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EFFECTS OF CONSERVATION THINNING ON SECONDARY MIXED CONIFER FOREST GROWTH AND SPECIES DIVERSITY

ZIXUAN ZHOU[1], DELING YANG[1*], LEI HUANG[2], SUDIPTA SAHA[2] AND FAN YANG[1]

[1]College of Mechanical and Electrical Engineering, Northeast Forestry University, Harbin 150040, China
[2]College of Forestry, Northeast Forestry University, Harbin 150040, China
**Corresponding author's e-mail: yangdeling@nefu.edu.cn*

Abstract

Conservation of plant species diversity is a global issue in both secondary and natural forests. To clarify the effects of different conservation thinning intensities (10, 15, 20, 25, 30, and 35%) on forest growth and species diversity, data from seven mixed forest plots in Dongfanghong Forest Experimental Bureau, Heilongjiang Province, China, were utilized to observe the evolution of natural mixed forests and the diversity of species in the tree, shrub, and herb layers. In all sites, apart from plot F (35% intensity of thinning), diameter at breast height (DBH) was greater than the control site six years after thinning in terms of both the cumulative growth and the yearly growth of DBH. Plot C (20% intensity of thinning) showed the highest growth, with a total DBH growth of 3.394 cm and a DBH annual growth of 0.567 cma^{-1}. Total height growth in all plots was greater than in the control plot, with the highest increase in plot B (15% intensity of thinning). The total growth of tree height was 5.71 m in six years, and the growth of tree height in successive years was 0.95 ma^{-1}. Therefore, it was informed that thinning could significantly affect the diameter distribution and tree height distribution of the forest stand. However, the distribution of the diameter order gradually shifted to the right with the increase in intensity of thinning, and the average productivity of the tree layer of the natural coniferous and broadleaf mixed forests could be increased by the thinning. Overall, species diversity at each thinning sample site improved, but thinning decreased the average biomass of the tree layer. This drop in biomass was proportional to the degree of thinning. Conservation thinning enhances tree productivity and species diversity, promoting large-diameter tree cultivation and natural mixed coniferous and broad second-growth forest growth.

Key words: Biomass, DBH, Natural-mixed coniferous forests, Species diversity, Thinning intensity, Productivity.

Introduction

Biodiversity plays a pivotal role in ecosystem services, including hydrological cycles, primary production, nutrient storage, and plant species diversity within conifer plantations (He *et al.*, 2019; Gou *et al.*, 2023). These services, fundamental for human well-being, sustain the hydrological cycle and primary production (Ahonen *et al.*, 2022). Mixed broadleaf and conifer forests in Northeast China significantly bolster the national economy by utilizing a substantial proportion of harvested wood for both civic and national applications(Liu *et al.*, 2019). Mixed broadleaf and conifer forests are naturally found in regions like Europe, North America, and the Far East (Makryi and Skirina, 2020). Forest types, varying with the region, each exhibit distinct composition and structure(Asefa *et al.*, 2020). Thinning, a prominent silvicultural practice in China, is employed to promote natural regeneration and preserve shelter benefits (Li *et al.*, 2020).

Sustainable forest management has become a prominent concern for foresters worldwide (Kuuluvainen *et al.*, 2021). Nevertheless, previous research has primarily focused on the effects of thinning on understory vegetation, soil microorganism diversity, stand structure, and individual environmental factors(Dong *et al.*, 2021; Odland *et al.*, 2021; Wang *et al.*, 2021). Comprehensive studies on the impact of thinning intensity on tree layer productivity, species abundance, and the diversity of understory shrubs, herbs, and overall tree growth are still limited (Li *et al.*, 2020; Heinrichs *et al.*, 2022).

Stand growth, the development of trees in a forest, is influenced by factors such as tree height, diameter at breast height (DBH), and other parameters (Zhao *et al.*, 2023). The growth of the North China larch is notably influenced by stand density and age; the effect of density on growth amplifies with increasing stand age (Sun *et al.*, 2023). Others investigated the effects of target tree management, integrated nursery management, and no disturbance on Mongolian oak natural forests (Feng *et al.*, 2018). They found that while target tree management supported replanted species growth, stands without disturbance had higher average tree heights and more optimal layer distribution in the short term, leading to higher productivity. Further research and monitoring are essential to assess the long-term impacts of each management approach.

Species diversity directly influences the ecological functionality of communities and serves as a vital metric for assessing forest quality (Rahman *et al.*, 2022). Researchers investigated species diversity in three typical forest stands in Huzhong, Daxinganling, indicated that in miscellaneous forests, the tree layer had the highest values for tree height, height beneath branches, richness, and diversity indices. Shrub canopy, herb layer cover, and multiplicity were identified as principal determinants of species diversity (Zhang *et al.*, 2021). A separate study by another researcher also found elevated tree height, height beneath branches, richness, and diversity indices in the tree layer of mixed forests (Zhang *et al.*, 2018). Similarly, shrub canopy, herb layer cover, and multiplicity significantly influenced species diversity.

Thinning in conifer plantations facilitates hardwood recruitment, aiding the transition from monoculture to mixed hardwood-conifer forests (Seiwa *et al.*, 2020). Sensible thinning not only improves the forest's microclimate and tree productivity but also alters stand structure and promotes biodiversity, vital for forest development (Aszalós *et al.*, 2022). Studies on the effects of thinning primarily focus on metrics like DBH, tree height, volume, and understory vegetation. However, they should also account for forest stand type, ground conditions, and thinning methods (Akashi *et al.*, 2021). A study on the long-term effects of thinning on upland black spruce trees at varying intensities (0, 25, and 50%) found that, when evaluated by net lumber output instead of net stocking, the thinning response was initially insignificant for 15 years. However, there was a 33% increase in net lumber output in plots with low thinning intensity compared to control plot (Soucy *et al.*, 2012).

The plot with high thinning intensity exhibited superior tree growth and minimized senescence mortality, eventually matching the growth of the control plot (Ward & Wikle, 2019). Twelve years post-thinning, European Korean pine exhibited significant radial growth compared to the control plots. Light thinning increased in-ring wood density by 5%, whereas the medium treatment showed no significant change (Peltola *et al.*, 2007). Across all treatments, Shannon diversity indices were consistent; the 67% thinning treatment exhibited the highest diameter growth in conifers, surpassing the control treatments (Chen *et al.*, 2015). Intensive thinning has proven to be an effective strategy of transitioning conifer plantations for mixed forests, albeit with some decline in primary production. In *Pinus Sylvestris* forests with 5 densities, a study found a negative correlation between DBH and stand density, and a rising height-to-diameter ratio as density increased (Daiqing *et al.*, 2015). Post-thinning, Japanese larch stands exhibited an increase in average diameter, tree height, and timber volume as thinning intensity rose. Notably, plant diversity and biomass peaked with the most intensive thinning (Tang *et al.*, 2018). Studies on *Eucalyptus* spp. under various thinning intensities revealed a sequential rise in species diversity, peaking at 30% thinning intensity. Correspondingly, DBH and tree height for this species set were also highest at this thinning level (Chen *et al.*, 2017).

However, biodiversity conservation is essential for sustaining ecosystem functions like hydrological cycles, primary production, nitrogen storage, and plant diversity in conifer plantations. Comprehensive studies evaluating the effects of thinning intensity on productivity, species abundance, and vegetation layers (understory shrub, herb, tree growth) remain limited. Thinning practices, key to sustainable forest management, play a significant role in determining tree growth and species diversity globally. In conifer plantations, thinning is a common practice to enhance hardwood recruitment and biodiversity. The absence of scientific management for natural mixed forests in Xiaoxing'anling Mountain has compromised stand quality. This paper investigates the effects of varying conservation thinning intensities on forest growth and species diversity. The objective of this study is to offer insights to refine thinning strategies in natural mixed forests. We hypothesize that optimizing thinning intensity will boost the growth of retained wood. It was further divided into the following research questions: (1) how thinning intensity affects the growth of retained wood; (2) how thinning intensity affects productivity and biomass in the tree layer; and (3) how thinning intensity affects changes in species diversity.

