Early basal area growth response of reserved lodgepole pine to shelterwood harvesting in central Montana

P. Chris Roy

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EARLY BASAL AREA GROWTH RESPONSE OF RESERVED LODGEPOLE PINE TO SHELTERWOOD HARVESTING IN CENTRAL MONTANA

by

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B.Sc. University of Montana, 2000

Presented in partial fulfillment of the requirements for the degree of

Master of Science

The University of Montana

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Approved by:

Chairperson

Dean, Graduate School

Date
Lodgepole pine often forms pure, even-aged stands in the northern Rocky Mountains resulting from stand-replacing wildfire. Clearcutting with natural regeneration has been the preferred silvicultural system used in lodgepole pine management. In recent years, there has been wider acknowledgement of naturally occurring multi-aged structures in lodgepole pine forests, in some instances due to mixed severity fire. Silvicultural alternatives to even-aged management are often desirable given multiple resource objectives and may emulate mixed severity disturbances in lodgepole pine. Partial harvesting (or variable retention) approaches in lodgepole pine have received little study. One important aspect of partial harvesting is the effect of the treatments on the growth and vigor of the residual overstory. This study examines early basal area growth response of reserved lodgepole pine retained in two distinct spatial arrangements (even vs. clumped) following shelterwood harvesting implemented in mature (90+ year old) stands in central Montana. Growth response of individual trees was assessed by comparing a ratio of the five-year post-treatment basal area growth to that of the five-year period that preceded treatment.

The evenly-distributed reserve trees in this study averaged a 66% increase in basal area growth rate in the five years post-treatment relative to pre-treatment growth rate. Basal area growth among evenly-distributed reserves was substantially higher than in overstory trees within reserve groups or in uncut controls. Within reserve groups, only the trees in closer proximity to the group edge were released by treatment. Relationships between individual tree characteristics and growth response were also assessed. Reserve trees that had longer crowns (live crown ratios > 30%) generally showed greater response to treatment than trees with lesser crowns. In the multi-aged stands in this study, tree age, crown class, and diameter were interrelated and did not offer clear trends with basal area growth response. The results of this study suggest that shelterwood harvesting with evenly-distributed reserves may be a viable option for improving growth and vigor of residual lodgepole pine, even when applied in old stands. Within reserve groups, basal area growth response may be improved by altering group shape to create higher proportions of 'edge' conditions.
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Introduction

Vast expanses of lodgepole pine (*Pinus contorta* var. *latifolia*) dominated stands are found in the Rocky Mountains of western North America. Lodgepole pine occupies about 14.8 million acres of commercial forest lands in the US Rocky Mountains, the region’s third most common timber type (Koch 1996). In the northern Rocky Mountains of Montana, lodgepole pine is typically found at middle to upper elevations and its successional role depends upon environmental conditions and extent of competition from associated species (Lotan and Critchfield 1990). Lodgepole pine is a dominant seral species in cool, dry habitats in Montana (such as those covering large expanses east of the Continental Divide) and a minor seral species in warm, moist habitats (such as those found in northwest Montana) (Schmidt and Alexander 1985). Lodgepole pine forests provide many tangible benefits. Lodgepole pine has become a highly valuable commercial species. Wood products range from post and poles, pulp and fuelwood to dimensional lumber and house logs. In addition, lodgepole pine forests also provide valuable wildlife habitat, livestock forage, sources of clean water, and recreational opportunities.

Disturbance plays a central role in the landscape dynamics of seral lodgepole pine. Throughout lodgepole pine’s range, fire and insects are important disturbance agents. Lodgepole pine is most often associated with infrequent, high severity wildfires (also referred to as ‘stand replacement’ fires). Stand replacement fires in lodgepole pine forests are often large in size and involve a mixture of lethal surface fire and crown fire (Brown 1995). Such fires usually occur in times of drought, as high fuel moisture limits...
ignition and spread in most years (Lotan and others 1985). Throughout the Rocky Mountains of the United States and Canada, stand replacing fires in lodgepole pine forest types historically occurred at average return intervals ranging from about 70 years to more than 300 years (Brown 1995, Barrett 1993). Lodgepole pine is a fire-adapted species, though thin-barked and easily killed by fire, the well known serotinous cone habit provides a competitive advantage in early site colonization by lodgepole pine following crown fire (Lotan and others 1985). The proportion of serotinous cones within stands and individual trees is variable (Lotan and others 1985). The presence of non-serotinous cones provide a seed source following surface fire and adjacent unburned lodgepole pine stands provide reservoirs for seed dispersal (Lotan and others 1985). Following stand replacement fire, the dramatically reduced competition and creation of mineral seedbeds present ideal conditions for the establishment of a new even-aged cohort of pioneering lodgepole pine (Lotan and others 1985).

