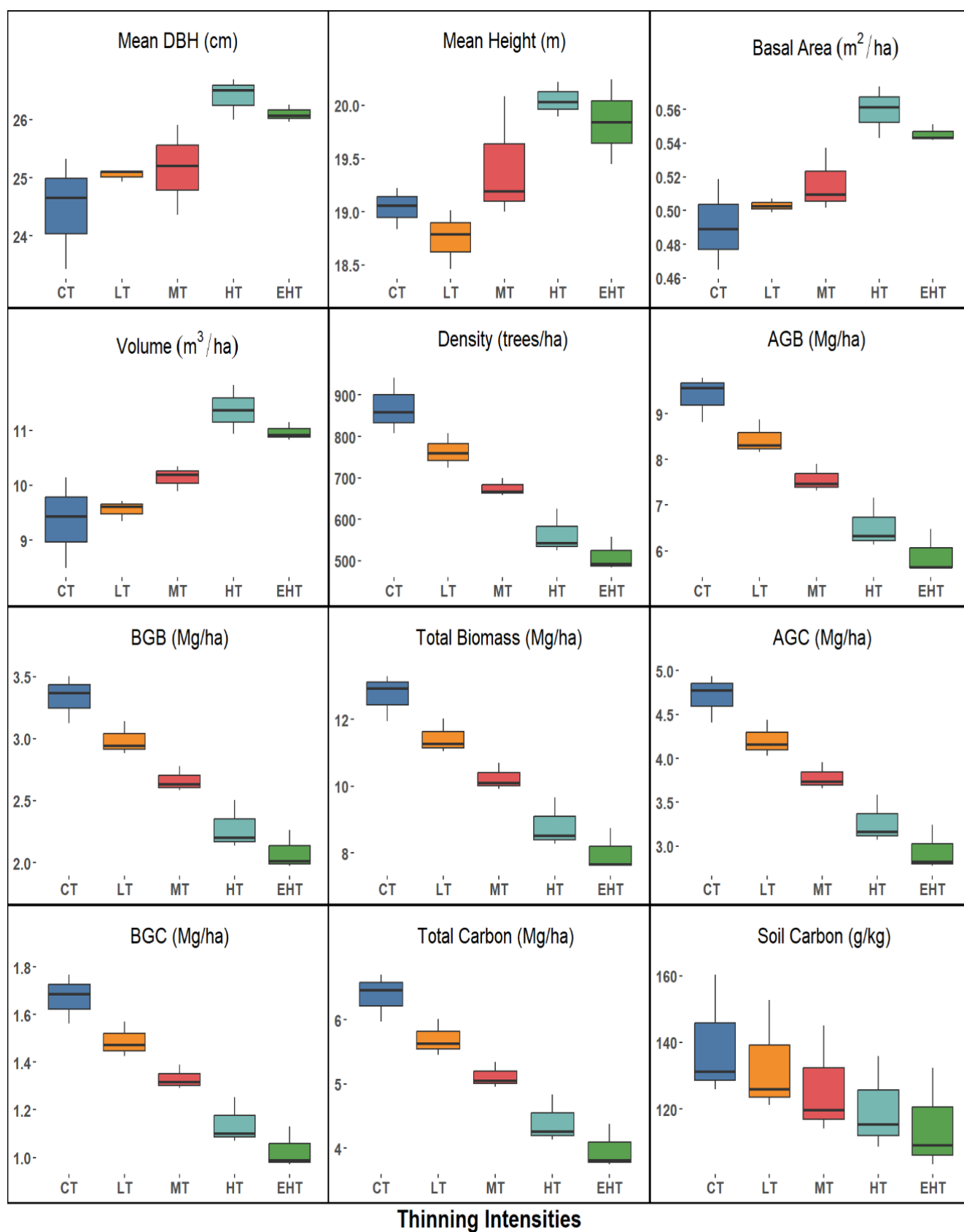


Figure 5. Box Plot for Thinning Intensities of 50-Year-Age of *Larix principis-rupprechtii* Mayr Plantation. (CT; control thinning, LT; light thinning, MT; moderate thinning, HT; heavy thinning, EHT: extreme heavy thinning).

