Multidecadal Growth of Western White Pine and Interior Douglas-Fir Following Site Preparation

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Abstract: Site preparation is used to favor seedling regeneration and establishment by enhancing growing conditions and increasing resource availability, yet few studies have compared different site preparation techniques on growth and yield of trees over multiple decades. We destructively sampled 34-year old trees of western white pine (Pinus monticola Douglas ex D. Don) and Interior Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco var. glauca (Beissn.) Franco planted at two sites using a replicated experiment to test the effectiveness of different site preparation treatments: (1) no site preparation, (2) scalping, (3) bedding, and (4) bedding plus three years of competition control with herbicide. Growth and yield were compared among the treatments, and models of growth were developed for each species and treatment combination. The herbicide treatment was the only treatment that consistently improved growth and yield of both species resulting in 19%–30% gains in height, 43%–63% gains in diameter, and 31%–109% gains in stem volume by age 34. Height growth response to herbicide was sustained until age 14 for white pine and age 12 for Douglas-fir, while the diameter response was sustained until age 23 for white pine and 20 for Douglas-fir. The later peak in growth for white pine suggests a better response to treatment and that the species was able to maintain higher growth following crown closure. Both species exhibited a Type 2 growth response to herbicide, suggesting competition control resulted in sustained gains over time with associated age shifts of 8.5 and 9.7 years for white pine and 7.1 and 10.2 years for Douglas-fir, height and diameter, respectively. This compares to scalping and bedding which produced no detectable difference in growth compared to the control, and in some instances, reduced growth. In the Northern Rocky Mountains, moisture is most limiting. This is likely why trees showed the greatest response to competition control. Interestingly, this growth was sustained well beyond seedling establishment.

Keywords: scalping; bedding; forest vegetation management; herbicide; Northern Idaho

1. Introduction

Site preparation is commonly applied to improve tree seedling microenvironments and enhance the success of seedling establishment and early growth. Treatments can be divided into two broad categories: those that control competing vegetation and favor different soil substrates (e.g., blackened, mineral, organic) and those that ameliorate mineral soil properties, such as subsoiling, diskimg, and bedding [1]. Research repeatedly demonstrates that site preparation improves seedling success in the short- and long-term [2], but studies are often limited to comparison of a single treatment versus an untreated control or factorial combinations of treatments, and thus few studies have compared the multidecadal effects of unique treatments on tree growth, such as bedding versus herbicide.
Site preparation is typically used to improve germination, establishment, and growth of desirable regeneration [3]. Site preparation can occur as a multitude of treatment types, depending on the climate and condition of a site. Mechanical site preparation can involve using heavy soil-altering equipment or manual vegetation control, while chemical site preparation often entails fertilizer or herbicide application. In cold forest regions such as the maritime-influenced forests of the northern Rocky Mountains, mechanical, chemical, and prescribed burning site preparation methods are often used both individually and in tandem [4]. Proper site preparation method selection and implementation is imperative, as selecting an inappropriate treatment relative to site conditions and desired species composition can lower growth and survival of the regeneration [1].

Morris and Lowery [5] proposed three potential growth responses to site preparation. Type 1 growth responses occur when an initial growth increase occurs due to site preparation, effectively decreasing the time required to reach maturity by a fixed amount. A Type 2 response is quantified as a continually increasing age shift and would be indicative of site improvement beyond competition release. Type 3 growth responses to site preparation occur when untreated stands eventually have greater yield than stands treated with site preparation, or the amount of time required to reach stand maturity increases due to site preparation. South et al. [6] proposed a Type C growth response when an initial short-term increase in volume production occurs from site preparation but later declines, eventually resulting in no age shift in growth compared to no treatment.

Quantifying the long-term effects of site preparation are often limited by studies that only collect measurements for the first few years after applying site preparation or by the lack of frequent inventories to track development. Stem analysis is one possible way to reconstruct temporal responses to treatment [7], where disks are removed incrementally along the stem for radial increment analysis [8]. This method of analysis can be used to reconstruct a tree’s temporal trends in height, diameter, and volume. Stem analysis is also used to determine individual tree growth response to silvicultural treatments, historical disturbances, or site conditions [9,10] and is used to develop growth models [11].

Tree growth reconstruction often entails fitting models of growth as a function of age. Multiple model forms have been used to model individual tree growth, but the most common are variations of sigmoid or allometric curves. Fontes et al. [12] modelled dominant height growth of Douglas-fir (Pseudotsuga menziesii mirb. Franco) across 12 sites in Portugal and found the McDill–Amateis function [13] outperformed the commonly used Chapman-Richards and Schumacher-derived growth equations. The choice of model form depends on the age of the trees as younger trees typically do not show asymptotic behavior in growth compared to older trees [11].