Material and Methods

Experimental site: The experimental sample plot was located at 46°50′08″47°21′32″N, 128°37′46″129°17′50″E. It was in small class 13 of the 414-forest class in the Dongfanghong Forestry Experimental Bureau, the Dailing Forestry Experimental Bureau, and the Xiaoxing'anling prefecture (Fig. 1). The forest comprises a natural mix of coniferous and broad-leaved secondary species. The region experiences a continental humid monsoon climate characterized by warm, humid summers with cool rains and cold, windless winters with abundant snow. The test area, situated mid-mountain, has a northwest-facing slope of 14° and spans approximately 54.93 hm^2. The area receives an average annual precipitation of 661mm, with about 130 rainy days, predominantly in July and August. The frost-free period lasts around 110 days annually. The predominant soil type is dark brown clay, though some forest areas contain soil from valley meadows and swamps. The primary tree species include *Pinus koraiensis*, *Picea asperata*, *Abies fobri*, *Fraxinus mandschurica* and *Tilia tuan.* These trees have an average age of 70 years, DBH of 16cm, height of 11m, and a forest closure exceeding 0.8. The herb layer primarily consists of ferns, *Scirpus planiculmis* and *Carex callitrichos*, with a 65% average distribution. Dominant shrubs include *Lonicera japonica*, *Acanthopanax senticosus*, *Spodiopogon cotulifer*, and *Lespedeza bicolor*, covering about 60% of the area uniformly.

Sample plot setup and survey: Six experimental plots, each measuring 100 m by 100 m, were set up in 2016; their stand densities were identical to those of the research area's pre-renovation plots. Based on the harvested to total volume ratio, assign the sample plots A, B, C, D, E, and F, each of which corresponds to interval logging intensities of 10, 15, 20, 25, 30, and 35%. A control plot was also established, labeled as CK. An overview of the sample plots is shown in (Fig. 2). Intercutting was executed as per timber forest fostering guidelines. We employed understory fostering to remove non-target species, locally overcrowded trees, and compromised specimens, including diseased, decayed, suppressed, dying, or malformed trees.

After establishing the plots, the DBH of the sample trees was measured and the tree height was calculated using a height meter. To guarantee consistent measurement points in upcoming years, the DBH position was marked on sample trees. The understory vegetation survey utilized a sample survey method, establishing two to three 5m x 5m shrub samples to evaluate shrub species and coverage. Within these, arrange five 1 m x 1 m herbaceous samples in a "Z" formation was arranged to investigate the herbaceous species and their coverage.

Research methodology: The distribution of diameter and tree height forms the foundational data for forest stand assessments and management activities. In undamaged natural or plantation forests, diameter and tree height was measured following stable structural patterns. Thus, choosing an appropriate distribution model can predict and regulate these distributions in mixed conifer forests post-deforestation. The tree layer constitutes most of the forest biomass, typically around 90%. The shrub and herb layers contribute minimally to the overall biomass. Analyzing biomass and productivity of the tree layer in mixed conifer and broadleaf forests can reveal thinning's impact on tree quality. Since any thinning intensity impacts species diversity, understanding its effects across varying intensities is crucial.

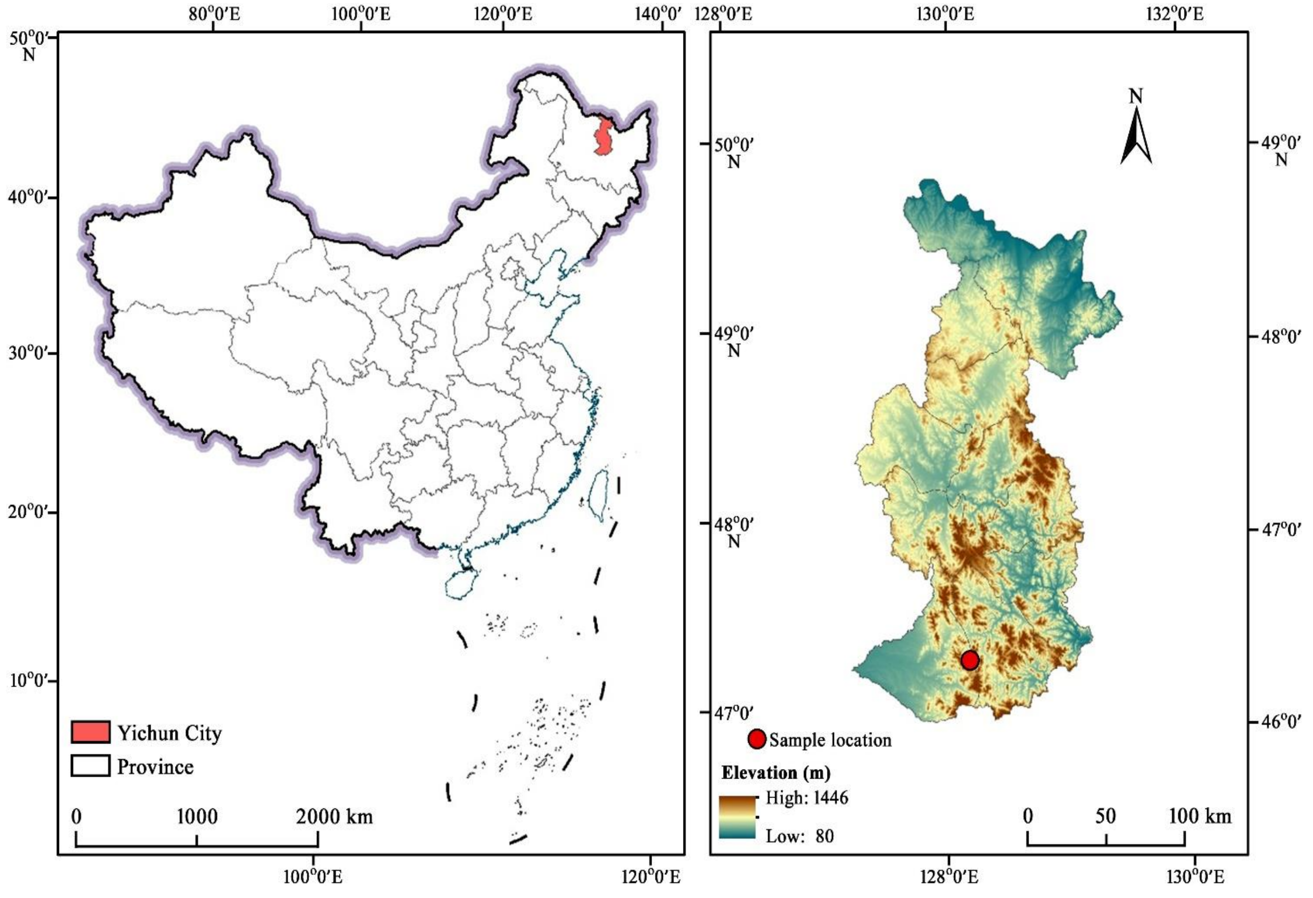

Fig. 1. Study area map of the experimental fields (GS(2023)2765).