The stand replacement fire regime has traditionally been used as a conceptual guide for silvicultural systems used in lodgepole pine management (Hardy and others 2000). Even-aged systems, usually clearcutting with natural regeneration, have been the primary regeneration method (Schmidt and Alexander 1985). Clearcutting has generally been preferred because of economics and logistic efficiency, because it provides a means of eradicating debilitating dwarf mistletoe, and because lodgepole pine is highly intolerant of shade and susceptible to windthrow due to its shallow root system (Alexander 1975, Smith and others 1997).
In recent decades, however, there has been increasing public opposition to large-scale clearcutting, much of which has centered on negative visual aesthetics of large, geometrically shaped clearcuts, but also because of the potential for greatly simplifying forest structure and composition. Clearcutting, as a technical silvicultural term, refers to treatments in which nearly all of the vegetation is removed and virtually all of the growing space is then made available to newly established plants (Smith and others 1997). Even severe fires leave behind significant biological legacies such as scattered surviving trees of varied size, as well as abundant snags (Mitchell and others 2003). The large volumes of dead wood created by fires, both as standing snags and as fallen logs, can offer critical habitat for birds and other wildlife (Arno and Fiedler 2005), provide partial shade that moderates the surface microclimate, and promote long-term transfer of organic material and nutrients as down woody debris decays (Franklin 1995).

In order to meet various multiple resource objectives related to aesthetics, wildlife habitat structure, landscape diversity, or fuel reduction, there has been increased interest in alternative silvicultural approaches that employ partial retention of mature trees. Though they have generally been overlooked, silvicultural systems for multi-aged lodgepole pine may be a viable option in the northern Rocky Mountains (O’Hara and Kollenberg 2003). Partial cutting or ‘variable retention’ systems that create two to three-aged structures can provide sufficient light for intolerant species such as lodgepole pine to regenerate while requiring few entries into the stands (O’Hara 2004). Group selection and shelterwood with reserves are two promising methods. With group selection, patches of trees are removed in shapes and sizes that may vary but must be large enough to allow for the regeneration and development of a new cohort (Smith and others 1997).
Shelterwood methods retain mature trees in varied numbers and patterns as seed sources and partial shade for regeneration. Under the classic definition of shelterwood regeneration methods, overstory trees are removed once regeneration is secured. With reserve tree systems, an overstory component is maintained throughout the life of the regenerated stand to provide greater structural diversity and future snags and coarse woody debris (Graham and others 1999). While further investigation of multi-aged management of lodgepole pine is desirable given social and multiple resource objectives, natural precedence also exists for multi-aged structures.

Though less common than stand replacement fires, evidence of ‘mixed severity fires’ in lodgepole pine stands exist in several areas throughout the northern Rocky Mountains (Hardy and others 2000). Mixed severity fires burn in a patchy manner, killing perhaps 20 to 70% of the pre-fire basal area (Agee 1993). Such fires tend to occur in relatively dry lodgepole pine stands with gentle topography, with an average frequency of about 25 to 75 years (Arno 2000). Mixed severity fire regimes in lodgepole pine forests have been described for areas in the Bitterroot National Forest (Arno 1976), the Bob Marshall Wilderness (Gabriel 1976), Glacier National Park’s North Fork Valley (Barrett and others 1991), Alberta’s Jasper National Park (Tande 1979), and in central Montana’s Little Belt Mountains (Barrett 1993). In addition to mixed severity fires, multiple age classes in lodgepole pine stands may be created by insects that thin the upper canopy layers and provide growing space for a new age class (Kollenberg 1997). Mountain pine beetle (*Dendroctonus ponderosae*) is the most severe insect pest associated with lodgepole pine (Lotan and Critchfield 1990), and periodic outbreaks may cause widespread mortality. Though the spatial configuration of surviving overstory trees following insect attack or
mixed severity fire can be highly variable, a new age class of lodgepole pine is often initiated in the resulting openings. Broad age distributions in lodgepole pine stands may also be created without intervening disturbance, particularly in the early stages of stand development following stand replacing fire (Schoennagel and others 2003). Lodgepole pine can produce cones at early ages e.g. as young as 10 years (Schmidt and Alexander 1985) and a higher proportion of non-serotinous cones may be present in younger trees, allowing for ongoing establishment where growing space is available (Schoennagel and others 2003).

