



ISSN: (Print) (Online) Journal homepage: <https://www.tandfonline.com/loi/tfst20>

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To cite this article: Batsaikhan Ganbaatar, Tsogtbaatar Jamsran, Alexander Gradel & Gerelbaatar Sukhbaatar (2021) Assessment of the effects of thinnings in scots pine plantations in Mongolia: a comparative analysis of tree growth and crown development based on dominant trees, Forest Science and Technology, 17:3, 135-143, DOI: [10.1080/21580103.2021.1963326](https://doi.org/10.1080/21580103.2021.1963326)

To link to this article: <https://doi.org/10.1080/21580103.2021.1963326>



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Published online: 01 Sep 2021.



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# Assessment of the effects of thinnings in scots pine plantations in Mongolia: a comparative analysis of tree growth and crown development based on dominant trees

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## ABSTRACT

The post-thinning stand density and spacing in forest plantations influence individual tree growth and crown development, and the changes detected in dominant tree growth are a good indication of the thinning effect. The objective of this study was to determine the effects of different thinning intensities on diameter and height growth in a Scots pine (*Pinus sylvestris* L.) plantation. The field measurements were carried out between 2016 and 2020 on a Scots pine plantation, growing in Selenge province of northern Mongolia. Following this, experimental thinnings were carried out with different intensities. Thinning treatments comprised thinning with very low, low, medium, and high intensities, as well as an unthinned control stand. Stem analyses were performed to calculate the annual and cumulative diameter, height, and volume growth. For tree crown measurements several parameters were analyzed: crown diameter, crown projection area, and crown index. A total of 300 trees (5 treatments\*3 replications\*20 dominant trees from each plot) were subjected to the comparative analyses. This study revealed that thinning showed a stronger positive effect on diameter and volume growth of dominant trees in the plantation. Our results showed a gradual increase in diameter, basal area, and volume growth depending on the thinning intensity. An ANOVA test for growth analyses of dominant trees showed a significant difference in diameter ( $p < 0.0001$ ) and height ( $p < 0.0001$ ) growth performance following experimental felling with different thinning intensities. Finally we elaborated linear mixed effect models (LMM) for tree growth between 2016 and 2020 of selected dominant trees. With the help of the LMM we analyzed and described the thinning impact on DBH, BA, height, volume and crown diameter. The models confirmed that higher thinning intensity triggered growth of the response variables except for height. A greater height growth was found in very low (10%) and low (15%) intensity treatments. Due to reduction of competition and optimization of the distance between individuals, thinnings contributed to a relatively faster development of the tree crown in radial directions. Based on our analysis results and comparative graphs representing post-thinning dominant tree growth in diameter, height, basal area, and volume, we recommend medium- (30%) and high-intensity (45%) thinnings as at the beginning stage of plantation establishment.

## ARTICLE HISTORY

Received 7 April 2021  
Accepted 18 July 2021

## KEYWORDS

Thinning intensity;  
dominant height; growth;  
crown development;  
tree spacing

## 1. Introduction

To achieve forest management objectives, individual tree and stand development are manipulated by applying an array of silvicultural treatments. A number of previous studies have shown that changes in growth performance of planted trees may be due to limited light availability (Kunstler et al. 2005; Hattori et al. 2009), nutrient deficiencies (Óskarsson et al. 2006; Lof et al. 2007), interspecific competition (Osunkoya et al. 2005), and changing environmental factors (Hattori et al. 2013). Among silvicultural treatments, thinning is one of the most common and effective silvicultural

practices for regulating competition between individual trees, and gives an advantage to the selected remaining trees (Pretzsch 2009).

Previous thinning studies have demonstrated a strong effect on the individual tree diameter and volume growth with decreasing stand density (Mäkinen & Isomäki 2004; Kim et al. 2016), and weak effect on height growth (Weiskittel et al. 2009). Forest stand diameter and height, which are important variables in forest growth modeling, can be defined either as mean or dominant stand diameter and height (Tarmu et al. 2020). Burkhart and Tomé (2012) noted that dominant stand height, which is suggested to be an indicator

**Table 1.** Description of the sample plots, inventoried for this study.

| Treatments               | Thinning year | Year of planting | Thinning intensity | Aspect | Slope (°) | Altitude (m) | Soil type  | Stand density (stems ha <sup>-1</sup> ) | Mean distance between trees in row (m) |
|--------------------------|---------------|------------------|--------------------|--------|-----------|--------------|------------|---|--|
| Control stand (CS)       | 2016          | 2003             | –                  | NE     | 3         | 720          | Sandy loam | 2150                                    | 1.0                                    |
| Very low intensity (VLI) | 2016          | 2003             | 10                 | NE     | 4         | 726          | Sandy loam | 2100                                    | 1.2                                    |
| Low intensity (LI)       | 2016          | 2003             | 15                 | NE     | 3         | 735          | Sandy loam | 2000                                    | 1.3                                    |
| Medium intensity (MI)    | 2016          | 2003             | 30                 | NE     | 3         | 720          | Sandy loam | 1233                                    | 2.1                                    |
| High intensity (HI)      | 2016          | 2003             | 45                 | NE     | 2         | 721          | Sandy loam | 680                                     | 3.0                                    |

measure of site productivity, is widely used in other countries. One of the most common definitions is top height, which is defined as the average height of a fixed number of trees per unit area with the largest diameters at breast height (Sharma et al. 2006; West 2009; Burkhart and Tomé 2012). This is a key assumption underlying the use of a site index, defined as the maximum height (mean height of dominant and codominant trees) of a stand at a specified (index) age, as an indicator of site quality (productivity).