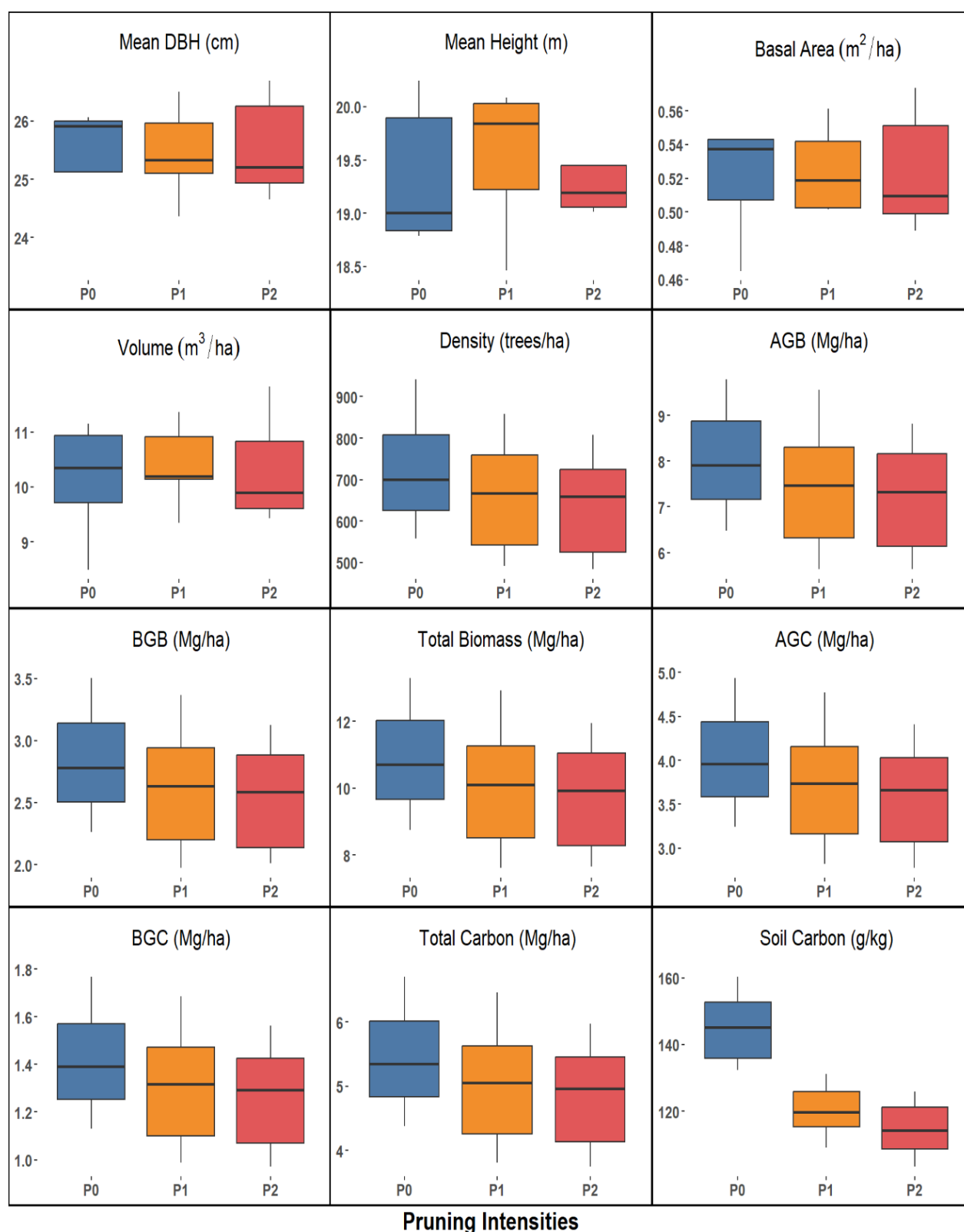
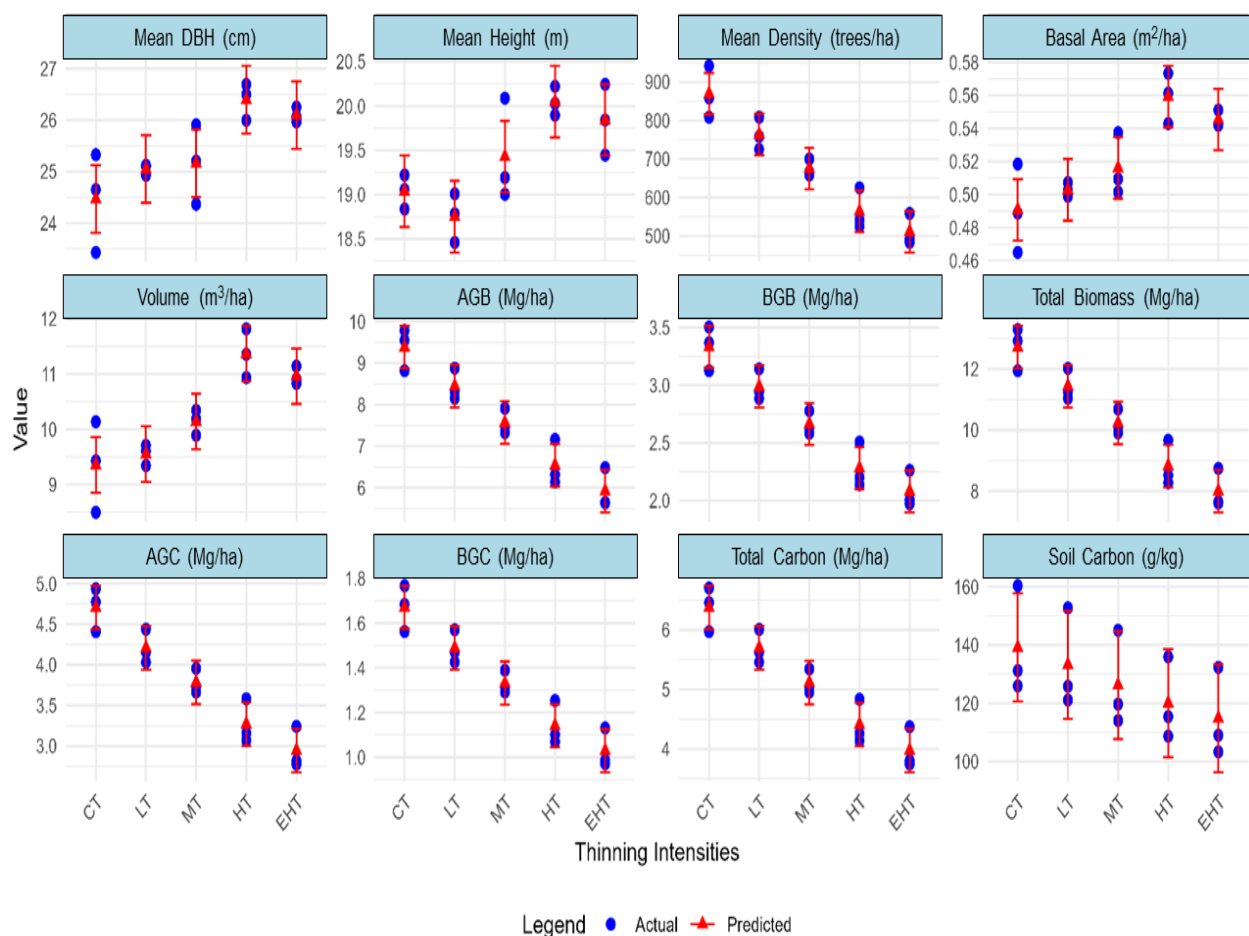


Figure 6. Box Plot for Pruning Intensities of 50-Year-Age of Stand of *Larix principis-rupprechtii* Mayr Plantation. (P 0; control Pruning, P1; light thinning; P2; High Pruning)

3.6. Response of Thinning Intensities on Different Parameters

A remarkable arrangement exists between actual and predicted values, underscoring the predictive models' rel

iability. DBH and mean height appear strong to thinning intensities, with actual and predicted values showing minimal divergence. However, there is a notable decline in tree density with increased thinning, which is expected as thinning reduces stand density. Total biomass and total carbon metrics generally decrease as thinning intensity increases, corresponding with the reduction in stand density and biomass removal. This pattern holds for actual and predicted data, although the predictive models suggest a slightly broader confidence interval, especially at higher thinning intensities, indicating variability in the response. While showing some decrease in the actual measurements with increased thinning, soil carbon is predicted to maintain higher values even at greater thinning intensities. This could suggest that factors beyond thinning alone may influence soil carbon dynamics, such as soil composition, moisture, and organic matter input variations post-thinning. In conclusion, the results suggest that while thinning has expected impacts on stand structure and biomass, the soil carbon pool may exhibit a more complex response, potentially maintaining stability across a range of silvicultural treatments. These findings are critical for forest management and carbon accounting, particularly in climate change mitigation, where understanding carbon sequestration dynamics in forest ecosystems is vital.



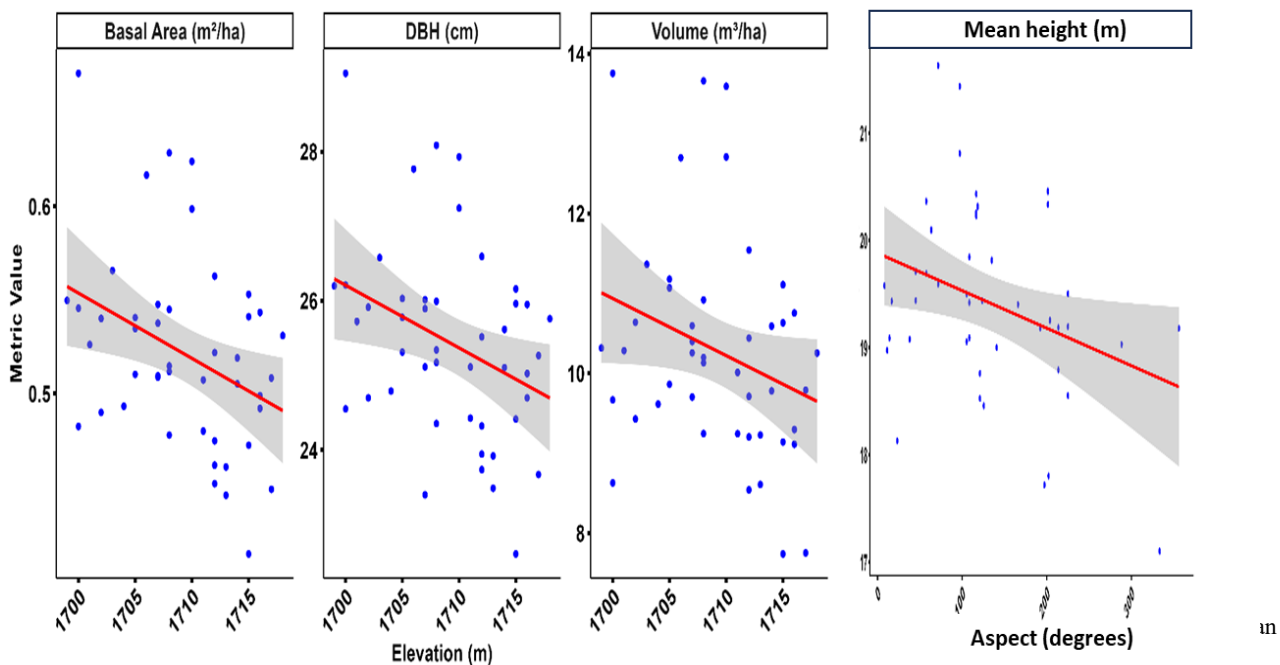
3.7. Effect of Topographic Variables on Tree Biometric Parameters.