A replicated study at two sites was established in 1982 to evaluate short-term effects of establishment and growth of seedlings at U.S. Forest Service Priest River Experimental Forest in northern Idaho, USA. This study has been maintained since establishment and provided a unique opportunity to evaluate growth and yield over multiple decades. The objectives of this study were to (1) examine temporal trends in tree growth for western white pine (Pinus monticola Dougl. Ex. D. Don) and interior Douglas-fir (Pseudotsuga menziesii var. glauca) in response to different site preparation treatments over a 34 year period of development, and (2) to develop individual tree growth models in response to different site preparation treatments to determine the longevity of treatment effects over the 34 year period and to determine if any potential initial competitive advantage was sustained.

2. Materials and Methods

2.1. Site Description and Experimental Design

In 1982, two study sites were established 21 km northeast of Priest River, Idaho on the United States Department of Agriculture, Forest Service Priest River Experimental Forest. The low elevation site, Fire Weather, is on a flat alluvial bench adjacent to the Priest River, at 715 m in elevation. After initially being burned as part of a 1922 research study, the site was used in forest fuel flammability studies until 1978 [14]. Prior to being clearcut and study establishment in 1982, Fire Weather contained
a low stocking of lodgepole pine (*Pinus contorta* Douglas ex Loudon var. *latifolia* Engelm ex S Watson), as well as grasses and forbs [15]. All residual slash and debris from harvesting were removed from the site prior to study establishment to create homogenous surface conditions prior to treatment installation [16]. Mission silt loams within the Inceptisol order, with 2% to 12% slopes, and a fragipan at 30 cm depth are present throughout the site [17,18]. Average annual precipitation at Fire Weather is 798 mm per year, with a mean annual temperature of 6.7 °C [19]. This site is characterized as a *Tsuga heterophylla/Clintonia uniflora* habitat type [20].

The midelevation site, Observatory Point, was a 110-year old western hemlock (*Tsuga heterophylla* (Raf.) Sarg), grand fir (*Abies grandis* (Dougl.) Lindl.), Interior Douglas-fir, and western white pine stand that was clearcut harvested in 1981. All harvesting debris was piled and burned in 1982 prior to study installation. The Observatory Point site is located at elevation of 1456 m, with slopes ranging from 10% to 35% [15]. Typic Udivitrands soils within the Andisol order are present across the site [17]. The site is also *Tsuga heterophylla/Clintonia uniflora* habitat type but is subject to less extremes in temperature. Mean annual temperature at Observatory Point is 5.3 °C, with annual precipitation averaging 912 mm [15,19].

A restricted randomized design at Fire Weather and a randomized complete block design at Observatory Point were installed in 1982. Treatments consisted of three site preparation treatments and an untreated control applied in rows. The treatment rows were approximately 30 m long and 4 m wide. Fire Weather consisted of four blocks, where each block was adjacent to another block in a strip with the long edge oriented north to south, whereas Observatory Point consisted of three isolated but nearby replicated blocks, each having similar slope, habitat type, soil, and aspect [21]. Rows at Fire Weather were oriented east to west, while rows at Observatory Point were oriented north to south to align with the slope of the blocks. The order of treatment rows at Fire Weather were the same for all four blocks, while the order was randomized within blocks at Observatory Point. Treatments included:

1. scalping where the uppermost 10 cm of organic material and mineral topsoil were displaced (Scalp),
2. soil bedding that incorporated organic material with mineral soil (Bedding),
3. soil bedding with competition control (Herbicide), and
4. an untreated control with minimal soil disturbance (Control). Scalloped organic material and mineral topsoil were used to create the raised beds using a tractor crawler [15]. Each of the beds were 1.5 m wide and approximately 46 cm high. Competing vegetation was controlled by hand pulling the year of planting in the Herbicide treatment followed by chemical vegetation control using a banded application of Roundup® (active ingredient glyphosate) in the second and third years of the study at a rate of 1.68 kg ha⁻¹ active ingredient. Planted seedlings in the Herbicide treatment were covered with buckets during herbicide applications in order to prevent accidental herbicide contact [16].

In April 1983, one-year-old container-grown seedlings of western white pine and interior Douglas-fir were planted at both sites. Seedlings were planted approximately 50 cm apart within the rows. Each block consisted of the four site preparation treatments for each of the two tree species. One genetic seed source was used for western white pine at both sites, while Douglas-fir seedlots originated from 805 and 1460 m elevation to match study site elevations [15]. Postestablishment destructive sampling for prior studies and natural mortality resulted in between 12 and 55 trees in each treatment row at the time of sampling in 2017. No harvesting, inventorying, or sampling occurred between 1990 and 2017.

### 2.2. Data Collection

Prior to destructive sampling in 2017, both sites were inventoried to determine the number of remaining trees in each treatment row. The diameter at breast height outside the bark (DBH; 1.37 m from the ground) was measured for all 360 trees, 219 trees at Fire Weather and 141 trees at Observatory Point. Trees were grouped into DBH quartiles by site, species, and treatment. One to two trees from each site, species, treatment, and diameter quartile were randomly selected for destructive sampling, with an additional tree being chosen for harvest if a treatment row was not included in the initial random selection (Table 1). A total of 36 white pine and 39 Douglas-fir trees were destructively sampled.
Mature forest surrounded the blocks of treatment rows at both sites. Since Fire Weather was one large block of rows, the edge effect was minimal, with only three Douglas-fir trees sampled from edge rows to ensure enough trees from each treatment were sampled. The three blocks at Observatory Point were spatially separated, so there was more edge effect at that site with five white pine and two Douglas-fir trees sampled from edge rows.