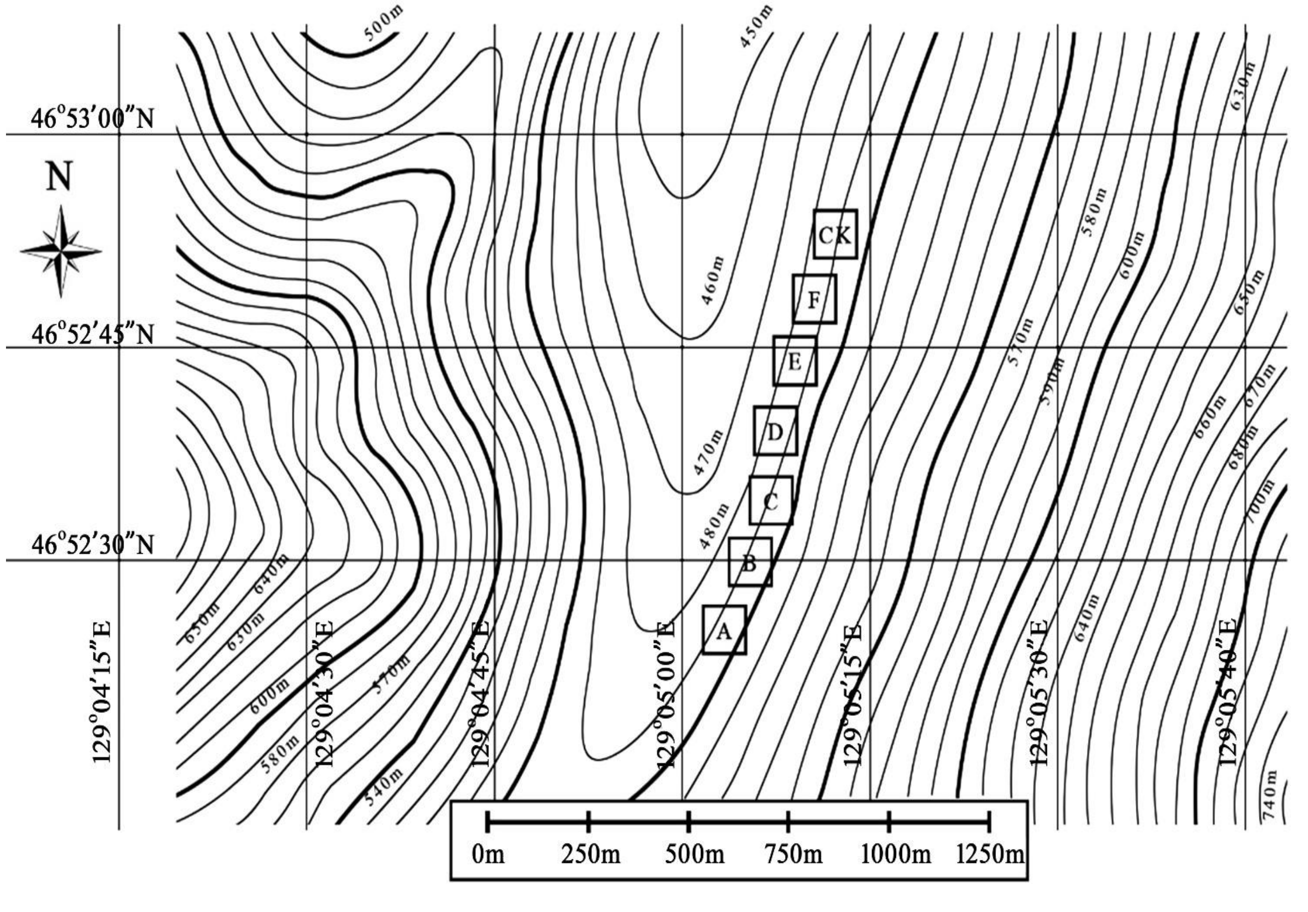

Fig. 2. Setting of sample plot.

Table 1. The model of density function of probability distribution. (Aragao *et al*., 2007).

Distribution type	Probability density function	Parameters
Normal distribution	$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[\frac{-(x-\mu)}{2\sigma^2}\right]$	μ, σ
Log-normal distribution	$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[\frac{-(\log(x)-\mu)}{2\sigma^2}\right]$	μ, σ
Logistic distribution	$f(x) = \frac{1}{1+\exp\left[\frac{x-a}{b}\right]}$	a, b
Exponential distribution	$f(x) = \lambda e^{-\lambda x}$	λ
Gamma distribution	$f(x) = \frac{x^{\alpha-1}}{\beta^\alpha \Gamma(\alpha)} \exp(-x/\beta)$	α, β
Weibull distribution	$f(x) = \left(\frac{\gamma}{\beta}\right)\left(\frac{x-\alpha}{\beta}\right)^{\gamma-1} \exp\left[-\left(\frac{x-\alpha}{\beta}\right)^{\gamma}\right]$	α, β, γ

Methods for fitting stand diameter and tree height distributions: Both normal and various non-normal distributions can model the DBH and tree height. In this study, 6 probability distribution functions-normal, log-normal, exponential, Gamma, Logistic, and Weibull distributions-were chosen to fit the diameter and tree height frequency distribution, with specific functions detailed in (Table 1). The derived model was tested to select the optimal fit for the forest stand distribution. The K-S test was chosen as the testing method in this study.

Calculation of biomass and productivity in the tree layer: Tree biomass can be categorized into two parts: underground, consisting of root biomass, and aboveground, encompassing trunk (wood and bark), branch, and leaf biomass. Tree biomass determination primarily involves measuring the dry weight of each organ's biomass. Given that the calculation of single tree biomass entails assessing the trunk, branch, leaf, and root biomass, which is a challenging, time-consuming, and labor-intensive measurement process, we employed the grading standard wood method and the stump biomass model to calculate the tree layer's biomass across all years. Furthermore, the tree layer productivity of the sample plots is determined by the difference between the tree layer biomass of adjacent years, for calculating the biomass and productivity of the tree layer following formula was used (Rousseau *et al*., 1990; Germany *et al*., 2017):

$$Y_a = 0.15483 \times D^{2.17100}$$
$$W_a = \sum\nolimits_{i=2,4,6,\cdots,2n} n_i \times Y_a$$
$$NNP_a = W_a - W_{a-1}$$

where, Y represents the standard wood tree layer biomass ($t \cdot hm^{-2}$); 'a' signifies the stand age; D designates the standard wood diameter at breast height (cm); 'i' indicates the diameter step (cm); W stands for the tree layer biomass ($t \cdot hm^{-2}$); 'n' is the number of plants; and NPP defines the aboveground net productivity ($t \cdot hm^{-2} \cdot a^{-1}$).

Vegetation diversity calculations: Understory plant species diversity serves as a key index, reflecting the composition, function, succession patterns, and stability of the understory plant community structure. Herein, 3 indices were employed to delineate the community's species diversity: the species richness index (*S*), Shannon-Wiener diversity index (*H'*), and Pielou evenness index (*J*). The formulas for calculating the indices are as follows (Strong *et al*., 2016):

$$S = \text{Sum of all species in the survey sample}$$
$$H' = -\sum_{i=1}^{s} p_i \ln p_i$$
$$J = H'/\ln S$$
$$p_i = n_i/N$$

where,$p_i$as the relative plurality of the ith species, $n_i$as the cover of species I, and Nas the total cover across all species in the community. The "ith species" refers to the species at the iths position in this ordered list.

Data processing and analysis: Data on DBH and tree height growth for retained wood are compared here. Using SPSS 26.0 to conduct a descriptive statistical analysis and one-way ANOVA. Plotted and fit-tested the radial order frequency for both DBH and tree height, selecting an appropriate distribution function for further analysis. The productivity of the tree layer and the biomass, based on the radial order distribution, were derived from equation (Y_a) using Origin 2022 for plotting and one-way ANOVA. After determining the species diversity index via equation (H'), describe the changes in species diversity across the tree, shrub, and herb layers.

Results

Influence of conservation interval intensity on the growth of retained wood: Changes in stand DBH growth were observed across all thinning plots. The data revealed that plot A exhibited the lowest average DBH following felling in 2015, which was lower than the control plot, while it peaked in plot E (Table 2). Following the 2021 survey, disparate results emerged: the average DBH in plots A and F was lower than the control, while the remaining plots exhibited higher values than the control, with plot F the smallest average diameter at breast height, at 13.64cm was recorded. Except for plot F, both the total and annual diameter at breast height growth in the other intercutting plots surpassed those of the control plots. It was observed that the enhancement of tree DBH under intense thinning was reduced. Plot C displayed the highest total and annual growth of DBH, presenting a significant difference from the other plots (P<0.05). Over seven years, the total growth of DBH was 3.394 cm, surpassing the control plot by 1.92 cm. Moreover, the annual growth of DBH was 0.567 $cm\cdot a^{-1}$, which was 0.32 $cm\cdot a^{-1}$ greater than the control plot.