The trend line suggests a slight negative correlation, indicating that the basal area tends to decrease as elevation

ion increases. Findings indicate that basal area significantly influences elevation change, as demonstrated by the linear regression model with an ($R^2 = 0.1121$) and a ($P < 0.05$). where DBH values decrease as elevation increases.

There is a noticeable negative trend. The corresponding regression model reveals an ($R^2 = 0.09901$) and a ($P < 0.05$). The negative slope of the regression line implies that volume decreases with increasing elevation, as evidenced by the ($R^2 = 0.0773$) and ($P = 0.064$) (S1).

As the aspect increases, the mean height of trees tends to decrease. As shown by the ($R^2 = 0.1071$) with a ($P < 0.05$). The aspect is found to significantly affect only the height of the forest, with no noted impact on other forest metrics (S2). The analysis also reveals that slope does not have a significant effect on the forest matrices examined (S3).



3.8. Influence of Thinning Intensities on Forest Structural Parameters

Our linear regression analysis of various forest metrics demonstrates that thinning treatment influences forest growth characteristics. The DBH showed significant growth under EHT and HT treatment, with P-values indicating statistical significance ($P < 0.05$). This positive relationship is further supported by the high ($R^2 = 0.6917$) values for DBH and tree height ($R^2 = 0.7338$), underscoring the strong connection between the dependent and independent variables and the significant explanatory power of these treatments.

Our findings indicate that basal area and volume show significant growth under EHT and HT treatment, showing the positive effects of increased thinning intensity. The basal area outcomes were statistically significant, with ($P < 0.05$) and ($R^2 = 0.7858$). Similarly, the volume demonstrated remarkable growth, supported by ($P < 0.05$) and ($R^2 = 0.8231$).

Tree density demonstrated a negative trend with increased thinning intensity, particularly under the different t

reatment, ($P < 0.05$). This suggests that while increasing thinning practices positively affect individual tree growth, they may adversely impact tree density, Biomass and carbon stock (S4).

3.9. Influence of Thinning Intensities on Total Biomass

The study investigates the effects of various thinning treatments on the AGB, BGB and total biomass in forest ecosystems, highlighting the implications for biomass production. The results indicate that the EHT treatment, significantly reduces AGB, as evidenced by a highly negative coefficient and a statistically significant ($P < 0.05$). Similarly, the thinning effects on AGB remain significant for LT, MT and HT intensities, demonstrating a reduction in AGB with a ($P < 0.05$) threshold. The high ($R^2 = 0.9195$) underscores that more intensive thinning correlates with comparatively severe decreases in AGB.

The EHT Intensity exerts a strong negative effect on BGB, with statistical significance ($P < 0.05$). Furthermore, thinning intensities also significantly reduced BGB for LT, MT, and HT ($P < 0.05$) with ($R^2 = 0.9233$).

The total biomass, including AGB and BGB, shows similar reduction patterns across all thinning treatments. The EHT treatment has the most severe negative effect on total biomass ($P < 0.05$), followed by LT, MT, and HT intensities, all showing significant reductions ($P < 0.05$). The aggregate explanatory power of the model is highlighted by an ($R^2 = 0.9206$), suggesting that intensive thinning leads to a severe reduction in total biomass. This is likely due to the combined impacts on AGB and BGB.

In conclusion, this study highlights the need for a balanced approach to forest management practices. While thinning can be beneficial for managing forest density and health, its impact on biomass and carbon storage cannot be ignored. Future forest management policies should incorporate these findings to optimize forest ecosystems' ecological health and carbon sequestration potential (S5).

3.10. Influence of Thinning Intensities on Total Carbon

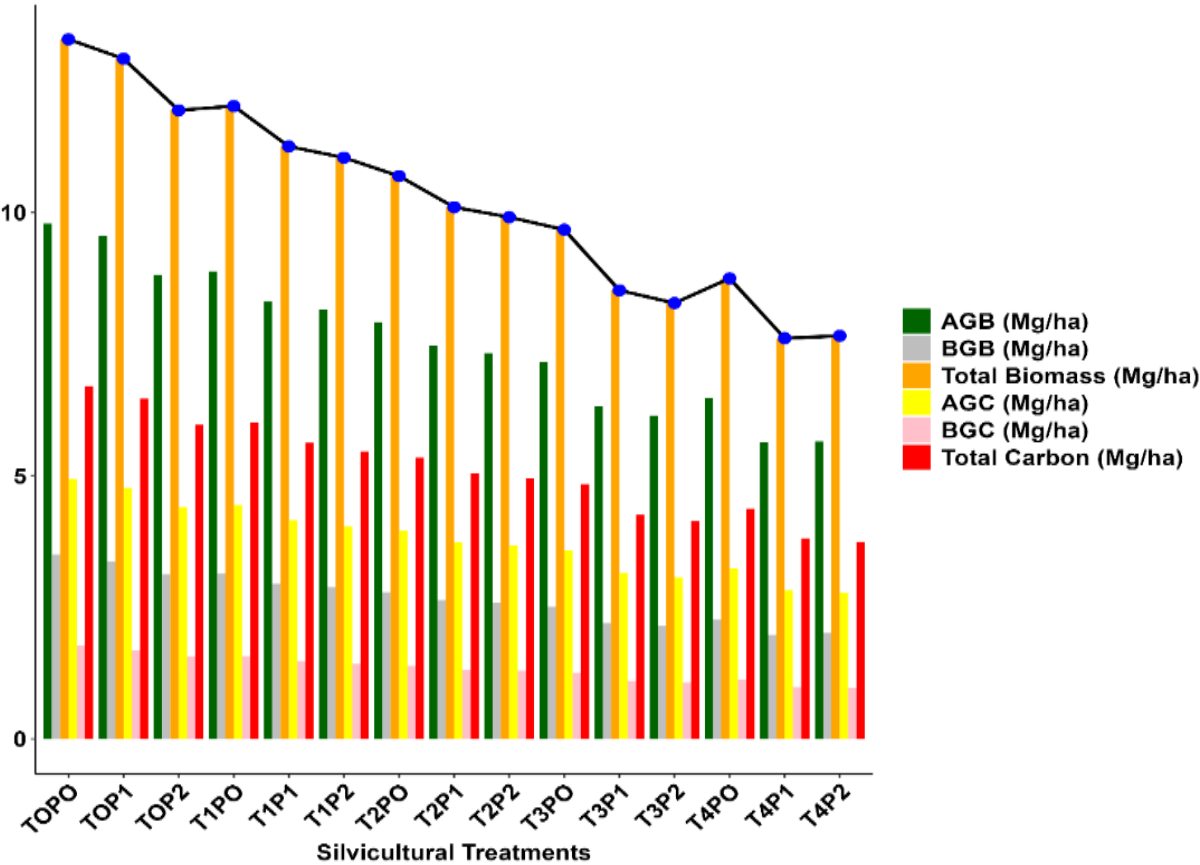
The linear regression analysis evaluates the impact of varying thinning intensities on aboveground carbon (AGC), belowground carbon (BGC), total carbon storage, and soil organic carbon (SOC) within forest ecosystems. The analysis reveals a significant reduction in AGC as thinning intensity increases, with the most pronounced effect observed in the EHT intensity ($P < 0.05$). Significant reductions in AGC were also noted in LT, MT and HT intensities ($P < 0.05$). The model demonstrates a high explanatory power for AGC variation, as indicated by an ($R^2 = 0.9142$).