Table 1. Summary statistics of trees sampled for destructive harvest to recreate temporal growth. Shown are the number of sampled trees (n), means and ranges (in parentheses) for diameter at breast height (DBH) (outside bark measured with a DBH tape), total height, stem volume, and neighborhood competition index at age 34 across both sites.

| Treatment | n  | DBH (cm)    | Height (m) | Volume (dm³) | Competition Index |
|-----------|----|-------------|------------|--------------|-------------------|
| **White pine** |    |             |            |              |                   |
| Control   | 9  | 18.8 (10.3–30.7) | 17.4 (8.1–25.9) | 296.9 (34.9–805.5) | 22.8 (9.3–30.9)  |
| Scalp     | 9  | 17.1 (12.3–22.2) | 17.4 (10.6–22.9) | 210.8 (52.2–405.3) | 26.6 (15.8–33.3) |
| Bedding   | 10 | 17.4 (9.8–24.6)  | 16.4 (7.0–21.0)  | 202.2 (31.6–416.9) | 32.2 (14.8–82.7) |
| Herbicide | 8  | 23.6 (14.5–31.4) | 19.8 (10.3–24.9) | 421.2 (80.2–855.9) | 21.4 (12.9–33.3) |
| **Douglas-fir** |    |             |            |              |                   |
| Control   | 10 | 13.5 (7.6–21.3) | 12.7 (9.2–15.5) | 105.2 (23.8–247.9) | 34.4 (24.4–41.5) |
| Scalp     | 9  | 12.5 (4.1–23.8) | 12.0 (6.4–16.5) | 101.8 (6.6–277.9)  | 45.4 (8.7–101.2) |
| Bedding   | 10 | 14.8 (6.1–23.6) | 13.2 (7.3–18.7) | 139.7 (12.4–341.3) | 34.9 (12.1–60.9) |
| Herbicide | 10 | 17.7 (11.8–25.1) | 15.8 (12.4–20.0) | 206.5 (71.8–432.3) | 27.7 (15.5–42.8) |

Neighboring trees around each subject tree were measured to estimate neighborhood competition. The eight closest neighboring trees, one in each cardinal direction, were measured for distance between neighbor tree and subject tree, neighbor tree crown radius towards and away from the subject tree, neighbor tree height to base of live crown and total height, and cardinal location of the neighbor tree relative to the subject tree. Mature forest trees outside the treatment areas were measured if the focal tree was in an edge row.

After all neighboring tree measurements were recorded, the subject trees were destructively sampled for stem analysis. Each subject tree was felled with efforts to limit stem and crown damage. Once the subject tree was successfully felled, a measuring tape was used to measure total height and height to the base of the live crown. Stem disks were harvested at 0.152, 0.762, and 1.372 m from the forest floor up the main bole, followed by disks every 0.914 m after 1.372 m (breast height), as well as at the base of each live crown section.

2.3. Laboratory Processing and Analysis

Each stem disk was sanded starting with 60–80-grit sandpaper to remove coarse chainsaw marks, and then with 120-grit paper to expose growth rings. Finer rings were exposed using 150-grit sandpaper. Each disk was scanned using WinDendro™ (Regent Instruments Inc., Quebec, ON, Canada) software and a flatbed scanner at 1200 or 1600 dpi, depending on ring exposure and visibility. Radial increment was recorded along two paths per disk, either at 90° angles or along the largest and smallest radii for trees with high stem eccentricity. Data was transferred to XLStem™ (Regent Instruments Inc., Quebec, ON, Canada), to generate temporal stem growth data, including cumulative height, DBH, and stem
volume. Annual height growth was calculated using the approach of Carmean [22], while volume was calculated using a truncated cone volume formula (Equation (1)).

\[ V = \frac{1}{3} \pi (R_1^2 + R_1 R_2 + R_2^2) L \]  

where \( V \) is volume (dm\(^3\)), \( R_1 \) is the average radius inside the bark of the lower disk (dm), \( R_2 \) is the average radius inside the bark for the upper disk (dm), and \( L \) is the distance between disks (dm). Data from the year of harvest was excluded, as trees were still growing during the sampling period.