Data from Table 3 revealed that at post-thinning, the average tree height was lowest in plot C and peaks in plot E. Seven years later, survey results indicated that while the average tree height of plot C remains below the control, the deficit had diminished from 2.868m to 0.851m. Concurrently, all other plots surpassed the control, with plot B exhibiting the greatest average height of 16.21m. Each thinning plot demonstrates total and consistent annual tree height growth higher than the control, peaking at plot B with a total tree height growth of 5.71m and an annual increment of 0.95 $m\cdot a^{-1}$ over seven years. Furthermore, total and annual tree height growth displayed a pattern of initial increase, subsequent decrease, and final increase in tandem with the escalating intensity of thinning. Plot D exhibited the least variation in total tree height and annual growth, recording increases of 1.371 m and 0.228 $m\cdot a^{-1}$respectively, compared to the control plot.

Influence of the intensity of nursery intervals on the diameter distribution of forest stands: The diagram illustrates the characteristic values of the diameter distribution in the forest stand after varied thinning (Table 4). The tree layer exhibited a DBH of 5cm, establishing 5cm as the minimum value, while plot A recorded the maximum DBH value of 45.1cm. Average DBH varied between 12.93cm and 18.38cm, and post-conservation thinning, the plots demonstrated average DBH values lower than those in the control plots. Employing a diameter step distance of 2cm, the frequency distribution was analyzed, with results presented in Fig. 3 below. Diameter distribution in the control plot was predominantly within 12cm~22cm diameter steps, contrasting with the thinning plot, which was largely concentrated in the 6cm~18cm range. With a positive skewness, the diameter distribution exhibited a left-skewed single peak distribution. The diameter distribution in the thinning plots leaned towards medium and small diameter timber, with a reduced distribution of large diameter timber trees, notably those with a DBH exceeding 32cm were notably scarce.

Six distribution functions—Normal, Lognormal, Exponential, Gamma, Logistic, and Weibull-were selected to fit the diameter distribution of various nursery thinning plots, based on the characteristics of forest stand diameter distribution (Table 5). The K-S test indicated a better fit for the Gamma, Lognormal, and Weibull distributions in plots A, C, D, and F, excluding the remaining three distributions. In plot B, only the Weibull distribution passed the goodness-of-fit test, while plot E did not adhere to the exponential distribution but the remaining five did pass. Furthermore, the control plots adhered to the Gamma, Logistic, Normal, and Weibull distributions. In summary, the Weibull distribution most aptly fitted the diameter distribution for each plot post thinning.

Table 2. The change of DBH growth in different thinning intensity plots.

Plots	Average DBH after felling/cm	Average DBH at the end of the survey period/cm	Total growth/cm	Continuous growth volume/$cm\cdot a^{-1}$
A	11.446±5.614	14.146±6.143	2.823±1.485	0.472±0.247
B	14.372±7.612*	17.032±8.682*	2.932±2.271*	0.488±0.324
C	13.287±8.864	17.566±9.770**	3.394±2.242*	0.567±0.374*
D	13.472±5.250	14.942±5.897	1.631±0.971	0.271±0.162
E	15.183±5.764*	17.408±5.799**	2.391±1.869	0.398±0.312
F	12.275±6.421	13.641±6.605	1.313±1.060	0.218±0.177
CK	13.175±6.275	14.375±4.387	1.473±0.853	0.246±0.142

Note: The significance levels are labelled as: *, p<0.05; **, p<0.01; *** p<0.001, respectively

Table 3. The change of height growth in different thinning intensity plots

Plots	Average tree height after felling/m	Tree height at the end of the survey period/m	Total growth/m	Continuous growth volume/ $m\cdot a^{-1}$
A	9.973±4.462	15.000±6.241	4.976±63.094	0.829±0.516
B	10.513±4.428	16.207±7.251*	5.713±3.291**	0.952±0.548**
C	8.095±2.414	11.733±3.955	3.473±2.486	0.579±0.414
D	11.141±4.500	13.489±5.346	2.954±2.073	0.492±0.346
E	13.027±5.508*	16.091±5.435*	3.400±1.821	0.567±0.303*
F	12.388±7.402*	14.838±7.117	2.967±2.398	0.494±0.400
CK	10.963±3.658	12.584±4.639	1.583±1.438	0.264±0.136

Note: The significance levels are labelled as: *, p<0.05; **, p<0.01; *** p<0.001, respectively

Table 4. The characteristic values of the diameter of different thinning intensity plots.

Plots	DBH/cm						
	MIN	MAX	AVG	STD	CV	SK	KU
A	5.1	45.1	14.08	7.56	0.537	1.27	2.12
B	5.0	38.8	12.93	7.27	0.562	0.98	0.08
C	5.4	41.0	14.50	7.56	0.523	0.99	0.34
D	5.1	42.0	15.97	8.01	0.501	0.80	-0.21
E	5.2	42.3	17.28	7.79	0.451	0.44	-0.27
F	5.2	45.0	15.35	7.57	0.493	0.97	1.16
CK	5.1	42.6	18.38	7.53	0.410	0.61	0.12

Table 5. Parameters and test results of diameter distribution models of different thinning intensity plots.

Plots	Test	Index	Gamma	Logistic	Normal	Log-normal	Weibull
A	Parameters	0.071	3.472, 4.056	14.081, 4.167	14.081, 7.558	2.514, 0.508	5.086,9.438, 1.149
	K-S	0.307**	0.077	0.135**	0.123**	0.081	0.053
B	Parameters	0.077	3.234, 3.997	12.927, 3.963	12.927, 7.188	2.417, 0.526	5.000,7.963, 0.982
	K-S	0.321**	0.107**	0.185**	0.198**	0.112**	0.064
C	Parameters	0.069	3.662, 3.958	14.498, 4.177	14.498, 7.576	2.548, 0.498	5.384,9.603, 1.164
	K-S	0.074**	0.090	0.157**	0.136**	0.093	0.067
D	Parameters	0.063	3.950, 4.044	15.973, 4.431	15.973, 8.037	2.647, 0.501	5.041,11.891, 1.339
	K-S	0.290**	0.085	0.150**	0.129**	0.072	0.057
E	Parameters	0.058	5.00, 3.445	17.224, 4.247	17.224, 7.703	2.735, 0.493	4.268,14.464, 1.687
	K-S	0.251**	0.067	0.076	0.059	0.095	0.069
F	Parameters	0.065	4.117, 3.728	15.351, 4.171	15.351, 7.565	2.612, 0.493	5.137,11.026, 1.302
	K-S	0.295**	0.050	0.124**	0.111**	0.061	0.051
CK	Parameters	0.055	5.682, 3.215	18.266, 4.225	18.266, 7.663	2.812, 0.448	4.172,15.860, 1.902
	K-S	0.296**	0.053	0.070	0.079	0.085**	0.056

Note: The Significance levels are labelled as: *, $p<0.05$; **, $p<0.01$; *** $p<0.001$, respectively

Table 6. The characteristic values of the tree height of different thinning intensity plots.

Plots	DBH/m						
	MIN	MAX	AVG	STD	CV	SK	KU
A	4.1	26.7	11.85	5.29	44.65	0.52	-0.81
B	4.1	35.3	11.52	6.06	52.62	1.24	1.15
C	3.8	34.6	12.32	5.98	48.58	1.24	1.59
D	5.6	34.9	14.68	5.32	36.28	0.32	-0.51
E	3.1	29.8	16.02	5.44	33.94	0.11	-0.47
F	7.1	31.2	15.40	5.49	35.68	0.37	-0.57
CK	4.8	35.4	13.99	6.78	48.48	0.71	-0.13

Table 7. Parameters and test results of tree height distribution models of different thinning intensity plots.