The thinning intensity significantly impacts BGC. The EHT intensity resulted in the highest reduction in BGC, with statistical significance ($P < 0.05$). Significant reductions in BGC were also observed in the LT, MT and HT intensities ($P < 0.05$), with the model revealing a strong explanatory power ($R^2 = 0.9172$).

The results of total carbon storage align with those for AGC and BGC. The EHT treatment caused the most substantial reduction in total carbon storage ($P < 0.05$), followed by significant reductions in the LT, MT and HT intensities ($P < 0.05$). The model explains the variability in total carbon storage, as evidenced by an ($R^2 = 0.9151$).

Conversely, SOC exhibited a different trend. The effect of EHT on SOC was less pronounced and not statistically significant ($P > 0.05$), indicating that increased thinning intensity does not significantly impact SOC based on conventional statistical thresholds. This is reflected in the model's lower explanatory power for SOC, with an ($R^2 = 0.2993$).

In conclusion, the study highlights the need to balance thinning practices to optimize carbon sequestration while maintaining forest health. The significant responses of AGC, BGC, and total carbon storage to thinning underscore the potential for thinning to significantly influence carbon dynamics. However, the non-significant response of SOC indicates that other factors may govern its variability. Future forest management strategies should incorporate



ate these insights to enhance the efficacy of carbon stock management in forest ecosystems (S6).

Figure 9. Silvicultural treatments with Total Biomass and Total Carbon stocks

3.11. Pearson Correlation Analysis with their Parameters

Several key observations can be made from the heatmap. First, there are consistently high correlations (≥ 0.85) between Total Biomass and its components (AGB and BGB), signifying that AGB and BGB are reliable indicators of Total Biomass. Volume and Basal Area also show strong positive correlations with Total Biomass (0.89) and Total Carbon (0.86), suggesting their effectiveness as proxies for biomass and carbon estimates. Moderate correlations are observed between Mean Height and both Volume (0.63) and Basal Area (0.65), indicating that tree height can be an indicative

metric for these variables, though with some variability. Soil Carbon exhibits moderate correlations with Total Carbon (0.40) and BGB (0.39), reflecting its role in overall carbon storage but with less influence than other variables. Conversely, Density shows a relatively low correlation with Mean DBH (0.05), implying that tree density is not a strong predictor of the average tree diameter within the studied environment. However, Mean DBH demonstrates low to moderate correlations with most variables, except for a notable correlation with Volume (0.85), indicating that larger tree diameters are associated with higher volume.

These findings reveal intricate interdependencies among the studied variables, emphasizing critical relationships essential for ecological modeling and forest management. The high correlations between Total Biomass and its components underscore the importance of considering both AGB and BGB in biomass assessments. The strong associations of Volume and Basal Area with biomass and carbon metrics highlight their utility in forest carbon stock estimation. This comprehensive understanding enhances the accuracy of biomass and carbon modeling, thereby informing strong strategies for forest conservation and carbon sequestration initiatives.

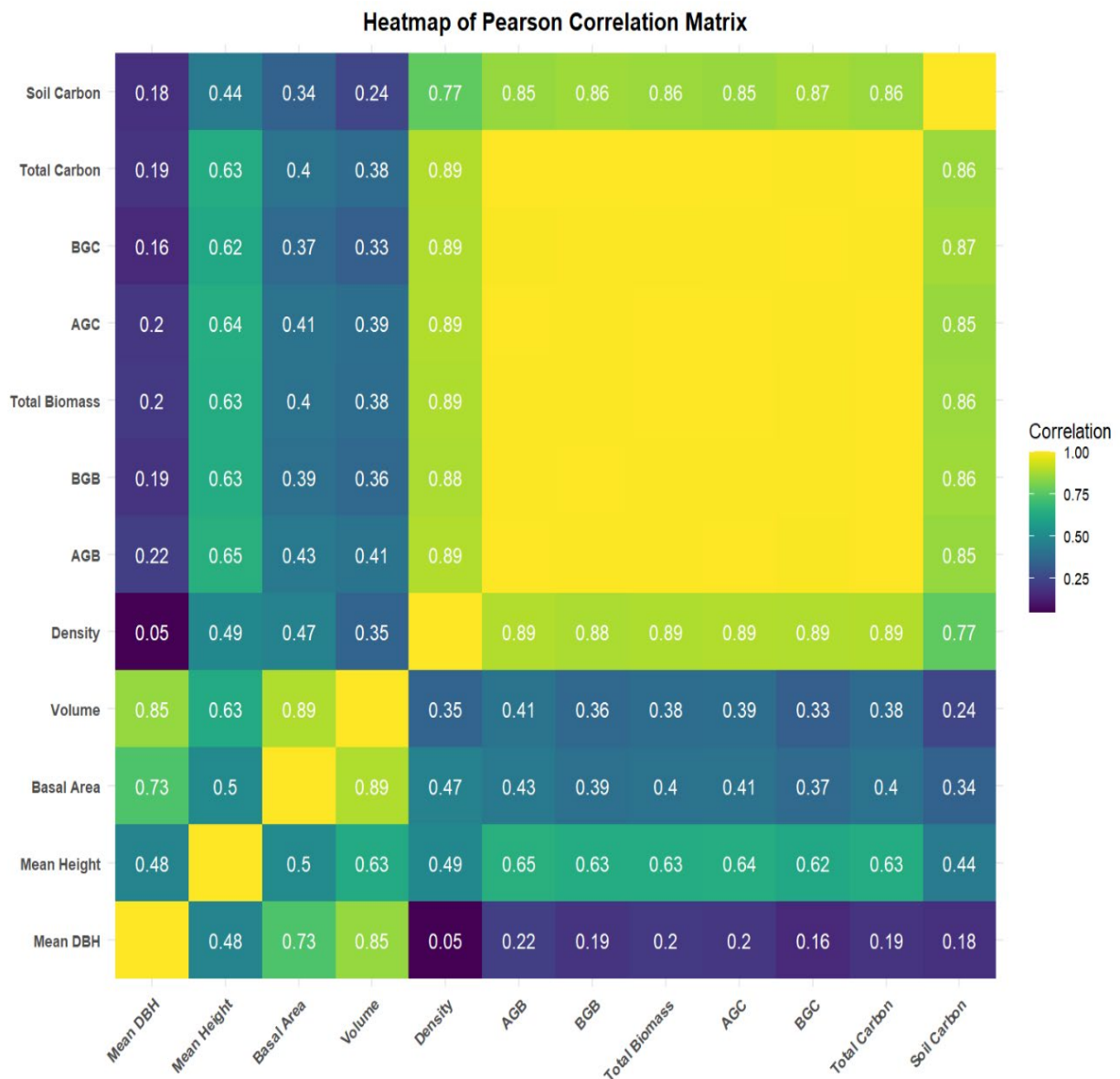


Figure 10. Heat Map of Pearson Correlation of 15 treatments with 5 Thinning and 3 Pruning intensities in Stands of

50-Year-Age of *Larix principis-rupprechtii* Mayr Plantation.