2.4. Statistical Analysis

Cumulative trends in DBH, volume, and height under each site preparation treatment were modelled using the “lme” function of the nlme package in R version 3.4.2 [23,24]. Analysis of variance was performed to determine if age and treatment had significant effects on cumulative trends in height, DBH, and volume with site and block within site included as random effects. Normality was checked with qq-plots and residuals were heterogeneously distributed, so transformation of the response variables was not required. Temporal trends in growth were observed by plotting data and fitting trendlines using smoothed conditional means with the “geom_smooth” function of the ggplot2 package in R software [25]. Local polynomial regression, or Loess curve fitting, was used to display cumulative trends (Appendix A, Figure A1). Loess trendlines were then visually compared to model forms described in Sit and Poulin-Costello [26]. Initial parameter estimates were obtained with the MODEL procedure in SAS software, Version 9.4 for Windows (Copyright© 2017 SAS Institute, Inc., Cary, NC, USA) that included treatments as indicator variables and year since planting as a predictor variable. Parameter estimates were then supplied as starting values in the “nlme” function of the nlme package in R. Separate models were fit for each species with treatment indicator variables and the year predictor variables as fixed effects and site and block within site as a random effect to account for within site and between site variability. Given cumulative size in one year is serially correlated with size the previous year, a conditional autoregressive correlation function of order 1 was included in the models. Additionally, preliminary examination of the models suggested heteroscedastic residual variance; therefore, models included an estimated between-year variance power parameter. Including the correlation function and variance power parameter in all cases reduced model Akaike information criterion (AIC) and was significantly better than the base models based on likelihood ratio tests [27]. Only parameters with \( p \)-values \( \leq 0.05 \) were considered significantly different from zero and retained in models. Once a model had only significant explanatory variables remaining, goodness of fit was evaluated using likelihood ratio tests, AIC, root mean squared error, and generalized R\(^2\) values.

A distance dependent competition index (CI) was modified from O’Neal et al. [28] to determine the impact of neighboring tree competition on the most recent five-year height and DBH growth for both species. The competition index was calculated as:

\[ \sum_{i=1}^{n} CI = \frac{R_s + 0.5(R_s + R_c)}{D_{sc}} \times \frac{R_s}{0.5(R_s + R_c)} \times \frac{HT_c - D_{sc}}{HT_s} \]  

where \( n \) is number of competitor trees, \( CI \) is the competition index, \( R_s \) is the competitor tree crown radius towards subject tree, \( R_c \) is the competitor tree crown radius away from subject tree, \( D_{sc} \) is the distance between stems of subject and competitor, \( HT_c \) is the total height of the competitor tree, and \( HT_s \) is the total height of the subject tree. Five-year height and DBH growth were calculated by subtracting the total size in year 29 from the total size in year 34, based on stem analysis performed in XLStem™. A mixed-effects analysis of variance test was performed to determine the effects of CI, species, and treatment on 5 year height and DBH increment with site and block within site as a random effect using the “lme” function in the nlme package of the R software [24]. Post hoc mean comparisons
and Tukey’s honestly significant difference test were used to evaluate differences in growth at a 95% confidence level.

Age-shifts [6] (i.e., the number of years gained on the size of a tree or stand yield compared to untreated control conditions) were calculated based on the yield models. Equations were rearranged to solve for the number of years and then the yield of the control was inserted into the rearranged model to estimate the years before when the yield was the same in the Herbicide treatment.

3. Results

3.1. Cumulative Size and Growth by Treatment

Neighborhood competition calculated using Equation (2) showed no significant effect for relative height or DBH growth calculated as growth divided by tree size at age 29 for white pine or Douglas-fir ($p \geq 0.11$). Therefore, neighborhood competition was not included in further analysis.

Height of the sampled trees in the Herbicide treatment was slightly greater than the Control at age 5 for both species, but by age 34, height of white pine did not differ, while Douglas-fir height was 24% greater (Table 2). The Scalp and Bedding treatments resulted in no gains in height over the Control through time for either species, and as observed, Douglas-fir height in the Scalping treatment was 7% lower than the Control. Comparatively, inside-bark DBH of white pine from stem reconstruction in the Herbicide treatment was greater than the Control at age 10, which persisted through age 34, where the DBH was 31% greater (Table 3). Scalping also produced a negative effect on Douglas-fir DBH, where by age 34, DBH was 16% lower than the Control.

| Treatment   | Age 5 | Age 10 | Age 15 | Age 20 | Age 25 | Age 30 | Age 34 |
|-------------|-------|--------|--------|--------|--------|--------|--------|
| **White pine** |       |        |        |        |        |        |        |
| Control     | 0.75 ab | 2.41 a | 4.97 a | 8.23 ab | 11.53 ab | 14.90 a | 17.17 a |
| Scalp       | 0.69 a  | 2.71 ab | 5.13 ab | 8.10 a  | 11.19 a  | 14.94 a  | 17.22 a  |
| Bedding     | 0.71 a  | 1.97 a  | 4.28 a  | 7.12 a  | 10.65 a  | 14.55 a  | 16.55 a  |
| Herbicide   | 1.05 b  | 3.18 b  | 6.50 b  | 10.34 b | 14.25 b  | 17.92 a  | 20.10 a  |
| Std. Error  | 0.13   | 0.70 a  | 1.75 a  | 2.54 a  | 2.93 a   | 3.26 a   | 3.33 a   |
| **Douglas-fir** |       |        |        |        |        |        |        |
| Control     | 0.94 ab | 2.45 a  | 4.42 a  | 6.82 a  | 9.36 a  | 12.01 a  | 13.24 a  |
| Scalp       | 0.63 a  | 1.87 a  | 3.86 a  | 6.16 a  | 8.87 a  | 11.08 a  | 12.41 a  |
| Bedding     | 0.78 a  | 2.20 a  | 4.39 a  | 6.79 a  | 9.41 a  | 12.05 a  | 13.52 ab |
| Herbicide   | 1.34 b  | 3.58 b  | 6.16 b  | 9.26 b  | 12.11 b | 14.99 b  | 16.37 b  |
| Std. Error  | 0.13   | 0.30 a  | 0.37 a  | 0.50 a  | 0.64 a  | 0.93 a   | 1.35 a   |