Plots	Test	Index	Gamma	Logistic	Normal	Log-normal	Weibull
A	Parameters	0.084	5.015, 2.364	11.854, 2.918	11.854, 5.293	2.3703, 0.459	3.963,8.697, 1.468
	K-S	0.306**	0.113**	0.171**	0.150**	0.096	0.084
B	Parameters	0.087	3.611, 3.189	11.516, 3.341	11.516, 6.060	1.778, 0.779	4.084,8.047, 1.277
	K-S	0.335**	0.146**	0.221**	0.204**	0.143**	0.125
C	Parameters	0.081	4.238, 2.907	12.320, 3.300	12.320, 5.985	2.406, 0.453	3.729,9.559, 1.511
	K-S	0.327**	0.069	0.136**	0.122**	0.074	0.061
D	Parameters	0.068	7.599, 1.932	14.677, 2.936	14.677, 5.325	2.616, 0.383	5.182,10.774, 1.832
	K-S	0.347**	0.085	0.114**	0.092**	0.100**	0.082
E	Parameters	0.062	8.682, 1.845	16.02, 2.997	16.02, 5.437	2.708, 0.381	1.409,16.384, 2.959
	K-S	0.345**	0.098	0.081	0.128	0.095**	0.067
F	Parameters	0.065	7.856, 1.961	15.401, 3.030	15.401, 5.495	2.668, 0.372	6.711,9.598, 1.531
	K-S	0.369**	0.078	0.098	0.076	0.095	0.095
CK	Parameters	0.071	4.255, 3.288	13.99, 3.739	13.99, 6.782	2.519, 0.497	4.736,9.969, 1.292
	K-S	0.295**	0.083**	0.135**	0.113	0.077**	0.075

Note: The significance levels are labelled as: *, $p<0.05$; **, $p<0.01$; *** $p<0.001$, respectively

Upon analyzing each parameter of the stand diameter's Weibull distribution, the location parameter *a* was observed to range from 4.17 to 5.39. All values of *a* from thinning were larger than those of the control plot, indicating that the thinning targeted trees with the smallest diameter class for felling. The scale parameter *b* ranged from 9.842 to 15.86, with *b* values lower than those in control plots. Notably, the reduction of *b* value was more pronounced at low thinning intensities and less so at high thinning intensities, recording reductions of 39.59%, 49.42%, 38.80%, 29.60%, 11.30%, and 31.55% from the control, respectively. Values for the shape parameter *c* ranged from 0.866 to 1.902, revealing a positively skewed mountainous distribution curve. Furthermore, *c* values were lower than those in the control plots.

Influence of the intensity of nursery thinning on the tree height distribution of a forest stand: As depicted in Table 6, the distribution of tree heights in the forest stands exhibited substantial variations post-conservation thinning, with minimum values ranging between 3.8m and 7.1m, maximum values between 26.7m and 35.4m, and average tree heights spanning 11.52m to 16.02m. Notably, under 10%-20% conservation thinning, the average heights were lower than those in control plots, reaching their apex in the E plots. The tree height's coefficient of variation (CV) generally proved to be higher across varied plots, with plot B recording the largest CV and plot E the smallest. All plots demonstrated a skewness in tree height distribution greater than 0, indicative of a left-skewed distribution. Moreover, kurtosis values exceeded 0 in plots B and C, representing a sharp peak relative to the normal distribution, while other plots showcased flat peaks. As illustrated in Fig. 4, in the A and B sample plots, tree height distribution between 4m and 8m exceeded 40% (43.27 and 53.96%). With escalating thinning intensity, the number of medium-height strains burgeoned, clustering within 10 to 20m range, with respective cumulative strain percentages of 52.47, 71.37, 68.48, and 68.32%, and the control sample plots exhibited percentages of plants within the two tree height ranges at 31.05 and 51.62%.

The K-S test revealed distinct variances in tree height distribution functions when fitted to tree heights following varying thinning intensities (refer to Table 7). For plots A and B, the lognormal and Weibull distributions were the best fit, excluding the remaining four distributions; in plot C, the Gamma, Lognormal, and Weibull distributions provided a superior fit, with the remaining three distributions excluded. Plot D adhered to the Gamma and Weibull distributions, excluding the rest; plot E did not comply with the exponential and lognormal distributions, although the remaining four passed the goodness-of-fit test. In plot F, only the exponential distribution was not adhered to, with all other distributions being accepted; and the control sample plots adhered to the normal and Weibull distributions. In conclusion, the Weibull distribution can effectively fit the distribution of tree heights post-thinning in this stand type.

Upon analyzing each parameter of the Weibull distribution of stand tree height, it was observed that the location parameter *a* ranged from 1.409 to 5.182, the scale parameter *b* from 8.047 to 16.384, and the shape parameter *c* from 1.277 to 2.959. Both parameters *b* and *c* exhibited a trend of initially increasing and subsequently decreasing with the escalation of thinning intensity, reaching their maximum values in plot E.

The effect of nursery thinning on productivity and biomass of the tree layer: This study delineates the productivity per diameter step in mixed conifer forests subject to various thinning intensities (Fig. 5). Observing, the post-thinning productivity percentage for 20-24 cm diameter steps was recorded as 15.48, 25.01, 32.41, 40.64, 45.36, 50.14, and 63.81% for plots CK, A, B, C, D, E, and F, respectively (Fig. 5). Moreover, for diameter steps exceeding 26cm, the percentages were 2.02, 3.64, 5.73, 6.21, 7.32, 7.45, and 8.03%. Evidently, the productivity proportion of larger diameter steps (20cm and above) ascended with intensifying thinning, a consequence of the promotion of forest tree growth by thinning, and thereby elevating the count of plants in larger diameter steps of 20cm and above as thinning intensity amplifies.

Upon analyzing the average biomass and productivity of the tree layer in mixed conifer forests, subjected to six different thinning intensities (Table 8), a clear pattern emerges: six years post-thinning, a consistent decrease in the biomass of each tree layer correlates with an increase in thinning intensity, whereas average productivity of the tree layer conversely increases. ANOVA results indicate that while the difference in average biomass between plots B and C is not significant ($p>0.05$), distinctions between other treatments are significant ($p<0.05$). Similarly, the average productivity difference between plots C and D is not significant ($p>0.05$), whereas it is significant among the other treatments ($p<0.05$). It is evident that thinning enhances the productivity of the tree layer in mixed forests, with a more pronounced increase as thinning intensity escalates. Nonetheless, the number of plants notably influences the biomass of the tree layer, thereby reducing the average biomass due to thinning.

Table 8. Mean biomass and productivity of the tree layer in stands with different thinning intensities.

Plots	Average biomass of tree layer/ ($t\cdot hm^{-2}$)	NPP tree layer / ($t\cdot hm^{-2}\cdot a^{-1}$)
A	276.301±2.714 **	4.375±0.072*
B	266.804±4.784	4.497±0.087*
C	254.361±0.745	4.522±0.012
D	244.314±2.497*	4.589±0.014
E	213.578±1.247 *	4.621±0.036*
F	203.311±0.657 *	4.714±0.121*
CK	309.321±7.905 **	4.217±0.136*

Note: The significance levels are labelled as: *, $p<0.05$; **, $p<0.01$; *** $p<0.001$, respectively

Changes in species diversity after conservation thinning: Six years post thinning, approximately 16 tree species occupied the tree layer of the survey sample site, as depicted in (Table 9) Prominent species included *T. amurensis*, *A. fabri*, *A. mono*, *P. asperata*, *A. tegmentosum*, and *P. koraiensis*, contributing importance values of 10.7%, 12.28%, 13.68%, 11.31%, 11.01%, and 13.03% respectively, totaling 72.01%. (Table 10) reveals the species richness index (*S*) for each sample site's tree layer, indicating that sample plot A surpasses the control plot in value, while the remaining sample plots fall below it, with sample plot D exhibiting the lowest value of 5.As the monitoring time neared the renovation period, most tree species retained in the plots were remnants post thinning. Both species from artificial regenerative supplemental planting and those from natural regeneration are mature forests, consequently yielding a combined value lower than the control plot. Values for other indexes exceeded those of the control plot, with the Shannon-Wiener diversity index peaking at 2.01 in plot A and plunging to a minimum of 1.56 in plot D (As in Fig. 6). While Pielou's evenness index demonstrated a trend of initial increase followed by a decrease with intensified thinning, the variance among the plots was not significant.