Multi-aged management of lodgepole pine in the northern Rocky Mountains remains a somewhat novel concept and has received little study. The suitability of partial retention systems will hinge on several factors, including procurement of adequate regeneration and resistance to windthrow, insects, and disease. Another important criterion for the suitability of these types of variable retention treatments will be their effect on the growth and vigor of the reserve trees. The literature describing the effect of partial regeneration cutting on reserve trees in mature to over-mature lodgepole pine in the Rocky Mountains has largely focused on mortality due to windthrow or other factors. Substantial windthrow has been observed when more than half of the total basal area was removed in harvesting, resulting in negative net overstory volume growth (Alexander 1986, Hatch 1967). Little information is available regarding reserve tree growth response following partial harvesting, though Alexander (1986) has observed negligible lodgepole pine growth response in the central Rockies. For individual old lodgepole pine (e.g. >80 years), post-treatment growth response appears to be strongly correlated with crown size, vigor, and amount of release provided (Lotan and Critchfield 1990). The post-treatment
response of individual trees will likely also be affected by spatial pattern of the reserve trees (i.e., clumped vs. evenly distributed), as well as the relative crown stature and age of each tree.

Lodgepole pine is generally a short-lived species compared to other Rocky Mountains conifers, yet individual tree and stand ages vary considerably by location. A high proportion of the lodgepole pine stands in the region are mature to over-mature, in part related to more than 60 years of fire suppression (McCaughey and others 2006). Old lodgepole pine stands of high density tend to include many trees of poor vigor (O’Hara and Kollenberg 2003) and such stands may have only modest biological potential for dramatic growth response to release by partial harvesting. At the stand level it has long been observed that forest growth accelerates in young stands as crowns develop, peaks near the time when maximum leaf area is attained, then declines substantially (Binkley and others 2002). However, at the individual tree level, Binkley and others (2002) have hypothesized that trees that attain dominant crown positions can sustain higher growth rates for longer periods by utilizing a higher proportion of the available resources, while trees in lesser canopy positions (which are often more numerous) grow more slowly as a result of lesser resource acquisition. Kaufmann (1996) found growth trends in volume increment for an old-growth lodgepole pine stand in the central Rockies that suggested growth potential may increase with age for some trees, particularly those having higher leaf area (oldest trees were greater than 250 years). In contrast, trees with slower growth rates late in their life had shown declining growth for many decades (Kauffmann 1996).
Studies on the growth response of reserved trees following partial harvesting may influence managers who are considering alternatives to even-aged management of lodgepole pine. Reserve-tree growth may be of interest for consideration of merchantable product recovery in the event of subsequent overstory removal harvests and also because knowledge of overstory vigor is important given the desire to maintain healthy and productive forests that provide for multiple resource values.

Objectives

The purpose of this study was to examine the early basal area growth response of mature and overmature reserve lodgepole pine left in two distinct spatial patterns following shelterwood harvesting, relative to growth in uncut controls. Growth response for individual trees was assessed by comparing a ratio of the five-year post-treatment basal area growth to that of the five-year period that preceded treatment. This study addresses the following specific questions:

1. *Will mature and overmature lodgepole pine display increased basal area growth rates in response to release in a shelterwood harvest?*

2. *Will the level of growth response depend upon the spatial arrangement of reserve trees?*

3. *Will the level of growth response within grouped reserves vary dependent on tree position (i.e. proximity to the group edge)?*

4. *To what extent is growth response related to various tree characteristics, such as age, diameter, crown class, and live crown ratio?*
Methods

Study area

This study was conducted on the Tenderfoot Creek Experimental Forest (TCEF), located on the Lewis and Clark National Forest, approximately 40 kilometers north of White Sulfur Springs, Montana. The TCEF covers 3,693 hectares, nearly 95% of which is in lodgepole pine. Sampling occurred at elevations ranging from approximately 2,179 to 2,286 m with average annual precipitation of approximately 635 mm, most of which falls as snow. Tenderfoot Creek is a westward flowing tributary of the Smith River, and the Tenderfoot Creek watershed within the Experimental Forest boundary is made up of several sub-watersheds. This study was part of a larger set of studies undertaken by the Rocky Mountain Research Station designed to determine the effects shelterwood with reserves harvesting and prescribed fire treatments have on conifer regeneration, growth response of residual overstory, and associated hydrologic changes (McCaughey and others 2000). This study focused on the effects of partial harvesting on residual overstory by examining early basal area growth response of the reserve trees, which were retained in two distinct spatial arrangements. Because of the limited time since prescribed burning was conducted (2002 and 2003), this study considers only the unburned shelterwood treatments, where five years of post-treatment growth had occurred. The treatments compared in this study fall within two sub-watersheds, Sun Creek and Spring Park Creek (Figure 1).