Therefore, tree spacing in plantations becomes an important silvicultural tool that influences the sequence of future silvicultural treatments required and, ultimately, the stand attributes at harvesting age. Scots pine, a light-demanding tree species, requires almost full sunlight to grow. Consequently, thinning is often practiced to open up the canopy to increase plantation productivity and reduce density-dependent mortality, redistributing the availability of light, nutrients and water to residual trees (Weng et al. 2020). Moreover, several studies have shown that thinning substantially improves stem diameter growth, but has little impact on tree height growth (Pape 1999; Mäkinen and Isomäki 2004; Hébert et al. 2016; Weng et al. 2020). These studies mainly focused on short- and long-term responses to incorporate thinning responses into growth and yield models.

Mongolia has a relatively low amount of forest resources. Forest cover represents roughly 7–8% of the territory (MPNFI 2016), and is found in the transitional zone between the Siberian boreal forest and the Central Asian dry steppe (Mühlenberg et al. 2012). This transition zone is characterized by a sharply continental climate with dry winters. Forests in Mongolia mainly grow on mountain slopes between 700 and 2500 m a.s.l. The first reforestation trials were carried out in Mongolia in the 1970s. However, efforts at forest rehabilitation with native species have had relatively limited success across the country (Sukhbaatar et al. 2020). All of these plantations were created to limit deforestation in the country, and were mainly focused on restoring heavily logged and burned areas.

Despite the importance of forest plantations in Mongolia, there is little information on the optimal thinning intensity, which is well-adapted in the semi-humid conditions of northern Mongolia. The main objectives of this study were as follows: (1) to

investigate the relationship between tree growth and thinning intensity using measurement data collected from dominant trees in sample plots and (2) to determine the optimal thinning intensity to accelerate tree growth in the early stage of plantation establishment.

## 2. Methods and materials

### 2.1. Study area

The present study was carried out on Scots pine plantations (50°05' and 50°12'N, 106°14' and 106°31'E) established in 2003 in the territory of “Tuijin nars” National park of Selenge province, Mongolia. The study area lies within the northern boreal forests of northern Mongolia, which are located along the southern edge of the Siberian Sub-taiga forests (Mühlenberg et al. 2012). According to the Köppen-Geiger World Climate Classification Map (Peel et al. 2007), the region belongs to a climatic transition zone between a cool continental climate (Dwc) and a cold semi-arid climate (Bsk). According to observations of the climate from the last 20 years, the average temperature and annual precipitation in the study area were 0.6° C and 280.3 mm, respectively. The soil in the study area is Arenic podzols, which were derived from sandy sediments and loess (Batkishig 2016). The plantation was established on a clear-felled area using 2-year old bare-root seedlings of Scots pine with an initial planting density of 2500 seedlings ha<sup>-1</sup>, planted with 4.0 × 1.0 m spacing.

### 2.2. Experimental design and treatments

Experimental thinning operations were performed in May 2016. Comparative experimental cutting treatments included different thinning intensities: very low intensity (VLI), low intensity (LI), medium intensity (MI), high intensity (HI), and control stand without felling (CS) (Table 1).

The thinning intensity was determined based on the pre- and post-cutting basal area estimates. The cuttings involved priority suppressed, damaged and medium-sized trees growing in the plantation. All trees cut during the felling were removed from the experimental plots.

### 2.3. Tree measurements and data collection

Repeated field measurements and data collection on experimental rectangle-shaped (500 m<sup>2</sup>) sample plots were carried out annually at the end of each growing season between 2016 and 2020.

Field data collection and measurements included diameter at breast height (DBH), tree height, height up to lowest live branch, crown diameter (north + south; west + east) and distance between individuals using a digital caliper, altimeter and measuring tape. A total of 300 dominant trees (5 treatments\*3 replications\*20 dominant trees from each plot) were subjected to the comparative analyses.

### 2.4. Statistical analyses

The thinning intensity was expressed by the relative removal of basal area per plot (see Table 1), the thinning weight (rG) (Murray & Gadow 1993). Additionally, thinning type (NG) (Gadow et al. 2012) was calculated by using the following equations:

$$rG = \frac{G_{\text{removed}} (m^2/ha)}{G_{\text{total}} (m^2/ha)} \quad (1)$$

$$NG = \frac{(N_{\text{removed}}/N_{\text{total}})}{G_{\text{removed}}/G_{\text{total}}} \quad (2)$$

where: rG is the thinning weight, here denoted as THIN; N is the stem density (stem ha<sup>-1</sup>); G is the stem basal area (m<sup>2</sup> ha<sup>-1</sup>).