Dominant shrub layer species in the thinning plots comprised *S. cotulifer*, *C. heterophylla*, *L. japonica*, *S, sorbifolia*, *P, quinquefolia*, *A, senticosus*, *P, padus*, and *C, tomentosa*, among others. The species richness index of the shrub layer was lower than the control plot in plot A, equivalent in plots B and F, and higher in all remaining plots. Except for plot A, values of the Shannon-Wiener diversity and Pielou's evenness index in the shrub layer exceeded those in the control plot. These indices peaked in plots D (1.50) and C (0.95) respectively (As in figures 6 and 7), and generally exhibited an increase followed by a decrease with escalating intensity of thinning.

Dominant species in the herbaceous layer across thinning plots were *A. brevifrons*, *P. ternate*, *C. callitrichos*, *D. langsdorffii* and *U. cannabina*. In plots A and E, the species richness index (S) of the herb layer was below the control plot's value, while in the remaining sites, it matched the control plot (S = 3) (Fig. 8). The Shannon-Wiener diversity index (*H*) of the herb layer fell below the control plot's values in plots A, B, and E, hitting a minimum of 0.90 in B (Fig. 6). Conversely, it surpassed control plot values in the remaining plots, peaking at 1.09 in D. All thinning plots displayed a Pielou evenness index (*J*) for the herbaceous layer that exceeded the control plot's index, ranging from a low of 0.90 in plot B to highs of 0.95 in plots E and F (As in Fig. 7).

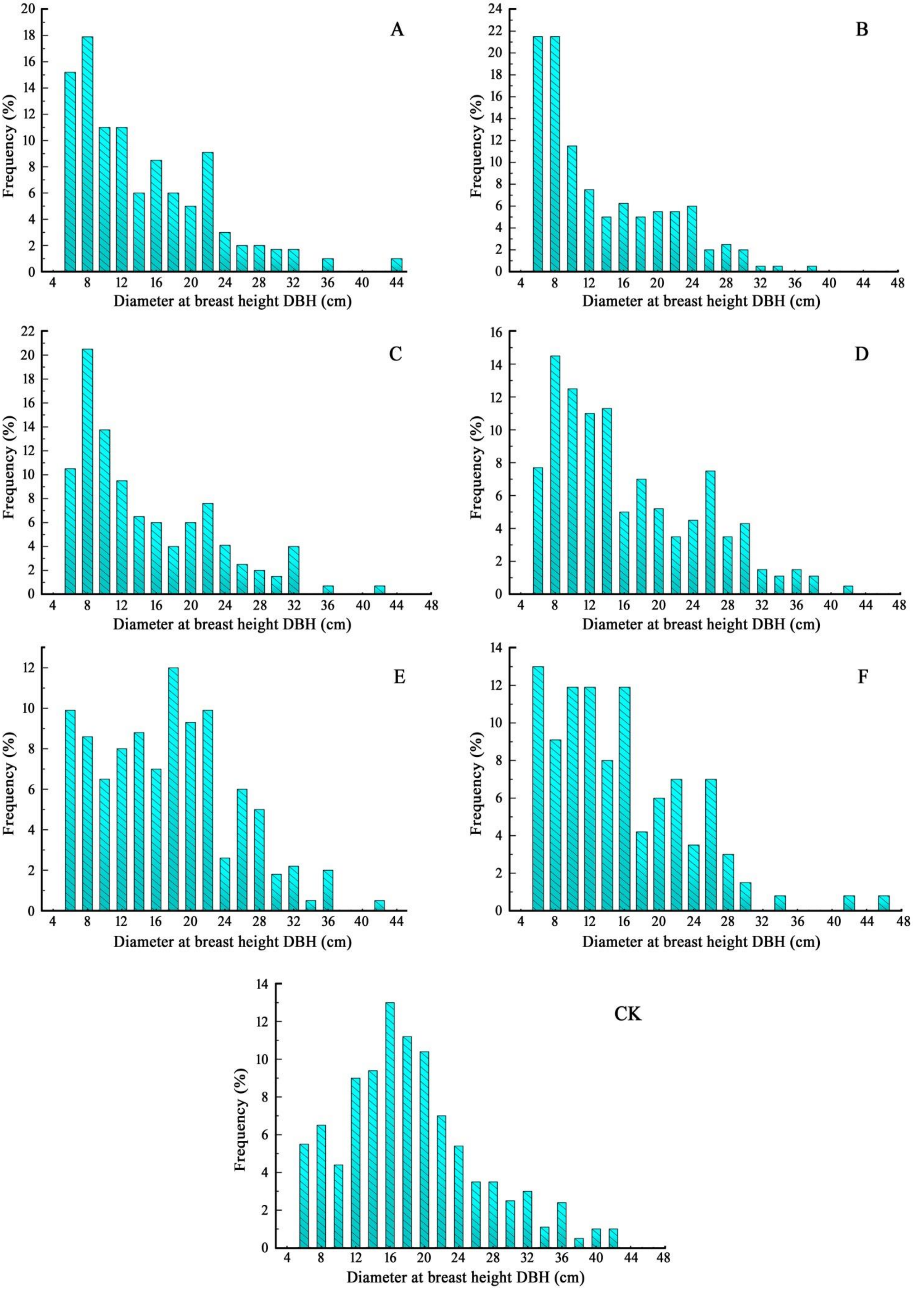

Fig. 3. The diameter distribution of different thinning intensity plots (Note: A=Plot-1, B= Plot-2, C=Plot-3, D=Plot-4, E=Plot-5, F= Plot-6, CK= Plot-7).