Recent fire history studies have determined that slightly over half of the lodgepole pine stands on the TCEF show two-aged structure apparently resulting from varied
disturbance patterns (McCaughey and others 2006, Barrett 1993). As an alternative to using clearcutting systems for managing lodgepole pine, shelterwood with reserves treatments were implemented in 2000 on the TCEF to emulate a range of natural structures and spatial patterns. Pre-treatment inventories had suggested two distinct stand structures that likely resulted from varied historical fire patterns (McCaughey and others 2006). One pattern seemed to indicate that fire had spread throughout stands, leaving surviving individual trees or small groups of trees somewhat evenly distributed within the fire perimeter. The second and more prevalent pattern suggested that fires had burned with high severity in swaths of varied size and shape, leaving unburned groups of trees and creating an irregular mosaic of small stands (McCaughey and others 2006). In response to this information, the shelterwood treatments implemented at TCEF have created two distinct spatial configurations of reserve trees, either uniformly distributed across the stand (even distribution) or left in uncut patches (grouped reserves) of about 0.1 to 0.8 hectares. In both treatment scenarios, approximately 40 to 60% of the pre-treatment basal area was intended to be removed, however, because of post-harvest mortality, total basal area reduction ranged from 55 to around 90% (Table 1).

Table 1. Characteristics of stands sampled in two separate sub-watersheds on the Tenderfoot Creek Experimental Forest. Treatment abbreviations are as follows: ‘SE’ is shelterwood with evenly-distributed reserves, ‘SG’ is shelterwood with grouped reserves, and ‘Control’ is unmanaged. Area and basal area stocking data were not collected for the untreated controls.

<table>
<thead>
<tr>
<th>Sub-watershed</th>
<th>Treatment</th>
<th>Size (ha)</th>
<th>Aspect</th>
<th>Habitat Type *</th>
<th>BA Pre (m²/ha)</th>
<th>BA Post (m²/ha)</th>
<th>Subject Trees (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Creek</td>
<td>SE</td>
<td>18</td>
<td>W</td>
<td>ABLA / VASC</td>
<td>43.3</td>
<td>5.7</td>
<td>34</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>SG</td>
<td>27</td>
<td>W</td>
<td>ABLA / VASC</td>
<td>44.0</td>
<td>20.0</td>
<td>25</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>Control</td>
<td>.</td>
<td>W</td>
<td>ABLA / VASC</td>
<td>.</td>
<td>.</td>
<td>26</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SE</td>
<td>9</td>
<td>W</td>
<td>ABLA / VASC</td>
<td>40.1</td>
<td>12.6</td>
<td>25</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SG</td>
<td>7</td>
<td>W</td>
<td>ABLA / VASC</td>
<td>30.0</td>
<td>1.8</td>
<td>25</td>
</tr>
<tr>
<td>Spring Park</td>
<td>Control</td>
<td>.</td>
<td>W</td>
<td>ABLA / VASC</td>
<td>.</td>
<td>.</td>
<td>25</td>
</tr>
</tbody>
</table>

* Following Pfister and others (1977) ‘ABLA’ is *Abies lasiocarpa* (subalpine fir), ‘VASC’ is *Vaccinium scoparium* (grouse whortleberry), ‘.’ indicates unknown
Pre-treatment stand densities ranged from 30 to 44 m$^2$ per hectare (Table 1). Detailed stand age information was unknown prior to sampling. The subalpine fir (Abies lasiocarpa) / grouse whortleberry (Vaccinium scoparium) habitat type is one of the most abundant habitat types near and east of the Continental Divide in Montana and are considered to be of low to moderate productivity (Pfister and others 1977). In both sub-watersheds, lodgepole pine was the dominant overstory species. In Sun Creek, the overstory appeared nearly single-storied, with scattered individual whitebark pine (Pinus albicaulis) and a sapling layer that consisted primarily of subalpine fir with some Engelmann spruce (Picea engelmannii). In Spring Park, succession was noticeably more advanced, with spruce and fir present in all canopy layers.
Figure 1. Schematic map of treatment units on the Tenderfoot Creek Experimental Forest. ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, ‘PB’ refers to prescribed broadcast burn, and ‘Control’ refers to unmanaged. Only unburned units were sampled in the study reported here. Sampled units are outlined in light blue.
Field sampling

Stand selection

Within both Sun Creek and Spring Park Creek, three stands were selected to include an uncut “control”, along with one stand from each of the two alternative harvest treatments (even distribution versus grouped reserves). The treated stands were selected on the basis of closest proximity to primary roads among the pairs of units previously delineated in the larger study (RMRS study number RWU 4151-1000) (Figure 1). Three treatment groups were sampled: shelterwood with evenly-distributed reserves (SE), shelterwood with grouped reserves (SG), and controls (Table 1). Each treatment type is replicated once; one of each treatment type is located in the Sun Creek sub-watershed and one in Spring Park Creek sub-watershed. The control areas were selected on the same aspect and habitat type (Pfister and others 1977) immediately adjacent to the shelterwood units sampled in each sub-watershed (Figure 1, Table 1).