3.12. PCA Analysis with Silvicultural treatments and their parameters

The biplot presented in Figure 11 demonstrates the results of a Principal Component Analysis (PCA), where the first two principal components (F1 and F2) collectively account for 92.79% of the total variance in the dataset. Specifically, the first principal component (F1) explains 85.79% of the variance, while the second F2 explains 7.00%. This high percentage indicates that these two components effectively summarize the multidimensional data.

The vectors on the biplot represent the original variables in the dataset, with their direction and magnitude indicating their contribution to the principal components. Notably, the variable 'Soil C' (Soil Carbon) shows a strong positive correlation with F1, suggesting it significantly contributes to the variance explained by this component. Similarly, variables such as 'Basal Area,' 'DBH' (Diameter at Breast Height), 'Volume,' and 'Height' positively correlate with F2, indicating their substantial contribution to this component.

Clusters of variables, including 'AGC' (Aboveground Carbon), 'Total C' (Total Carbon), 'AGB' (Aboveground Biomass), 'T.Biomass' (Total Biomass), 'BGB' (Belowground Biomass), and 'BGC' (Belowground Carbon), are tightly grouped, highlighting their positive inter-correlations and primary contribution to F1.

The points on the biplot represent individual observations or samples, coded based on different treatments or conditions. For instance, labels like 'T3P1,' 'T3P2,' and 'T4P0' refer to specific treatment and plot combinations. Observations near a particular variable vector suggest a strong influence of that variable on these samples. For example, samples such as 'T2P0,' 'T2P1,' and 'T2P2,' spread along the positive side of F1, indicate higher values for variables like AGC, Total C, and AGB. In contrast, samples like 'T3P1,' 'T3P2,' and 'T4P0,' located on the negative side of F1, suggest lower values for these variables.

Furthermore, clustering samples such as 'T1P0,' 'T1P1,' and 'T0P0' near the origin signifies average values for the analyzed variables, implying these samples do not exhibit extreme characteristics for any specific variable. This spatial distribution of points effectively illustrates the relationship between different sample groups and the variables affecting them.

In conclusion, this biplot effectively visualizes the complex relationships among the studied variables and their influence on various sample groups. The analysis reveals that Soil Carbon is a predominant factor influencing the first principal component, while structural variables like Basal Area, DBH, Volume, and Height significantly impact the second component. The distinct clustering of observations further underscores the varying impacts of different treatments on the samples (Figure 11).

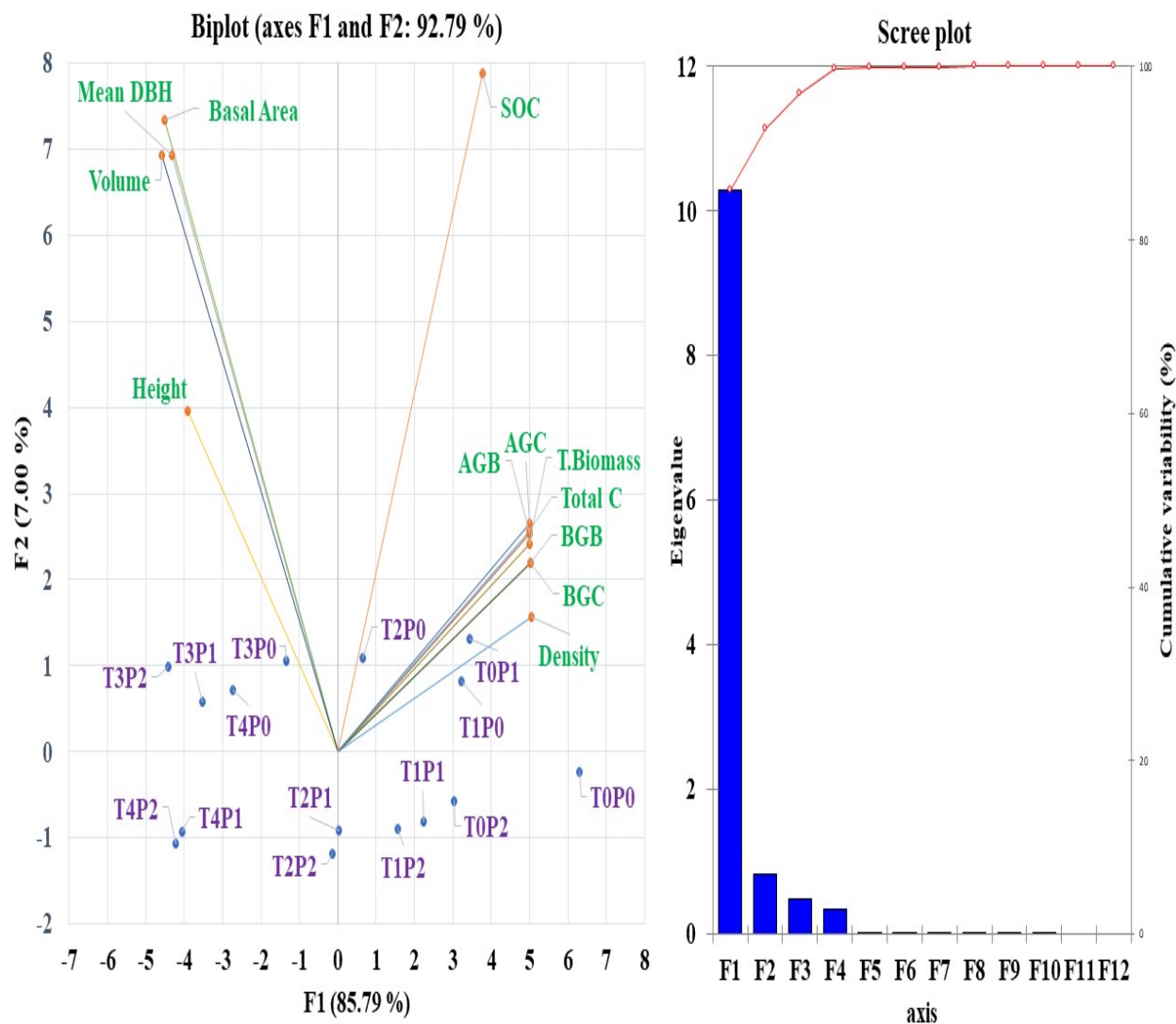


Figure 11: PCA bi-plot representing the ordination of Treatment, Forest biometric parameters, Total biomass, and Total Carbon (F1–F2). A Scree plot indicating the number of significant principal components.