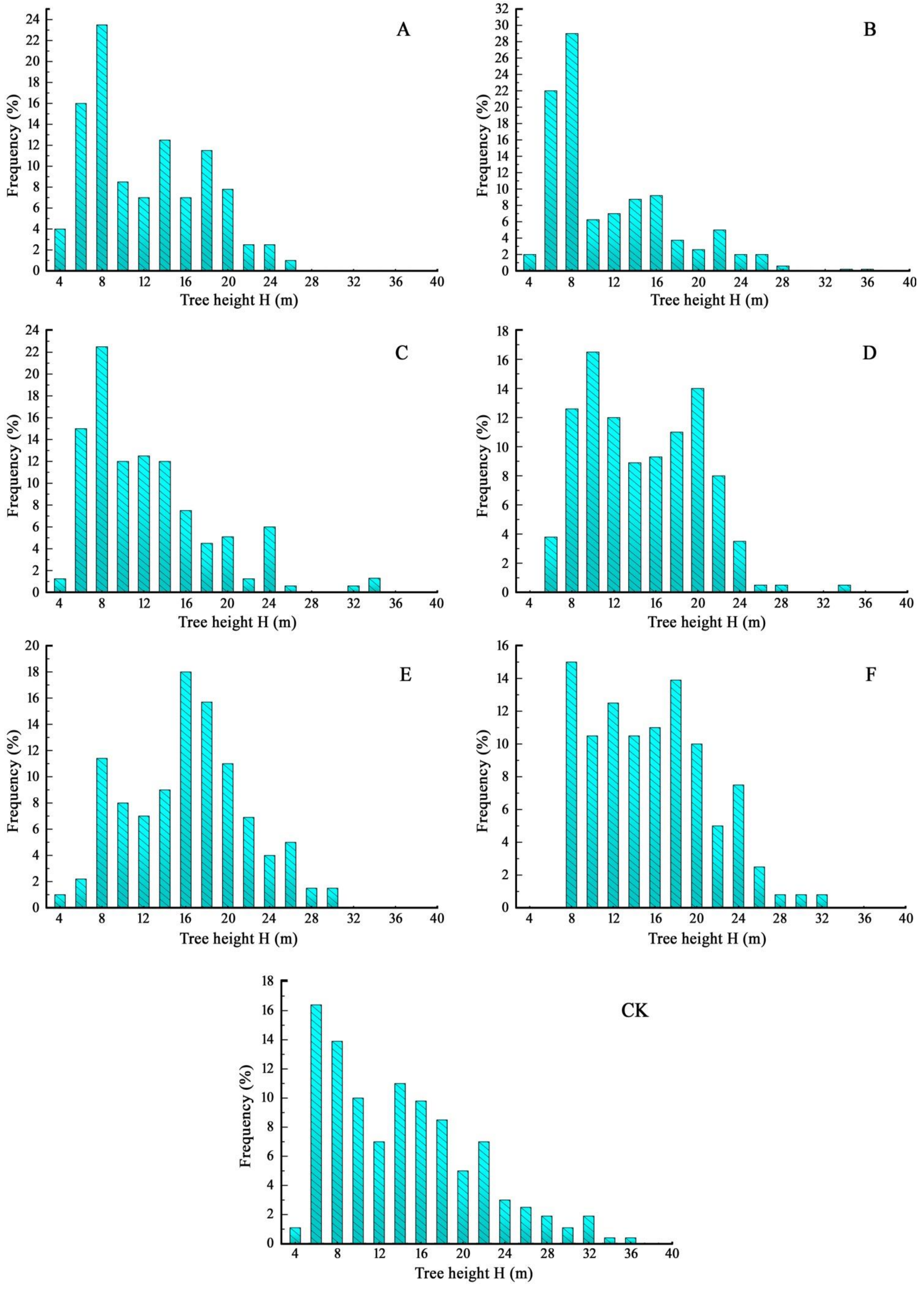

Fig. 4. The tree height distribution of different thinning intensity plots (Note: A=Plot-1, B= Plot-2, C=Plot-3, D=Plot-4, E=Plot-5, F= Plot-6, CK= Plot-7).

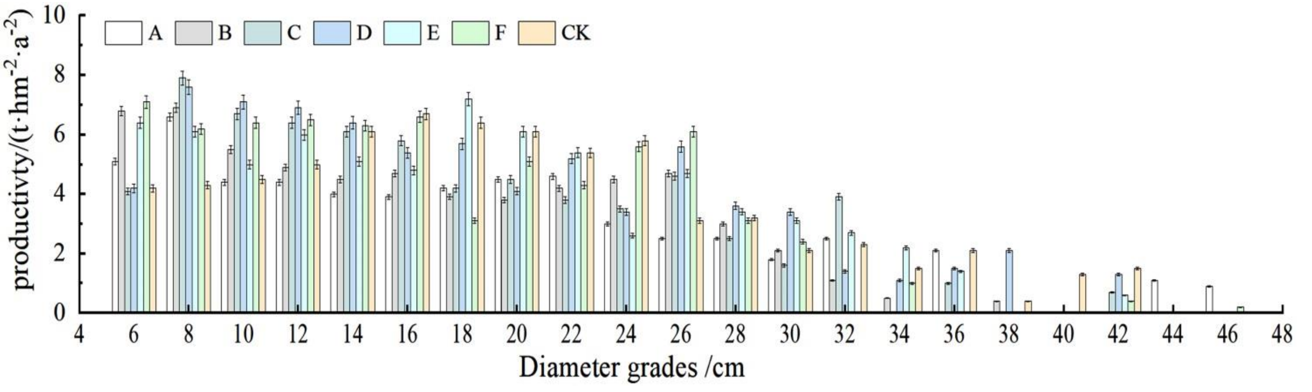

Fig. 5. Productivity distribution of retained wood by diameter step after different intensity of thinning.

Table 9. The important value of species composition in the plots.

Tree species	Relative abundance/ %	Relative superiority/ %	Relative frequency/ %	Important values/ %
Tilia amurensis	11.16	10.82	10.11	10.70
Phellodendronamurense	1.09	1.44	1.44	1.32
Abies fabri	10.15	14.24	12.45	12.28
Acer mono	13.06	16.61	11.37	13.68
Picea asperata	9.62	11.86	12.45	11.31
Populus ussuriensis	1.72	3.46	1.99	2.39
Fraxinus mandschurica	8.32	5.87	7.94	7.38
Betula costata	4.04	4.43	3.97	4.15
Acer tegmentosum	15.10	6.00	11.92	11.01
Pinus koraiensis	11.49	16.96	10.65	13.03
Acer ukurunduense	6.48	2.32	5.23	4.68
Syringa reticulata var. *amurensis*	1.20	0.28	2.17	1.21
Juglans mandshurica	0.76	1.01	0.72	0.83
Ulmus ropinqua	2.60	1.23	4.15	2.66
Amygdalus davidiana	1.27	1.55	1.99	1.60
Salix babylonica	1.94	1.93	1.44	1.77

Note: Significant values ($p<0.05$) are presented in lowercase

Table 10. Effects of different thinning intensities on biodiversity over a period of six years.

Plots	Trees			Shrubs			Herbal		
	S	***H***	***J***	***S***	***H***	***J***	***S***	***H***	***J***
A	10	2.01	0.89	3	0.95	0.81	2	0.91	0.91
B	8	1.86	0.89	4	1.15	0.92	3	0.90	0.90
C	7	1.77	0.90	5	1.47	0.95	3	1.08	0.94
D	5	1.56	0.94	5	1.50	0.94	3	1.09	0.93
E	7	1.78	0.94	5	1.40	0.92	2	0.95	0.95
F	6	1.63	0.91	4	1.14	0.89	3	1.01	0.95
CK	9	1.45	0.86	4	0.96	0.87	3	0.98	0.88

Discussion

Currently, nurturing thinning stands as the predominant method for restoring natural mixed conifer and broadleaf forests, with studies indicating diverse thinning intensities exert beneficial impacts on such forests. Light or moderate thinning may be employed if the objective is to foster the growth of small to medium-diameter timber. Heavy thinning proves more beneficial for cultivating large-diameter timber as the demand for it rises.

The study revealed a unimodal, left-skewed diameter and tree height distribution in the forest stand post thinning. Large-diameter trees were scarcer than their medium and small-diameter counterparts in the diameter distribution. The tree height distribution underwent a significant transformation following thinning. Specifically, less intense thinning concentrated tree height within 4 to 8 meters, whereas increased thinning intensity shifted this concentration to a 10 to 20 meters range. Contrary to these findings, the study asserted that optimal diameter distribution should adhere to an inverted "J" pattern, while the ideal tree height distribution should exhibit a continuous, negative exponential trend. The middle-aged forest stand, disturbed and destabilized post thinning, experienced intense tree competition, significantly inhibiting understory young tree growth due to suboptimal management post thinning. Inadequate management following thinning prevented the forest stand from progressing towards an ideal state.

The chosen fitted distribution functions encompass six distinct types: Normal, Lognormal, Exponential, Gamma, Logistic Steele, Weibull, and additional variants. Test analyses determined that the Weibull distribution function accurately simulates both the diameter and tree height distributions of the forest stand following nursery thinning. Furthermore, numerous past studies and this paper (Kohout, 2022) affirm the widespread use of the Weibull distribution. The Weibull distribution parameters do not exhibit clear patterns of change with increasing thinning intensity. Specifically, the diameter distribution's position parameter *a* range from 3.963 to 5.384, scale parameter *b* from 7.963 to 15.86, and shape parameter *c* from 0.982 to 1. 902. For the height distribution, position parameter *a* range from 1.409 to 5.182, scale parameter *b* from 8.047 to 16.384, and shape parameter c from 1.277 to 2.959. Moreover, the *b* and *c* values in the fostering thinning plots' diameter distribution were lower than those in the control plots. The *b* and *c* values of the Weibull parameter in the tree height distribution demonstrated an initial increase followed by a decrease with thinning intensity, peaking at 30% intensity.