Thinning weight reflects thinning intensity based on basal area of stand. The NG ratio indicates a removal from below of mostly suppressed trees (NG values > 1), or from above if the dominant trees are removed (NG values < 1). When the NG values are equal to one, the number of removed stems is proportional to the removed basal area (Gadow et al. 2012; Vítková et al. 2016).

Crown dimensions were calculated as follows:

$$CD = \frac{(D_{\text{north+south}} + D_{\text{west+east}})}{2} \quad (3)$$

$$CPA = \frac{3.14 * CD^2}{4} \quad (4)$$

$$CFI = \frac{CH}{CD} \quad (5)$$

where: CD is the crown diameter;  $D_{\text{north+south}}$  is the crown diameter from north to south;  $D_{\text{west+east}}$  is the crown diameter from west to east; CH is the crown height; CFI is the crown form index; and CPA is the crown projection area

Therefore, the tree crown diameter (Equation 3), form index (Equation 4) and projection area (Equation 5) were calculated to evaluate the effect of thinning on tree crown development. XLSTAT by Addinsoft was used for statistical analysis. A one-way analysis of variance (ANOVA) was adopted to assess the significance of differences among thinning intensities. Duncan's multiple range test (DMRT) was used for multiple comparisons.

### 2.5. Analysis of factors for increasing crown width on the thinned plots

We chose a linear mixed model approach (LMM) for analyzing fixed factors (Zuur et al. 2009; R-bloggers 2011) for the relative growth of the 5-year period (2016–2020). We elaborated different models for the relevant response variables with the thinning intensity (THIN) as fixed factor. As response variables we selected the following variables: DBH (cm), basal area (m<sup>2</sup>), height (m), volume (m<sup>3</sup>), crown diameter (m). The models were optimized based on the restricted maximum likelihood method (REML) (Zuur et al. 2009; R-bloggers 2011). Every initial model run was evaluated by a standard procedure of regression diagnostics with Q-Q plots with a 95% confidence envelope (Robinson and Hamann 2011). Outliers were detected and eliminated based on the distribution of internally studentized residuals. Models were selected according to Akaike's Information Criterion (AIC) and Bayesian information criterion (BIC), the plausibility of the intercept, the distribution of residuals, the p-values of the fixed factors and the plausibility of the respective model from an ecological point of view (Gradel et al. 2017). The thinning weight (THIN) as fixed factor provided the best results. Random effects (site and plot) were included. The following model was selected:

$$[Gr] = (\beta_0) \text{Intercept} + (\beta_{1,i}) \text{THIN} + u_e + \varepsilon_{ij} \quad (6)$$

where  $[Gr]$  is the average growth of DBH (cm), basal area (m<sup>2</sup>), height (m), volume (m<sup>3</sup>) or crown diameter (m) between 2016 and 2020,  $\beta_0, \beta_{1,i}$  are fixed-effect parameters (related to intercept and the thinning weight rG (THIN)),  $u_e$  is a random-effect parameter incorporated due to the nested plot design,  $\varepsilon$  is an error term.

We used the following software packages: R-statistics (R development Core Team 2016) with the packages nlme (Pinheiro et al. 2018), ncf (Bjornstad 2013), car (Fox and Weisberg 2011), and lattice (Sarkar 2008). For the LMM we used individual tree data of 100 selected dominant trees from the 5 treatments (20 trees per treatment).

## 3. Results

### 3.1. Post-thinning changes in stand characteristics

The stand characteristics of pre- and post-experimental cuttings with different thinning intensities are shown in Table 1. Depending on the thinning intensity, the stand variables were varied among treatments. All thinning treatments resulted in reduction of the stand density (680 to 2150 stems ha<sup>-1</sup>), basal area (6.40 to 15.83 m<sup>2</sup> ha<sup>-1</sup>) and growing stocks (27.94 to 75.42 m<sup>3</sup> ha<sup>-1</sup>) differently, depending on the thinning intensity (Table 2).

The above-mentioned variables tended to decrease with increasing thinning intensity, while the crown diameter tended to increase. In comparison, the mean DBH values in all thinned plots were often greater than in CS. In relation to different thinning intensity,

Table 2. Stand characteristics after thinning treatments by 2020.