Table 2. Height (m) by species and treatment for five-year increments based on stem reconstruction. Different letters within a column by species indicate significant differences at $\alpha = 0.10$. The standard error within a column is based on the estimate of the marginal means and standard errors.
Table 3. Diameter at breast height (1.37 m from ground; inside the bark) in cm by species and treatment for five-year increments based on stem reconstruction. DBH was calculated by averaging the length of the two radii per breast height cookie from the pith for each age, multiplied by two, to account for stem eccentricity. Different letters within a column by species indicate significant differences at \( \alpha = 0.10 \). The standard error within a column is based on the estimate of the marginal means and standard errors.

| Treatment   | Age 5 | Age 10 | Age 15 | Age 20 | Age 25 | Age 30 | Age 34 |
|-------------|-------|--------|--------|--------|--------|--------|--------|
| White pine  |       |        |        |        |        |        |        |
| Control     | -     | 1.0 a  | 4.7 a  | 8.5 a  | 11.9 a | 15.5 a | 18.3 a |
| Scalp       | -     | 1.4 ab | 5.0 a  | 8.3 a  | 11.4 a | 14.7 a | 17.1 a |
| Bedding     | -     | 0.4 a  | 3.7 a  | 7.9 a  | 11.9 a | 15.5 a | 18.0 a |
| Herbicide   | -     | 2.1 b  | 6.9 b  | 11.8 b | 16.3 b | 20.7 b | 24.0 b |
| Std. Error  | 0.7   | 2.1    | 2.7    | 2.7    | 2.8    | 2.6    |        |

| Douglas-fir |       |        |        |        |        |        |        |
| Control     | -     | 0.8 a  | 4.0 a  | 7.0 a  | 10.0 ab| 13.2 ab| 15.1 ab|
| Scalp       | -     | 0.4 a  | 3.0 a  | 6.1 a  | 8.9 a  | 11.4 a | 13.0 a |
| Bedding     | -     | 0.7 a  | 3.8 a  | 7.4 a  | 10.9 ab| 14.0 ab| 15.8 ab|
| Herbicide   | -     | 2.6 b  | 6.4 b  | 9.8 b  | 13.2 b | 16.5 b | 18.3 b |
| Std. Error  | 0.4   | 0.5    | 0.7    | 1.2    | 2.0    | 3.0    |        |

3.2. Growth and Yield Models

Cumulative trends in height exhibited an exponential relationship over time through age 25, after which height increment declined for both species (Appendix A, Figure A1). Cumulative DBH showed a similar trend to height over time but began to slow between ages 15 and 20 likely due to increasing stand density. Cumulative stem volume also increased exponentially but did not exhibit a decrease in growth over time.

The early exponential increase followed by a decrease in growth with time for cumulative height and DBH for both species, suggests the trajectories were best represented by a Type III exponential model form (Equation (3)). Treatment indicator variables were included on the intercept term as preliminary analysis found this provided the best fit to the data. The Type III exponential model was defined as:

\[
Y = ae^{b/\text{Year}}
\]  

(3)

where \( a = a_0 + a_1\text{Scalp} + a_2\text{Bedding} + a_3\text{Herbicide} \). The random effect of site for white pine was only included on the \( a_0 \) parameter as adding it to the \( b \) parameter did not improve fit. All treatment indicator parameters were significant for the white pine height model and therefore were retained in the final model (Table 4). The model predicted the Herbicide treatment produced the greatest increase over the Control, while the Scalp treatment was only slightly higher and the Bedding treatment slightly lower than the Control (Figure 1a). The white pine height model explained 78.1% of the variance in the data not accounting for the random effects of site and block within site but increased to 90.4% by accounting for the random effects. The Douglas-fir cumulative height model was similar to the white pine model in that the autoregressive term and weighting variance improved model fit, but the Bedding treatment was not significant \( (p = 0.141) \) and therefore was removed from the final model (Table 4). The Scalp treatment slightly decreased cumulative height (Figure 1b). Compared to white pine height, including site and block within site as a random effects produced a minimal increase in variance explained from 88.5% to 89.0%.
Table 4. Parameter estimates, with standard errors in parentheses, for cumulative height, DBH, and stem volume models for western white pine (white pine) and Interior Douglas-fir. CAR (1) is the conditional autoregression parameter of order 1 included to account for serial correlation. The power variance parameter is the variance weighting parameter included in the models to account for heteroscedastic residual variance. RMSE is the root mean square error of the model predictions.