This study found that retained wood exhibited robust growth at medium thinning intensity when soil moisture and fertility conditions were optimally enhanced. Additionally, the retained wood provided shade for the renewal of coniferous seedlings, benefiting early-stage seedlings less tolerant of shade. Overall, the growth of retained wood proved beneficial. This aligns with the findings of (Duan *et al.*, 2010; Xu *et al.*, 2010). Forest stand growth is influenced by numerous factors, including stand conditions, forest type, and disturbance degree, with stand conditions being predominant. Adopting a medium-weak conservation degree is typically apt under suboptimal stand conditions (Picchio *et al.*, 2020; Vacek *et al.*, 2023).

Thinning failed to simultaneously increase the tree layer's biomass and productivity (Moghli *et al.*, 2022). While thinning intensity in cedar plantation forests can enhance individual plant biomass and overall stand productivity, a reduced stand density causes a decrease in per-unit-area biomass with increased thinning intensity, aligning with the findings of this study (Lo Monaco & Cantiani, 2021). Comparing the biomass and productivity increase in the tree layer impacted by thinning revealed that the tree biomass of plots A, B, C, D, E, and F after six years of thinning was reduced by 10.67, 13.91, 17.80, 21.04, 31.07, and 34.30%, respectively, compared with that of plot CK, and the tree productivity was increased by 3.76, 6.60, 7.23, 8.82, 9.58, 11.79%, plots D and E experienced smaller biomass losses with similar productivity increases, signifying that plot E optimally balanced the relationship between biomass reduction and productivity increase in the stand's tree layer. Other concluded that in North China's larch plantation forests, heavy thinning (50%) effectively bolstered stand productivity while preserving tree layer biomass, suggesting varying optimal thinning degrees for different tree species to balance tree layer biomass and stand productivity (Shang *et al.*, 2019). Collectively, this study's results showed that the optimal balance between tree biomass and productivity in mixed conifer-broadleaved forests was achieved using medium thinning plot E, specifically, medium thinning (30%).

Understory shrub and herb diversity escalates with thinning intensity, primarily due to these plants' specific lighting requirements for growth (Li *et al.*, 2020). Reducing canopy closure post-thinning allows these plants to receive essential light, thereby accelerating understory plant development and promoting plant community growth (Yang *et al.*, 2023). Our synthesis and analysis found that medium-light-transparent thinning optimally maintains community species richness and diversity It was found that the results of other studies were different from compared to this study (Xu *et al.*, 2019). The strong thinning damaged the habitat conditions of the forest floor, and the brief duration of thinning hindered short-term recovery of forest regeneration growth (Pradhan *et al.*, 2023). Under moderate disturbance, forest stand habitat conditions altered, allowing some new or exotic species to gradually adapt. This, coupled with the absence of dominant species formation, resulted in enhanced species diversity (Vacek *et al.*, 2021; Vacek *et al.*, 2023). In conditions of low disturbance, overall ecosystem changes are minimal, dominant tree species gradually form the forest stand, and according to evolutionary theory, some inferior tree species are gradually eliminated, decreasing species diversity (Hoeber and Zotz, 2022). Consequently, it is inaccurate to assert that higher deforestation intensity invariably leads to increased stand species diversity (Koelemeijer *et al.*, 2021).

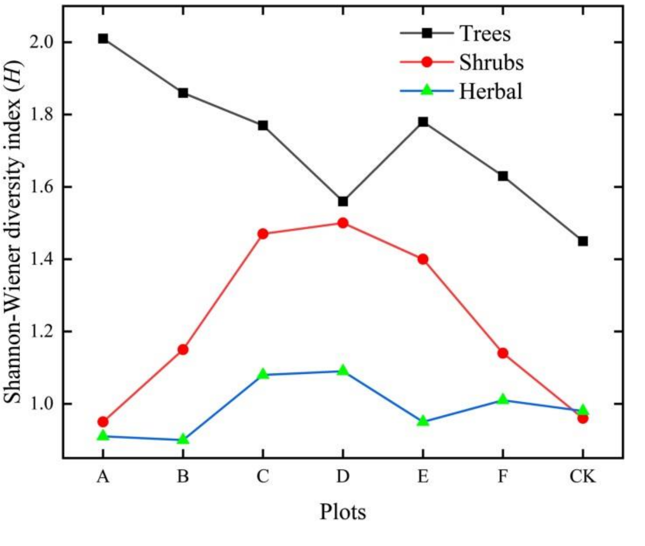

Fig. 6. Shannon-Wiener diversity index for different plots.

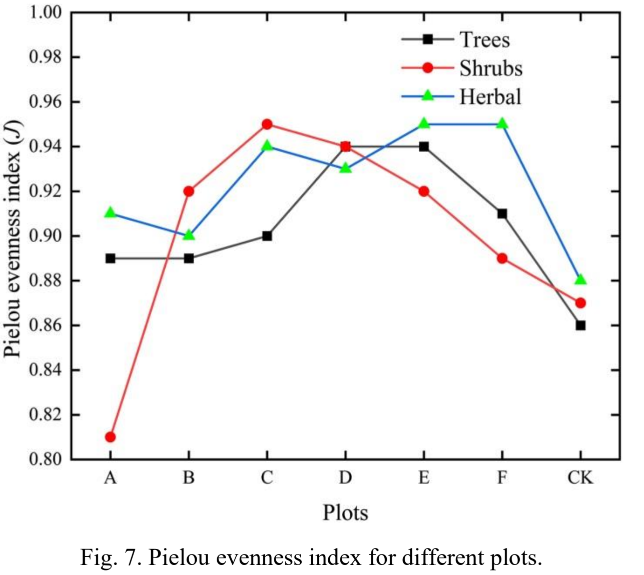

Fig. 7. Pielou evenness index for different plots.

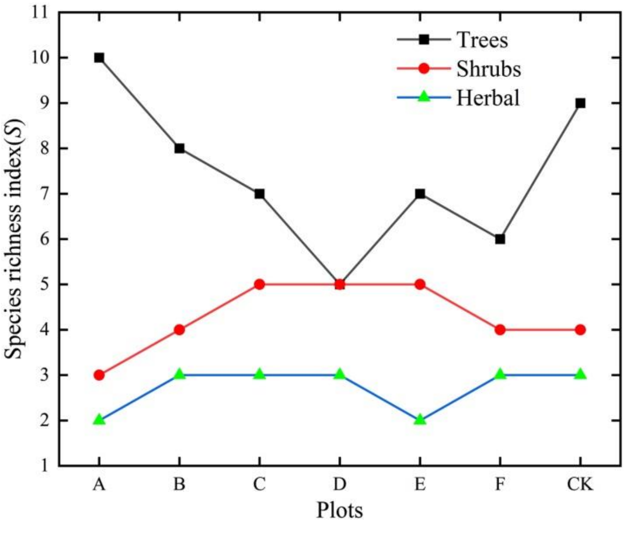

Fig. 8. Species richness index for different plots.

Conclusions

This study employed metrics such as tree height and DBH growth, tree height and DBH distribution, tree productivity, biomass, and species diversity to gauge the growth of forest stands subjected to various levels of thinning. Thinning notably accelerated both the average productivity of the tree layer and the growth of the stand, with the promotional effect strongly correlating with the intensity of thinning. Small-diameter trees in the stand demonstrated superior growth to large-diameter trees under conditions of light and moderate thinning. The height and diameter distributions of the stand adhered to the Weibull distribution function. Thinning significantly influenced stand diameter and height distributions, with increasing thinning intensity gradually shifting the diameter distribution to the right. This means that the percentage of large diameter trees was increased, while that of small diameter trees was decreased, elevating the proportion of trees in the large diameter class. All thinning plots showcased an overall enhancement in species diversity. Based on the experimental results, conservation thinning evidently fosters the development of natural mixed coniferous and broadleaf forests. This not only benefits the growth of large diameter class trees but also amplifies the productivity and species diversity of the entire stand.

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