| Plots | Mean               |                     |                                |                     |  |                     |   |                     |                    |                     |
|-------|--------------------|---------------------|--------------------------------|---------------------|--|---------------------|---|---------------------|--------------------|---------------------|
|       | Stem height (m)    |                     | Diameter at breast height (cm) |                     | Basal area ( $\text{m}^2 \text{ha}^{-1}$ ) |                     | Growing stock ( $\text{m}^3 \text{ha}^{-1}$ ) |                     | Crown diameter (m) |                     |
|       | Pre-cutting (2016) | Post-cutting (2020) | Pre-cutting (2016)             | Post-cutting (2020) | Pre-cutting (2016)                         | Post-cutting (2020) | Pre-cutting (2016)                            | Post-cutting (2020) | Pre-cutting (2016) | Post-cutting (2020) |
| CS    | 4.3                | 6.2                 | 7.0                            | 8.5                 | 7.66                                       | 11.52               | 23.62   | 51.23               | 1.1                | 1.8                 |
| VLI   | 4.5                | 6.5                 | 7.1                            | 9.3                 | 7.39                                       | 15.83               | 23.40   | 72.70               | 0.9                | 1.9                 |
| LI    | 4.2                | 6.8                 | 7.3                            | 9.9                 | 8.61                                       | 15.66               | 27.92   | 75.72               | 1.1                | 2.0                 |
| MI    | 3.9                | 5.8                 | 8.1                            | 10.7                | 7.26                                       | 11.50               | 18.81   | 47.16               | 1.2                | 2.2                 |
| HI    | 4.1                | 6.0                 | 7.7                            | 10.8                | 3.38                                       | 6.40                | 9.76  | 27.94               | 1.2                | 2.1                 |

To assess the effects of different thinning intensities on Scots pine plantations during the observation period between 2016 and 2020, the pre- and post-cutting means of the main variables are shown in adjacent columns.

the post-felling distance between individuals was ranged from 1.0 m to 3.0 m (Table 2).

### 3.2. Height and diameter growth performance of dominant trees following thinning

The ANOVA test for dominant trees showed a significant difference in DBH ( $p < 0.001$ ) and height ( $p < 0.001$ ) growth performance (Table 3). Measurement results over 5 years after thinning indicated that the thinning in the early stage of the plantation establishment is a potential silvicultural tool to accelerate both height and diameter growth. The cumulative diameter and height growth showed a strong positive effect from thinning on the diameter growth of dominant trees in the planted forest. In terms of diameter growth, the growth rate was often higher (3.0 to 18.0%) in all thinned treatments compared to CS, and the fastest diameter growth was observed in higher intensive (MI and HI) thinning treatments (Figure 1b).

In height growth however, we found different responses from dominant trees to the thinning intensity. Our results revealed that low-intensity thinning only promotes faster growth (from 5.9% (VLI) to 11.9% (LI)) for dominant tree height (Figure 1a). According to the DMRT, medium- and high-intensity thinning treatments resulted mostly in positive effects on diameter growth and basal area, and are ranked in first order (Figure 2 a,c). However, a rather different ranking was observed in height growth. Duncan's test showed the most positive effect of thinning in medium- and low-intensity treatments, where the Control stand and high-intensity treatments were ranked in the lowest orders (Figure 2b). Overall, all thinning treatments trigger a faster diameter, height and volume growth than in unthinned stands (Figure 2d).

### 3.3. Effect of thinning intensity on crown properties

The ANOVA test showed a significant difference in tree crown height ( $p < 0.0001$ ) and crown form index ( $p < 0.0001$ ), while showing an insignificant ( $p = 0.105$ ) difference in crown diameter for selected dominant trees under different thinning treatments (Table 4).