| Variable | Cumulative Height | Cumulative DBH | Cumulative Volume |
|----------|-------------------|----------------|------------------|
|           | White Pine | Douglas-Fir | White Pine | Douglas-Fir | White Pine | Douglas-Fir |
| a0       | 32.09774 | 24.32248 | 79.36525 | 48.16674 | 0.48165 | 0.33330 |
|          | (6.49013) | (0.93438) | (13.61810) | (0.05717) | (0.03168) |          |
| a1       | 2.38997 | –3.02248 | –8.45039 | –0.13564 | –0.33330 | –0.13564 |
|          | (1.09853) | (0.54826) | (1.31893) | (0.02973) | –          |          |
| a2       | –1.99569 | –23.67744 | –0.21425 | 0.13564 | 0.36238 | 0.13970 |
|          | (0.97916) | (2.38052) | (1.31893) | (0.02973) | (0.02360) |          |
| a3       | 9.64942 | 7.60409 | 23.67744 | 0.13564 | 0.36238 | 0.13970 |
|          | (1.04102) | (2.38052) | (1.31893) | (0.02973) | (0.02360) |          |
| b        | –28.64136 | –24.97974 | –40.69068 | 0.18634 | 0.16950 | 0.16950 |
|          | (0.66678) | (2.38052) | (4.19755) | (0.01117) | (0.00628) |          |
| CAR(1) Φ | 0.46404 | 0.24057 | 0.30560 | 0.01932 | 0.30208 | 0.02913 |
| Power variance parameter | 1.19325 | 0.87609 | 2.7609 | 2.3825 | 1.4950 | 1.2303 |
| R² (fixed) | 0.781 | 0.885 | 0.795 | 0.775 | 0.589 | 0.645 |
| R² (fixed + random) | 0.904 | 0.890 | 0.854 | 0.822 | 0.757 | 0.725 |
| RMSE | 3.64 | 2.26 | 4.31 | 3.70 | 88.08 | 44.15 |

Figure 1. Modeled change in tree size in response to treatment with 95% prediction confidence intervals: (a) cumulative height for western white pine; (b) cumulative height for Douglas-fir, (c) cumulative DBH for western white pine, (d) cumulative DBH for Douglas-fir, (e) cumulative stem volume for western white pine, and (f) cumulative volume for Douglas-fir. Treatments missing within a graph are because the indicator variable for that treatment was not significant in the models.
Models of cumulative DBH, like cumulative height, were best fit with a Type III exponential model (Equation (3)). The model form is flexible to account for the first five to seven years of height growth before the trees reached breast height (1.37 m). The Scalp treatment indicator variable was not significant for white pine \((p = 0.605)\) so it was removed from the model (Table 4), but the Bedding treatment resulted in smaller DBH than the Control treatment and the Herbicide treatment increased DBH compared to the Control (Figure 1c). Average modeled white pine DBH by treatment at age 34 was 20.1 cm, 14.1 cm, and 28.6 cm for the Control, Bedding, and Herbicide treatments, respectively. The Bedding indicator variable was not significant for Douglas-fir \((p = 0.552)\), while the Scalp treatment slightly decreased DBH and the Herbicide treatment substantially increased DBH compared to the Control (Figure 1d). Douglas-fir modeled DBH was overall smaller than white pine, while at age 34, DBH was 15.1 cm, 12.4 cm, and 24.3 cm for the Control, Scalp, and Herbicide treatments, respectively.

Compared to total height and DBH, stem volume was best fit with a Type I exponential function where volume continued to increase rapidly over time (Equation (4)):

\[
Y = a_0 + a_1 \text{Scalp} + a_2 \text{Bedding} + a_3 \text{Herbicide}.
\]

where \(a = a_0 + a_1 \text{Scalp} + a_2 \text{Bedding} + a_3 \text{Herbicide} \). Parameters for all indicator variables were significant for the white pine volume model (Table 4). The Scalp and Bedding treatments modeled a lower volume than the Control, while volume was much greater for the Herbicide treatment compared to the Control (Figure 1e). Douglas-fir volume showed a slightly different response to the treatments except for greater volume in the Herbicide treatment compared to the Control (Figure 1f). The Scalp treatment had no effect (Table 4), while Bedding slightly increased volume over the Control. Model fit for both species was substantially improved when site and block within site were accounted for as random effects: \(R^2\) increased by 0.168 and 0.080 for white pine and Douglas-fir, respectively (Table 4). Less variance explained by the volume model was likely due to the range of tree sizes sampled with minimal volume in the smaller trees. In addition, volume did not begin to increase rapidly until trees reached approximately 20 years old.

Annual growth of height, DBH, and volume was calculated using the differential forms of Equations (3) and (4) (Figure 2). Between the two species, height and DBH growth of white pine was much greater than Douglas-fir, where at age 15 in the Herbicide treatment, height growth was 15.2% greater and DBH growth was 5.5% greater than the Control. Peak in growth also differed between species. White pine height growth peaked at age 14, while Douglas-fir peaked at age 12. Peak DBH growth occurred at age 23 for white pine, while Douglas-fir DBH growth peaked at age 20. White pine maintained higher growth through age 34 in all treatments.