4. Discussion

In agreement with our hypotheses, the biomass and carbon stock in *L. principis-rupprechtii* plantations 50 years old stands in northern China were significantly influenced by silvicultural treatments. However, the aspect only affects the height of *L. principis-rupprechtii*. The slope did not affect the growth of *L. principis-rupprechtii* stands. In addition, increases in elevation DBH and Basal Area of the tree decreases. According to Mazón et al. (2020), more favorable growing conditions and the existence of numerous species capable of rapid growth would make the basal area higher at lower elevations. The mean tree height of the stands decreased significantly with increasing elevation. (Hertel & Wesche, 2008). Previous studies conducted Kim et al. (2016) showed that thinning promoted tree DBH growth more than height in different forest ecosystems. Considering the sign

ificance of intense thinning on individual Norway spruce's increment in basal area, stem, and height (Mäkinen & Isomäki, 2004).

Our findings show a significant reduction in Total biomass and total carbon stocks, increasing Silvicultural treatment intensity. The most significant declines were observed in treatments subjected to heavy Thinning (HT) and extreme Heavy Thinning (EHT) compared to Control Treatment (T0P0). This suggests that while thinning reduces competition and may promote the health and growth of remaining trees, it also substantially decreases the forest's overall biomass and, consequently, its carbon storage capacity. Those treatments led to the most intensive thinning T4P2 showed a decrease in AGB and BGB by up to 42.13% and 42.57% compared to the control treatment. The percentage decrease in total biomass from the control treatment, T0P0, to the most intensive treatment, T4P2, is approximately 42.44%. Similarly, the percentage decrease in total carbon over the same treatments is about 44.18%. Meng et al. (2022) stated that the AGB of larch progressively decreased as thinning intensity increased. The control group (CK) had a higher AGB than the thinning group. Just 36% less than the CK group's, the AGB of the thinned group is 34.4%. Analysis was done on the decreases in aboveground tree carbon storage of 27% and 22% caused by heavy- and medium-thinned stands as opposed to non-thinned stands. (Nilsen & Strand, 2008). The total carbon stock decreases with the thinning of larch forests (Shuyong et al., 2017).

The Study conducted by Hou et al. (2016) showed that the remaining trees on the thinned plots had more rapid-growth effects, especially for individual trees, than the trees on the non-thinned plots; ultimately, the total carbon stock of stands with thinning treatment showed less than that of the non-thinned stands. The effect of thinning was much stronger on individual trees than at the stand level, and thinning promotes the growth of particular trees. The remaining individual trees grow more quickly after being thinned because there is less competition and more light and nutrients are available. Thinning did not increase net carbon stocks in plantations of *Pinus taeda*. (Alvarez et al., 2016). Thinning affects the level of thinning intensity for Scots pine and Pyrenean oak (*Quercus pyrenaica* Willd) (*Pinus sylvestris* L). It was found that after thinning, the total carbon stock was lower in a 50-year loblolly pine rotation than in non-thinned stands (J.-C. Lin et al., 2018b). The accumulation level in the stand primarily depends on the growth rate, particularly the biomass of plants, because the amount of biomass and carbon stored in trees are strongly associated with forest increment. One way to control biomass production in forests is to manage stand density. This technique is typically used to determine the frequency and intensity of thinning operations. Thinning promotes tree development, lowers density, and enhances resource availability for the surviving trees. (Tahvonen et al., 2013; Giuggiola et al., 2013).

Because of the biomass component, the overall on-site C stock in the unthinned plots was considerably higher than in the thinned plots when considering all elements. This is consistent with findings from earlier research that looked at the long-term impacts of various management strategies on carbon stocks and found variations in the amounts of carbon in the biomass component of live trees. (De Simon et al., 2012); (Powers et al., 2011). My results showed that pruning had a less pronounced impact on biomass and carbon stocks. Altho

ugh statistically significant, the changes in AGB, BGB, and total biomass due to pruning were minor compared to those resulting from thinning. This observation suggests that pruning affects tree structure and health more than it influences forest carbon dynamics.

According to Clark & Matheny, (2010), pruning is one of the most common operations. Pruning impacts both tree health and structure. Pruning could be one of the best silviculture operations for a tree (Grabosky & Gilman, 2007). However, the growth rates of our trees had no responses to pruning, understory removal, and their interactions. (R. Li et al., 2020). The highest SOC levels were recorded as high in control plots, decreasing with increased management intensity. The SOC decreases by 35.56% compared to the control treatment (CT). The same study in the Lesser Xing'an Range, Northeast China, found that moderate thinning intensity can enhance litter retention and soil nutrient levels, improving carbon sequestration in degraded forests during spring and summer. However, higher thinning intensities led to carbon loss in autumn and winter (Zhang et al., 2024). Another research on a mixed broadleaved plantation in a subtropical area of China indicated that higher thinning intensities could initially reduce carbon storage in the soil, particularly in the humus layer. This effect was most pronounced in plots with the highest thinning intensity (41%-50%). In contrast, lower thinning intensities (20%-30%) were shown to promote carbon sequestration in the short term (N. Lin et al., 2024). With 15 treatments across five thinning and three pruning intensities. While this study provides valuable insights, there are some limitations that should be acknowledged. The study was conducted in a specific geographical region, and the results may not be directly applicable to other regions with different environmental conditions. Additionally, the study period was relatively short, and the long-term effects of the treatments were not assessed. Future research should consider longer study periods and multiple geographical locations to validate the findings. Future research should focus on long-term studies to assess the sustained effects of thinning and pruning on forest metrics. Additionally, research in different ecological regions would help generalize the findings. Investigating the effects of other silvicultural practices in combination with thinning and pruning could provide further insights into optimizing forest management strategies. Finally, studying the impacts of these practices on forest biodiversity and ecosystem services would contribute to a more holistic understanding of forest management.

5. Conclusion

This Study clarifies the effect of thinning and pruning intensities on biomass and carbon stock, using field investigative data and biomass allometric equations. After silvicultural treatments (5 thinning and 3 pruning intensities), the total biomass and carbon stocks of *L. principis rupprechtii* plantation gradually decreased in 50-year age stands in the Saihanba Mechanical Forest Farm Northern region of China. The thinning increased the carbon stock of individual trees, but it did not increase the carbon stocks at the stand level of *L. principis-rupprechtii* plantation. The carbon is stored more in the tree biomass of *L. principis-rupprechtii* stands subjected to light and moderate thinning in combination with light pruning compared to heavy thinning and heavy pruning intensities. Results indicate an apparent reduction in AGB, BGB, and total biomass with increasing thin

ning intensity, where the highest thinning level treatment T4P2 led to the most significant decrease in carbon storage, showed a decline in AGB and BGB by up to 42.13% and 42.57% compared to control treatment. The percentage decrease in total biomass from the control treatment, T0P0, to the most intensive treatment, T4P2, is approximately 42.44%. The percentage decrease in total carbon over the same treatments is about 44.18%. The SOC decreases by 35.56% compared to the control treatment. Pruning showed less impact on biomass and carbon stocks than thinning, as it maintains tree structure and health rather than overall forest carbon dynamics. While pruning is essential to maintaining tree health and safety, its effect on carbon storage is secondary to thinning. Thinning turns forests into carbon sources and decreases the ability of the larch forest ecosystem to operate as a carbon sink. Forest managers avoid thinning *L. principis-rupprechtii* forests before they reach maturity if the management strategy only provides carbon sinks. Light or medium thinning operations with light Pruning operations are better if some thinning and pruning are necessary.