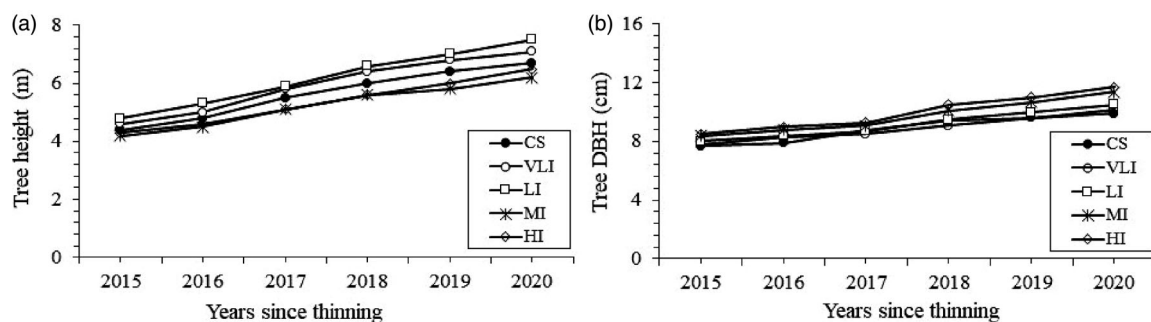
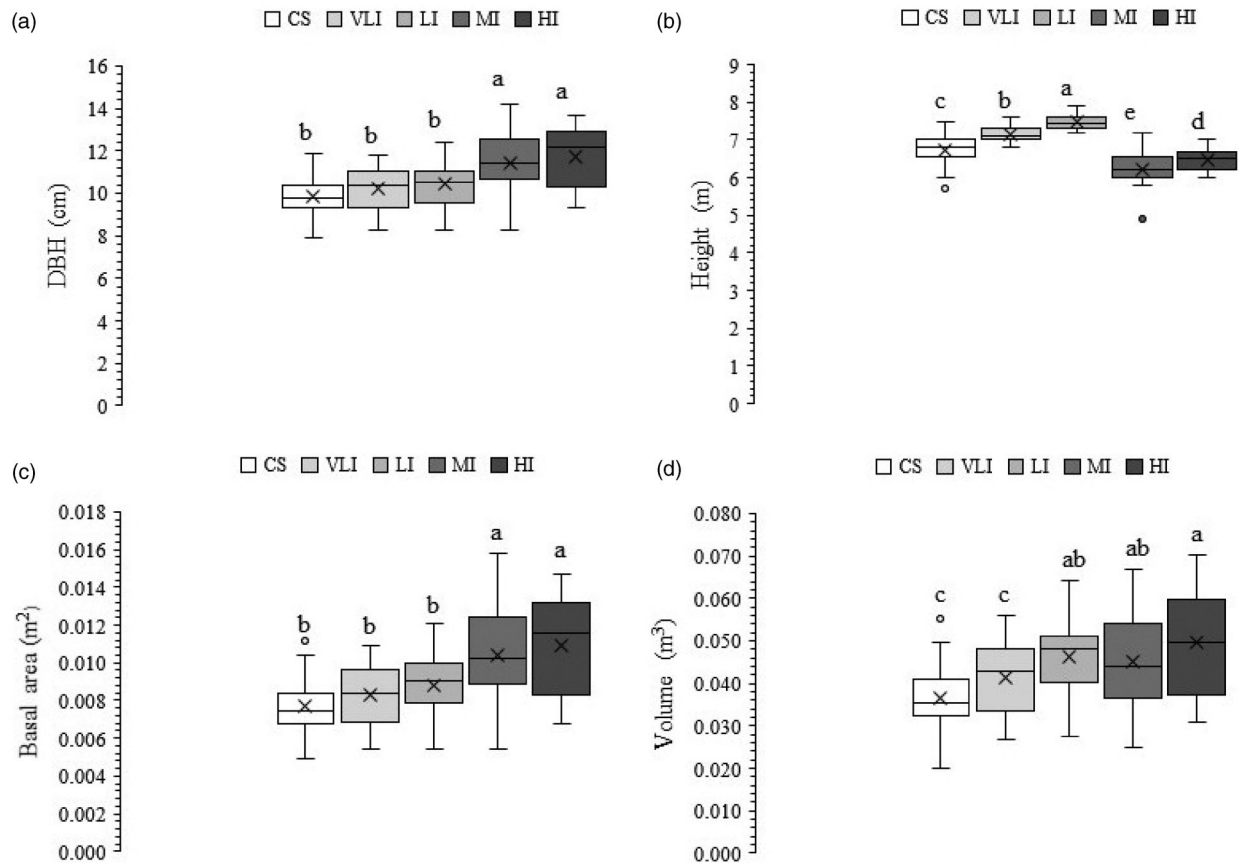
The results of the study showed that the intensity of thinning was positively correlated with the tree crown diameter ( $r = 0.32$ ) and projected area ( $r = 0.21$ ). On the other hand, it negatively correlated with the crown form index ( $r = 0.47$ ) of dominant trees (Figure 3).

Our elaborated LMM models showed that the thinning impact was most prominent on growth of DBH, basal area and volume with a level of significance of  $p < 0.05$ . The positive correlation of the thinning to the increase in crown diameter was also indicated, but with clearly less significance, when compared to DBH or variables related to DBH, with  $p = 0.1082$ . The effect on height was indicated to be even slightly negative, but rather insignificantly, with a very low level of



**Table 3.** One-way ANOVA test of significance in some growth variables among the selected dominant trees in the experimental treatments.

| No. | Variables                                      | Source    | DF  | MSE   | Sum of squares | Mean squares | F Value | Pr > F  |
|-----|--|-----------|-----|-------|----------------|--------------|---------|---------|
| 1   | DBH, cm  | Treatment | 14  | 1.340 | 153.5          | 10.9         | 8.183   | <0.0001 |
|     |  | Error     | 285 |       | 381.916        | 1.340        |         |         |
|     |  | Total     | 299 |       | 535.431        | —            |         |         |
| 2   | Height, m                                      | Treatment | 14  | 0.125 | 35.7           | 4.442        | 35.459  | <0.0001 |
|     |  | Error     | 285 |       | 35.702         | 0.125        |         |         |
|     |  | Total     | 299 |       | 97.887         | —            |         |         |
| 3   | Basal area, m <sup>2</sup> ha <sup>-1</sup>    | Treatment | 14  | 0.000 | 0.000          | 0.000        | 8.195   | <0.0001 |
|     |  | Error     | 285 |       | 0.001          | 0.000        |         |         |
|     |  | Total     | 299 |       | 0.002          | —            |         |         |
| 4   | Growing stock, m <sup>3</sup> ha <sup>-1</sup> | Treatment | 14  | 0.000 | 0.006          | 0.000        | 4.200   | <0.0001 |
|     |  | Error     | 285 |       | 0.029          | 0.000        |         |         |
|     |  | Total     | 299 |       | 0.035          | —            |         |         |