### 3.3. Herbicide-Related Age-Shifts

Interestingly, age shifts of height and DBH between the Herbicide and Control treatments increased with time based on the modeled growth and yield. The height age-shift at age 15 was similar between the two species with 2.1 years for white pine and 2.4 years for Douglas-fir (Table 5). By age 34 the height age shifts increased substantially due to differences in growth between the two treatments, where the age shift was 8.5 years for white pine and 9.7 years for Douglas-fir. The age-shifts associated with the Herbicide treatment at age 34 resulted in a 30% gain in height compared to the Control for white pine and a 19% gain for Douglas-fir. DBH age-shifts showed a similar increasing trend over time but with a higher age-shift for Douglas-fir compared to white pine. The white pine DBH age shift by age 34 was 7.1 years, while the Douglas-fir age-shift was 10.2 years. The results were 43% and 63% gains over the Control in DBH for white pine and Douglas-fir, respectively. The stem volume age shifts between the herbicide and control treatments were high for both species, resulting in a 31% gain for white pine and 109% gain for Douglas-fir at age 34 over the Control.
treatment compared to the Control (Figure 1e). Douglas-fir volume showed a slightly different response to the treatments except for greater volume in the Herbicide treatment compared to the Control (Figure 1f). The Scalp treatment had no effect (Table 4), while Bedding slightly increased volume over the Control. Model fit for both species was substantially improved when site and block within site were accounted for as random effects: \( R^2 \) increased by 0.168 and 0.080 for white pine and Douglas-fir, respectively (Table 4). Less variance explained by the volume model was likely due to the range of tree sizes sampled with minimal volume in the smaller trees. In addition, volume did not begin to increase rapidly until trees reached approximately 20 years old.

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Figure 2. Modeled annual tree growth in response to treatment with 95% prediction confidence intervals: (a) height growth for western white pine; (b) height growth for Douglas-fir, (c) DBH growth for western white pine, (d) DBH growth for Douglas-fir, (e) stem volume growth for western white pine, and (f) stem volume growth for Douglas-fir. Treatments missing within a graph are because the indicator variable for that treatment was not significant in the models.

Table 5. Age-shift in years between the herbicide treatment and the control treatment for white pine and Douglas-fir height, DBH, and stem volume. The percent gain in each variable for white pine and Douglas-fir at age 34 is also shown.

| Species          | Age 5 | Age 15 | Age 25 | Age 34 | Age 34 Gain |
|------------------|-------|--------|--------|--------|-------------|
| **Height**       |       |        |        |        |             |
| White pine       | 0.3   | 2.1    | 5.0    | 8.5    | 30%         |
| Douglas-fir      | 0.4   | 2.4    | 5.7    | 9.7    | 19%         |
| **DBH**          |       |        |        |        |             |
| White pine       | –     | 1.7    | 4.2    | 7.1    | 43%         |
| Douglas-fir      | –     | 2.5    | 6.1    | 10.2   | 63%         |
| **Stem Volume**  |       |        |        |        |             |
| White pine       | –     | –      | 25.2   | 33.8   | 31%         |
| Douglas-fir      | –     | –      | 28.0   | 36.7   | 109%        |
4. Discussion

Western white pine and interior Douglas-fir are two important tree species suitable for plantations in the Inland Northwest. White pine once dominated forests in the region but has experienced substantial decline due to the introduced white pine blister rust pathogen (*Cronartium ribicola*) and presalvage harvesting of surviving pine starting in the 1970s [29]. Interest in planting white pine has declined due to risk of mortality from blister rust before the end of the rotation, but substantial improvements in breeding disease resistance provide opportunities for increasing reforestation of the species [30]. Results from the current study show growth and yield of white pine was far superior to Douglas-fir and had greater responses to early vegetation management.

The only treatment that consistently improved growth and yield of white pine and Douglas-fir was the Herbicide treatment. All noncrop tree vegetation was controlled around seedlings for the first three growing seasons [16], which enhanced early seedling survival and growth [18]. The early advantage provided to these seedlings persisted for multiple decades. Similar long-term gains have been found for many other conifer species in plantations around the world [2]. A meta-analysis of Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson var. *ponderosa* C. Lawson) found that across 29 sites with a broad range of site productivity, wood yields from vegetation management ranged from 67% greater at age 15 to 91% greater at age 31 compared to no vegetation management [31]. Similar responses were also found for ponderosa pine and coastal Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) when shrub competition was controlled at age 2 [32]. In that study, not controlling competition resulted in 33% lower stand volume at age 26. Results from our study complement these finding whereby age 34 individual stem volume gain was 31% for white pine and 109% for Douglas-fir.

The minimal long-term effects from bedding without herbicide were consistent between species and across the different tree metrics investigated. Bedding did not increase DBH of all trees within the study over the Control at age 34 and had minimal effect on height development over time. Bedding is commonly used in plantation establishment to increase soil aeration and drainage and raise the root zone above the water table [21,33]. Thus, it is most applied on poorly drained sites. Neither of our sites were considered poorly drained, so the potential benefits were likely limited to the early stages of seedling establishment and growth since bedding can concentrate nutrients where seedlings are planted [34]. Bedding also has the potential benefit for seedlings by increasing soil pore space and decreasing resistance to root penetration [35,36], but soil physical properties can quickly return to prebedding treatments [37]. The result on poorly drained sites is that bedding can increase growth initially, but the initial gains can disappear over time [38]. Our results showed that bedding never resulted in height or DBH gains of white pine and Douglas-fir from age 5 through age 34 suggesting benefits, if any, were quickly lost.