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Conflict of interest statement

All the authors have read the present version of the manuscript and declare no conflict of interest.

Data availability statement

Data will be available upon request from the Corresponding author.

References

- Action, G. C. (2020). Climate Ambition Alliance: Net Zero 2050. Online] <https://Climateaction.Unfccc.Int/Views/Cooperative-Initiative-Details>. Html.
- Alm, E. (2019). Thinning response to weather variations in Norway spruce.
- Alvarez, S., Ortiz, C., Díaz-Pinés, E., & Rubio, A. (2016). Influence of tree species composition, thinning intensity and climate change on carbon sequestration in Mediterranean mountain forests: a case study using the CO2Fix model. *Mitigation and Adaptation Strategies for Global Change*, 21, 1045–1058.
- Aye, W. N., Tong, X., & Tun, A. W. (2022). Species diversity, biomass and carbon stock assessment of Kanhlyashay Natural Mangrove Forest. *Forests*, 13(7), 1013.
- Barzagli, F., & Mani, F. (2019). The increased anthropogenic gas emissions in the atmosphere and the rising of the E

arth's temperature: are there actions to mitigate the global warming. *Substantia*, 3(1), 101–111.

Cheng, F., Tian, J., He, J., He, H., Liu, G., Zhang, Z., & Zhou, L. (2023). The spatial and temporal distribution of China's forest carbon. *Frontiers in Ecology and Evolution*, 11, 1110594.

Clark, J. R., & Matheny, N. (2010). The research foundation to tree pruning: A review of the literature. *Arboriculture & Urban Forestry*, 36(3), 110–120.

Couwenberg, J. (2011). Greenhouse gas emissions from managed peat soils: is the IPCC reporting guidance realistic? *Mires & Peat*, 8.

Daba, D. E., & Soromessa, T. (2019). The accuracy of species-specific allometric equations for estimating aboveground biomass in tropical moist montane forests: case study of *Albizia grandibracteata* and *Trichilia dregeana*. *Carbon Balance and Management*, 14, 1–13.

Dar, J. A., Subashree, K., Bhat, N. A., Sundarapandian, S., Xu, M., Saikia, P., Kumar, A., Kumar, A., Khare, P. K., & Khan, M. L. (2020). Role of major forest biomes in climate change mitigation: An eco-biological perspective. *Socio-Economic and Eco-Biological Dimensions in Resource Use and Conservation: Strategies for Sustainability*, 483–526.

De Simon, G., Alberti, G., Delle Vedove, G., Zerbi, G., & Peressotti, A. (2012). Carbon stocks and net ecosystem production changes with time in two Italian forest chronosequences. *European Journal of Forest Research*, 131, 1297–1311.

Eshetu, E. Y., & Hailu, T. A. (2020). Carbon sequestration and elevational gradient: The case of Yegof mountain natural vegetation in North East, Ethiopia, implications for sustainable management. *Cogent Food & Agriculture*, 6(1), 1733331.

Fekadu Hailu, A., Soremessa, T., & Warkineh Dullo, B. (2021). Carbon sequestration and storage value of coffee forest in Southwestern Ethiopia. *Carbon Management*, 12(5), 531–548.

Forest, B. N., Ethiopia, S., & Tore, S. (2018). Estimation of above and below-ground carbon stock along altitudinal gradient of montane moist forest:

Forrester, D. I., Collopy, J. J., Beadle, C. L., & Baker, T. G. (2012). Interactive effects of simultaneously applied thinning, pruning and fertiliser application treatments on growth, biomass production and crown architecture in a young *Eucalyptus nitens* plantation. *Forest Ecology and Management*, 267, 104–116.

Forrester, D. I., Collopy, J. J., Beadle, C. L., & Baker, T. G. (2013). Effect of thinning, pruning and nitrogen fertiliser application on light interception and light-use efficiency in a young *Eucalyptus nitens* plantation. *Forest Ecology and Management*, 288, 21–30.

Gabira, M. M., Girona, M. M., DesRochers, A., Kratz, D., da Silva, R. B. G., Duarte, M. M., de Aguiar, N. S., & Wendling, I. (2023). The impact of planting density on forest monospecific plantations: An overview. *Forest Ecology and Management*, 534, 120882.

Gonçalves, A. C. (2021). Thinning: an overview. IntechOpen, London, 41–58.

Grabosky, J. C., & Gilman, E. F. (2007). Response of two oak species to reduction pruning cuts. *Arboriculture and Urban Forestry*, 33(5), 360.

Hao, Z., Le, Q., Song, J., Wang, N., Han, H., & Ma, J. (2024). Forest thinning increases surface soil temperature in *Larix principis-rupprechtii* (Pinaceae) plantations. *Journal of Soils and Sediments*, 24(2), 793–807.

- Hertel, D., & Wesche, K. (2008). Tropical moist Polylepis stands at the treeline in East Bolivia: the effect of elevation on stand microclimate, above-and below-ground structure, and regeneration. *Trees*, 22, 303–315.
- Hou, L., Li, Z., Luo, C., Bai, L., & Dong, N. (2016). Optimization forest thinning measures for carbon budget in a mixed pine-oak stand of the Qingling Mountains, China: A Case study. *Forests*, 7(11), 272.
- Joshi, R., & Singh, H. (2020). Carbon sequestration potential of disturbed and non-disturbed forest ecosystem: A tool for mitigating climate change. *African Journal of Environmental Science and Technology*, 14(11), 385–393.
- Juchheim, J., Ammer, C., Schall, P., & Seidel, D. (2017). Canopy space filling rather than conventional measures of structural diversity explains productivity of beech stands. *Forest Ecology and Management*, 395, 19–26.
- Kay, S., Rega, C., Moreno, G., den Herder, M., Palma, J. H. N., Borek, R., Crous-Duran, J., Freese, D., Giannitsopoulos, M., & Graves, A. (2019). Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. *Land Use Policy*, 83, 581–593.
- Khan, M. N. I., Islam, M. R., Rahman, A., Azad, M. S., Mollick, A. S., Kamruzzaman, M., Sadath, M. N., Feroz, S. M., Rakkibu, M. G., & Knohl, A. (2020). Allometric relationships of stand level carbon stocks to basal area, tree height and wood density of nine tree species in Bangladesh. *Global Ecology and Conservation*, 22, e01025.
- Kim, M., Lee, W.-K., Kim, Y.-S., Lim, C.-H., Song, C., Park, T., Son, Y., & Son, Y.-M. (2016). Impact of thinning intensity on the diameter and height growth of *Larix kaempferi* stands in central Korea. *Forest Science and Technology*, 12(2), 77–87.
- Lázaro-Lobo, A., Ruiz-Benito, P., Cruz-Alonso, V., & Castro-Díez, P. (2023). Quantifying carbon storage and sequestration by native and non-native forests under contrasting climate types. *Global Change Biology*, 29(16), 4530–4542.
- Lewark, S. (2022). Work in Plantation Forests. In *Work in Tropical Forests* (pp. 141–182). Springer.
- Li, R., Han, J., Guan, X., Chi, Y., Zhang, W., Chen, L., Wang, Q., Xu, M., Yang, Q., & Wang, S. (2020). Crown pruning and understory removal did not change the tree growth rate in a Chinese fir (*Cunninghamia lanceolata*) plantation. *Forest Ecology and Management*, 464, 118056.
- Li, Y., Li, X., Zhao, M.-H., Pang, Z.-Y., Wei, J.-T., Tigabu, M., Chiang, V. L., Sederoff, H., Sederoff, R., & Zhao, X.-Y. (2021). An overview of the practices and management methods for enhancing seed production in conifer plantations for commercial use. *Horticulturae*, 7(8), 252.
- Lin, J.-C., Chiu, C.-M., Lin, Y.-J., & Liu, W.-Y. (2018a). Thinning effects on biomass and carbon stock for young *Taiwania* plantations. *Scientific Reports*, 8(1), 3070.
- Lin, J.-C., Chiu, C.-M., Lin, Y.-J., & Liu, W.-Y. (2018b). Thinning effects on biomass and carbon stock for young *Taiwania* plantations. *Scientific Reports*, 8(1), 3070.
- Lin, N., Feng, M., Huang, H., Qiu, Z., Ma, T., & Chen, S. (2024). Effects of Thinning on Carbon Storage in a Mixed Broadleaved Plantation in a Subtropical Area of China. *Forests*, 15(4), 638.
- Lisboa, M., Acuña, E., Cancino, J., Chao, F., Muñoz, F., Rodríguez, R., & Volker, P. (2014). Physiological response to pruning severity in *Eucalyptus regnans* plantations. *New Forests*, 45, 753–764.
- Lu, D., Wang, G. G., Zhang, J., Fang, Y., Zhu, C., & Zhu, J. (2018). Converting larch plantations to mixed stands:

Effects of canopy treatment on the survival and growth of planted seedlings with contrasting shade tolerance. *Forest Ecology and Management*, 409, 19–28.

Mäkinen, H., & Isomäki, A. (2004). Thinning intensity and long-term changes in increment and stem form of Norway spruce trees. *Forest Ecology and Management*, 201(2–3), 295–309.

Matsushita, M., Nishikawa, H., & Tamura, A. (2022). Effects of girdling intensity, pruning season and thinning on tree growth, crown vigor and wound recovery in Japanese larch. *Forests*, 13(3), 449.

Mazón, M. M., Klanderud, K., Finegan, B., Veintimilla, D., Bermeo, D., Murrieta, E., Delgado, D., & Sheil, D. (2020). How forest structure varies with elevation in old growth and secondary forest in Costa Rica. *Forest Ecology and Management*, 469, 118191.

Meng, Y., Zhang, Y., Li, C., Wang, Z., & Li, Y. (2022). The effect of thinning management on the carbon density of the tree layers in larch–birch mixed natural secondary forests of the Greater Khingan Range, northeastern China. *Forests*, 13(7), 1035.

Montagu, K. D., Kearney, D. E., & Smith, R. G. B. (2003). The biology and silviculture of pruning planted eucalypts for clear wood production—a review. *Forest Ecology and Management*, 179(1–3), 1–13.

Nilsen, P., & Strand, L. T. (2008). Thinning intensity effects on carbon and nitrogen stores and fluxes in a Norway spruce (*Picea abies* (L.) Karst.) stand after 33 years. *Forest Ecology and Management*, 256(3), 201–208.

Nunes, L. J. R., Meireles, C. I. R., Pinto Gomes, C. J., & Almeida Ribeiro, N. M. C. (2020). Forest contribution to climate change mitigation: Management oriented to carbon capture and storage. *Climate*, 8(2), 21.

Olivier, J. G. J., & Berdowski, J. J. M. (2021). Global emission sources and sinks. In *The climate system* (pp. 33–77). CRC Press.

Powers, M., Kolka, R., Palik, B., McDonald, R., & Jurgensen, M. (2011). Long-term management impacts on carbon storage in Lake States forests. *Forest Ecology and Management*, 262(3), 424–431.

Putz, F. E., & Romero, C. (2015). *Futures of tropical production forests* (Vol. 143). CIFOR.

Sha, Z., Bai, Y., Li, R., Lan, H., Zhang, X., Li, J., Liu, X., Chang, S., & Xie, Y. (2022). The global carbon sink potential of terrestrial vegetation can be increased substantially by optimal land management. *Communications Earth & Environment*, 3(1), 8.

Shuyong, L., Shengong, L., & Mei, H. (2017). Effects of thinning intensity on carbon stocks and changes in larch forests in China northeast forest region. *Journal of Resources and Ecology*, 8(5), 538–544.

Siddiq, Z., Hayyat, M. U., Khan, A. U., Mahmood, R., Shahzad, L., Ghaffar, R., & Cao, K.-F. (2021). Models to estimate the above and below ground carbon stocks from a subtropical scrub forest of Pakistan. *Global Ecology and Conservation*, 27, e01539.

Song, C., Yang, B., Zhang, L., & Wu, D. (2021). A handheld device for measuring the diameter at breast height of individual trees using laser ranging and deep-learning based image recognition. *Plant Methods*, 17(1), 67.

Stolbovoy, V., Montanarella, L., Filippi, N., Jones, A., Gallego, J., & Grassi, G. (2005). Soil sampling protocol to certify the changes of organic carbon stock in mineral soils of European Union. Citeseer.

- Tao, C., Guo, T., Shen, M., & Tang, Y. (2023). Spatio-Temporal Dynamic of Disturbances in Planted and Natural Forests for the Saihanba Region of China. *Remote Sensing*, 15(19), 4776.
- Tebeje, Y. (2020). A Review Paper on the Role of Terrestrial Carbon Stocks for Climate Change Mitigation Mechanisms. *ms.*
- Ussiri, D. A. N., & Lal, R. (2017). Carbon sequestration for climate change mitigation and adaptation. Springer.
- Vernon, M. J., Sherriff, R. L., van Mantgem, P., & Kane, J. M. (2018). Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. *Forest Ecology and Management*, 422, 190–198.
- Vista, A., Cororaton, C. B., Inocencio, A. B., Tiongco, M. M., & Manalang, A. B. S. (2016). Impact Assessment of the National Greening Program of the Department of Environment and Natural Resources: Scoping or Process Evaluation Phase (Economic Component). PIDS Discussion Paper Series.
- Xu, A., Wang, D., Liu, Q., Zhang, D., Zhang, Z., & Huang, X. (2022). Incorporating stand density effects and regression techniques for stem taper modeling of a *Larix principis-rupprechtii* plantation. *Frontiers in Plant Science*, 13, 902325.
- Yanai, R. D., Wayson, C., Lee, D., Espejo, A. B., Campbell, J. L., Green, M. B., Zuckswert, J. M., Yoffe, S. B., Aukema, J. E., & Lister, A. J. (2020). Improving uncertainty in forest carbon accounting for REDD+ mitigation efforts. *Environmental Research Letters*, 15(12), 124002.
- Zhang, B., Gao, R., & Dong, X. (2024). The Seasonal Impact of Thinning Intensities on Soil Carbon Cycling in the Lesser Xing'an Range, Northeast China. *Forests*, 15(3), 449.
- Zhao, K., Ji, F., Liu, Y., Liu, X., Jia, Z., & Ma, L. (2016). Growth of *Larix principis-rupprechtii* with thinning and pruning. *Journal of Zhejiang A&F University*, 33(4), 581–588.
- Zhao KuangJi, Z. K., Ji FuLi, J. F., Liu YanWen, L. Y., Liu XiaoLan, L. X., Jia ZhongKui, J. Z., & Ma LüYi, M. L. (2016). Growth of *Larix principis-rupprechtii* with thinning and pruning.