**Figure 1.** Cumulative tree height (Figure 1a) and diameter (Figure 1b) growth of dominant trees during the monitoring period (5 years). CS is the Control stand; VLI is the very low intensity thinning; LI is the low-intensity thinning; MI is the medium-intensity thinning; HI is the high-intensity thinning; DBH is the stem diameter at breast height.**Figure 2.** Comparison of some variables, indicating the growth and productivity for dominant trees (a) DBH; (b) height; (c) basal area; (d) growing stock. CS is the control stand; VLI is the Very low-intensity thinning; LI is the low-intensity thinning; MI is the medium-intensity thinning; HI is the high-intensity thinning; DBH is the stem diameter at breast height. The letters a, b, c, d, and e for the Duncan's multiple range test indicate the relative strength of the thinning effect. Here, a is the strongest effect of thinning, while e is the weakest effect of the thinning.

**Table 4.** One-way ANOVA test of significance in tree crown variables among the selected dominant trees in the experimental treatments.

| No. | Variables                             | Source    | DF  | MSE   | Sum of squares | Mean squares | F Value | Pr > F  |
|-----|---------------------------------------|-----------|-----|-------|----------------|--------------|---------|---------|
| 1   | Crown projection area, m <sup>2</sup> | Treatment | 14  | 1.208 | 53.9           | 3.852        | 3.190   | <0.0001 |
|     |                                       | Error     | 285 |       | 344.215        | 1.208        |         |         |
|     |                                       | Total     | 299 |       | 398.147        |              |         |         |
| 2   | Crown height, m                       | Treatment | 14  | 0.179 | 56.4           | 4.029        | 22.449  | <0.0001 |
|     |                                       | Error     | 285 |       | 51.148         | 0.179        |         |         |
|     |                                       | Total     | 299 |       | 107.554        |              |         |         |
| 3   | Crown diameter, m                     | Treatment | 14  | 0.215 | 5.3            | 0.379        | 1.762   | 0.044   |
|     |                                       | Error     | 285 |       | 61.267         | 0.215        |         |         |
|     |                                       | Total     | 299 |       | 66.571         |              |         |         |
| 4   | Crown form index                      | Treatment | 14  | 0.183 | 21.8           | 1.557        | 8.524   | <0.0001 |
|     |                                       | Error     | 285 |       | 52.062         | 0.187        |         |         |
|     |                                       | Total     | 299 |       | 73.862         |              |         |         |

**Table 5.** Overview of the selected growth models.

| Response variable | Fixed effects | Outlier correction | Sample size | Model parameter (fixed effects) |         |           |         | AIC   | BIC   |
|-------------------|---------------|--------------------|-------------|---------------------------------|---------|-----------|---------|-------|-------|
|                   |               |                    |             | $\beta_0$                       | p-Value | $\beta_1$ | p-Value |       |       |
| DBH               | THIN          | Yes                | 92          | 3.346                           | 0.0000  | 0.0299    | 0.0223  | 108   | 120   |
| BA                | THIN          | No                 | 100         | 0.0042                          | 0.0004  | 0.0001    | 0.0066  | -1026 | -1014 |
| Height            | THIN          | Yes                | 97          | 2.378                           | 0.0000  | -0.0028   | 0.6165  | 11    | 23    |
| Volume            | THIN          | No                 | 100         | 0.0027                          | 0.0000  | 0.0002    | 0.0492  | -674  | -661  |
| Crown Diameter    | THIN          | No                 | 100         | 11.859                          | 0.0000  | 0.0143    | 0.1082  | 36    | 49    |

rel.gr. 5 years (average growth 2016–2020); DBH: diameter at breast height; BA: basal area (m<sup>2</sup>); THIN: thinning intensity; AIC: Akaike's information criterion; BIC: Bayesian information criterion.

confidence with  $p=0.6165$ . Due to the above mentioned outlier corrections the sample size for each response variable was finally  $\leq 100$  (see Table 5).

The largest crown projection area and crown diameter were recorded in high-intensity treatment, and the smallest in Control stand, respectively. In relation to the reduction of the competition rate between individuals and increased spacing, the thinning treatments facilitated relatively faster crown development, including crown diameter (Figure 3c) and projection area (Figure 3b). However, the lower means of tree crown height and crown form index observed in medium- and high-intensity thinning treatments (Figure 3 a, d), which indicated less competition and improved spacing for dominant trees, are more likely to promote horizontal development of tree crown rather than vertical.