A similar lack of response from scalping compared to the control was found from age 5 through age 34. Scalping is common around individual seedling microsites during planting to reduce competing vegetation and to access the mineral soil for planting seedlings. Less common is extensive scalping across a site unless it occurs during harvesting of the previous stand. Scalping reduced the seedling size of both species after three years even though the low amount of competition was similar to the Herbicide treatment [21]. The possible synergistic effect of nutrient concentration from bedding and the control of competition produced growing conditions suitable for seedling growth, while just initial mechanical control of competition along with the nutrient rich organic layer had the opposite effect. It is noteworthy that the initial reduction in seedling size from Scalping persisted through age 34. This contrasts results from the Long-term Soil Productivity installations in California across a range of site productivity classes where biomass of planted trees was not different than bole-only or whole-tree harvesting only compared to whole-tree harvesting plus organic matter displacement [39]. In that study the only decline in productivity was found for heavily compacted soils after 20 years, while the largest gains in planted tree biomass were observed with early competition control. The benefits of scalping are context dependent, as disturbances that expose mineral soil often increase density of
desirable natural regeneration in hardwood-dominated forests of eastern North America [40] and possibly increase species diversity due to a diversity of microsite conditions.

The age shift associated with the Herbicide treatment increased over time suggesting trees with more resources early in development grew better through age 34. This suggests a Type 2 response to early vegetation control [5]. The early release from competition allowed both species to increase their growth rates until new limiting factors emerged, such as belowground root contact between planted trees and crown interactions. Similar results have been shown by Macadam and Kabzems [41] where early chemical release directed white spruce (Picea glauca [Moench.] Voss) on an alternate development trajectory compared to no treatment 15 years after site preparation. Combined with previous research, our results provide further justification for use of vegetation management to improve long-term forest productivity.

Even though height and DBH in the Bedding and Scalping treatments were not significantly different than the Control from age 5 through age 34, Scalping resulted in trees with smaller size for both species. This suggests a Type 3 (i.e., reductions in productivity) or Type C response (no difference in productivity) [5]. This contrasts the response found for Radiata pine (Pinus radiata D. Don) following subsoiling and bedding in New Zealand through age 7 [42]. Reductions in growth at our sites could be due to a lack of competition control as modification of the soils increased the amount of area available for the colonization of forbs, shrubs, and grasses.

The current study focused on individual trees due to the original design of the study, while forest growth and yield models depend on the growth of all trees within the stand accounting for survival. Survival could not be assessed in our analysis since trees were not remeasured for nearly 30 years at the time of sampling. The variable number of trees within each row, plus some evidence of dead trees indicated self-thinning occurred over time. This is to be expected given the high initial planting density. The Herbicide treatment accelerated tree growth compared to the other treatments likely inducing self-thinning earlier. This would be expected given the positive age shifts associated with the Herbicide treatment. One benefit of accelerated growth following herbicide application is that stands can be thinned at an earlier age to maintain tree vigor and growth and yield and shorten rotations [43]. Mortality reduced the potential number of focal trees to randomly sample for the current study and therefore we inherently selected trees less affected by self-thinning. The study design of treatments applied in rows also limits the ability to scale the results to the stand level, which is the scale where the majority of age-shift growth patterns are documented [6]. Even with these study limitations, the Herbicide treatment produced a strong signal of enhanced growth, suggesting trees with early growth advantages continue to grow better later into the rotation.

5. Conclusions

Mechanical and chemical site preparation are common in intensively managed forests throughout the world yet results from long-term studies are limited. This is especially true in the northern Rocky Mountains where our study is the first to document the positive multidecadal effects of early competition control. Chemical site preparation is widely used in the region and Douglas-fir and western white pine are two of the most important species in plantations. The current study controlled competing vegetation for the first three years after planting, but multiple years of competition control may not be cost effective. Typically, competition is usually only controlled prior to planting and in some instances the first year after planting. The Type 2 response observed through age 34 suggests removing competing vegetation had a sustained effect on tree productivity through time that may persist to the end of the rotation. The deleterious effects from Scalping and Bedding suggest only physically modifying the soil provides limited long-term benefit and likely is not worth the investment on relatively good soils with surficial volcanic ash deposits and no shallow restrictive soil layers. Responses to different treatments vary by location and soil conditions, but in this region where moisture is the most limiting factor influencing tree growth, competition for available moisture is the most important thing to consider for early plantation establishment and sustained gains in growth and yield.
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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Figure A1. Observed growth trajectories of the individual trees of western white pine and Douglas-fir through age 34. Local polynomial regression, Loess, splines were fit to each unique species by treatment combination for height, DBH, and volume.
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