## 4. Discussion

### 4.1. Early thinning accelerates tree growth in planted forests

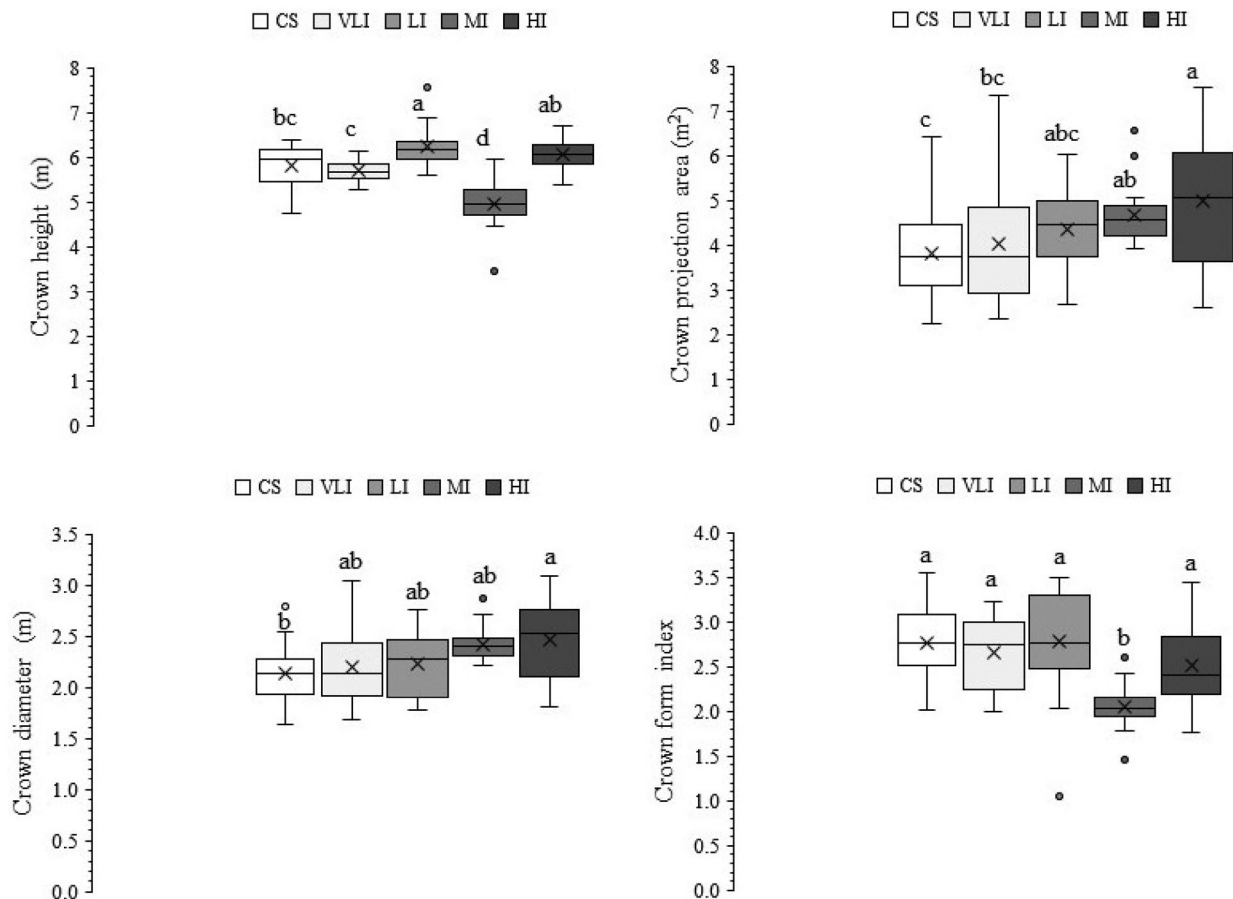
Determination of optimum thinning intensity (Pérez and Kanninen 2005; Weng et al. 2020) and its timing (Hébert et al. 2016) in planted forests that are well-adapted to the growing environment is a strategy for forest managers to improve forest productivity and shorten the forest rotation cycle in accordance with forest management goals. Therefore, the lack of management is especially evident in overly dense stands, which have increased competition between trees for space, light, soil nutrients and water (Liao et al. 2012; Manrique-Alba et al. 2020). Thinning time is important for successful plant density management, otherwise dense stands may stagnate and become unresponsive to increased growing area. Once the canopy is closed, thinning increases the growing space available to individual trees, resulting in increased basal area and

volume gain on individual trees, but reduced growth at stand level (Diaconu et al. 2015; Ferraz Filho et al. 2018).

In Mongolia, thinning from below is generally considered to be the most efficient silvicultural tool used to reduce canopy closure in young stands. But information on temporal trends in both DBH and post-thinning height growth in Mongolia is scarce. A number of studies have noted the importance of early implementation of selective thinning as the main tool for obtaining high-quality timber (Mäkinen and Isomäki 2004; Carino and Biblis 2009; Zhang et al. 2013; Manrique-Alba et al. 2020). In this regard, our results confirmed that all treatments with different thinning intensities showed a positive effect on tree diameter growth and to slightly less extend also on crown development as confirmed by our model results. However, selective thinning at medium to high intensity led to an increase in the growing stock, despite the slower growth in the height of the dominant trees. Thus, our results are consistent with other studies (Ginn et al. 1991; Pape 1999; Kim et al. 2016) that demonstrated that diameter growth, directly related to early thinning,

### 4.2. Tree spacing as a determining factor in crown development

Fowells (1965) noted that light-demanding tree species such as jack pine, exhibit a more open crown and higher photosynthetic capacity, and dominant trees of this species seem to benefit from access to sunlight during the first years after plantation establishment. Our results also supported the idea that plantation spacing is known to affect tree growth and individual tree morphology (Larson et al. 2001), with greater stem volume and basal area being obtained with the greatest spacing between trees (Newton and Jolliffe



**Figure 3.** Comparison of tree crown properties for selected dominant trees among thinning treatments during the monitoring period (5 years): (a) crown length; (b) crown projection area; (c) crown diameter; (d) crown form index. CS is the control stand; VLI is the very low intensity thinning; LI is the low-intensity thinning; MI is the medium-intensity thinning; HI is the high-intensity thinning. The letters *a*, *b*, *c*, *d*, and *e* for the Duncan's multiple range test indicate the relative strength of effectiveness. Here, *a* is the strongest effect of thinning, while *e* is the lowest mean of the variable.

1998; Carino and Biblis 2009; Cardoso et al. 2013; Zhang et al. 2013). Peterson et al. (1997) found that Loblolly pine in thinned stands rapidly expanded its crown horizontally, starting one year after thinning, together with a decrease in height gain. Likewise, Ginn et al. (1991) reported a decrease in height growth and an increase in diameter of the living crown in loblolly pine trees during the first year after thinning, and attributed the decrease in loblolly pine growth by the redistribution of photosynthates from height growth to expansion of the lower crown after thinning.

Our results agree with McEvoy (2004) and Cardoso et al. (2013), who stated that distance did not affect the height of the dominant *Pinus taeda* trees because the tree density was too low to create enough light competition to impair height growth. In this study, differences in stem diameter as a function of the distance between trees on the plantation appear to be the result of an early stage of growth due to the development of a longer living crown at the largest spacing of 680–2100 trees per hectare. In comparison, the thinning response in diameter growth was more clearly observed for heavier thinning treatments and when more time had elapsed since thinning.

According to Peterson et al. (1997) during the first 3 years after thinning, thinned stands had a greater DBH than untreated stands, but only after four growing seasons did the differences become significant.

Therefore, several studies reported that thinning response was independent of tree size (Moore et al. 1994; Hynynen 1995; Pape 1999). Consequently, our results showed that the effect of thinning intensity and its interaction with time on growth response to thinning was minimal during the first 5 years after thinning (Figure 1a, b), which is similar to other studies associated with thinning in loblolly pines (Ginn et al. 1991; Liu et al. 1995; Sharma et al. 2006). Based on a large-scale analysis carried out on plantations in the Tujiyn nars area, Gerelbaatar (2012) suggested to carry out the early thinning 12 years after plantation establishment. Our findings also support this idea, and a dominant tree-based assessment revealed that medium- and high-intensity thinning treatments performed in 13-year old Scots pine plantation showed an accelerating positive effect on planted trees in the beginning stage of plantation establishment.

Looking at comparative graphs representing post-thinning dominant tree growth with respect to diameter, height, basal area, and volume, medium- and high-intensity thinning should be recommended. In addition, the current planting design used for the planting ( $4.0 \times 1.0$  m spacing) contains several disadvantages that trigger relatively early thinning due to the quite small spacing between individuals along the planting row. To avoid large congestion, and therefore creation of less productive conifer plantations, the



initial planting design for the study region needs to be determined, taking into account the optimum spacing and competition between individuals. The findings of this dominant tree-based analyses provided a scientific basis for understanding how tree growth and stand productivity respond to thinning with different intensities in the forest – steppe and semi-humid environments of northern Mongolia.

## 5. Conclusion

In conclusion, it should be noted that the improved spacing between individual Scots pines caused by thinning had the expected effect of increasing radial and volume growth in the plantation. This study revealed that thinning showed a stronger positive effect on diameter and volume growth of dominant trees in the plantation. An ANOVA test for analyses of the growth of dominant trees showed a significant difference in DBH ( $p < 0.0001$ ) and height ( $p < 0.0001$ ) growth performance following experimental felling with different thinning intensities. Slower height growth was observed in heavily thinned stands compared with low-intensity treatments.

Therefore, we obtained a common tendency of a gradual increase in diameter, basal area, and volume growth related to the intensity of thinning. With regard to reducing competition between individuals and improving the distance between them, thinning contributed to a relatively faster development of the tree crown in the planted forest, including crown width and projection area. Here, we found a relatively faster development of the tree crown in the horizontal direction. Looking at comparative graphs representing post-thinning dominant tree growth in diameter, height, basal area, and volume, the medium- (30%) and high-intensity (45%) thinning should be recommended.

## Acknowledgements

The authors acknowledge the Tujiin Nars National Park Administration for providing human resources conducting field experimental felling, measurements and data collection. We are also thankful to Jonathan Chambers for the careful language editing of our manuscript.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

This work was supported by the National University of Mongolia within the framework of the project [P2020-3949].

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