Field data collection

Within each stand, a systematic grid with a minimum of 25 points or ‘plot centers’ was established using a random starting point for sampling diameter growth of individual lodgepole pine subject trees. Spacing between sample plots varied with stand size; spacing between transect lines ranged from about 40–60 m, while spacing between plots along transects ranged from about 40-120 m. From plot center, the nearest lodgepole pine from either the dominant, co-dominant, or intermediate crown classes was selected (immature and suppressed trees were ignored). In the case of the SG treatments, the spacing between plots along transects was amended if the predetermined systematic
random sample point fell within the open harvested area. If the predetermined point fell greater than 5 m from the group edge, the plot was discarded and the sampling continued on to the next predetermined point along the transect. Within each treatment stand, a minimum of 25 subject trees were visited. Total sample size was 160 subject trees (Table 1).

For each selected subject tree, radial growth was sampled at breast height (1.37 m) by extracting two increment cores at perpendicular angles (i.e., separated by 90 degrees around the trees' circumference). Each core included a minimum of the previous ten years of radial growth, with one full core taken to the pith for age estimation. Breast height age estimates were obtained from 155 of 160 sample trees. In addition to radial growth and age, information was collected on the size and condition of each subject tree, including diameter at breast height, crown class, live crown ratio, and damage (e.g. bole damage from logging, windthrow, or forking).

Crown class and live crown ratio were recorded for subject trees because it was presumed that these variables may affect growth rates. All subject trees were qualitatively assigned a crown class based on relative tree height and amount of light presumed to be available to its crown (following Smith and others 1997). For reserve trees within the shelterwood treatments, crown class assignments attempted to classify trees with respect to pre-treatment conditions. Overtopped or immature trees were ignored, thus trees were assigned to the ‘dominant’, ‘codominant’, or ‘intermediate’ crown classes. Crown class differentiation offers a link to tree vigor, particularly in pure even-aged stands, because trees with larger crowns and receiving more light have greater
resources available for growth (Smith and others 1997). Live crown ratio was determined visually for each subject tree to the nearest 10%. Live crown ratio offers a rough but convenient measure of pre-treatment tree vigor, as it approximates the ratio of photosynthetic to non-photosynthetic surface area (Smith and others 1997). It is commonly used as an input variable in distance-independent growth models such as the US Forest Service’s Forest Vegetation Simulator (FVS). In general, it would be expected that trees that support higher live crown ratios have larger amounts of foliage allowing for greater growth potential. When ratios decline to 30 percent or less, the general decline in vigor can cause substantial reduction in diameter growth (Smith and others 1997).

For the SG treatments, the distance to the edge of the reserve group was recorded, if the subject tree fell within 10 m from the edge. The 10 m distance was selected to represent at least two full crown widths for dominant trees in the area. It was presumed that beyond this distance individual trees would not experience a reduction in competition, i.e. represented ‘interior’ conditions similar to those expected where no treatment had been conducted. For those trees within 10 m from the edge, distance was measured (to nearest 0.1 m) from the center of the subject tree’s bole to the group’s ‘drip line’ (outer edge).

Tree growth assessment

Increment cores collected in the field were placed in paper straws, labeled, and stored in packing tubes for transport back to the University of Montana. In the lab, the cores were dried and mounted on grooved boards. Cores were sanded with progressively finer
grades of sandpaper until individual rings were clearly apparent. Radial growth was measured using a binocular microscope mounted on a dendrochronometer with a Velmex sliding stage and Accurite measuring system. Annual radial growth increments were measured to the nearest 0.001 mm. Average ring width for each year was calculated from the two cores collected for each subject tree.

Growth for all subject trees was determined for two five-year periods, both before and after harvesting. The five-year post-treatment tree growth increment (2001 to 2005) was contrasted with the five-year growth period preceding treatments (1996 to 2000). For comparative purposes, the growth patterns for trees in the control stands are expressed by contrasting the incremental growth from the same time periods. Raw radial growth for the five-year pre- and post-treatment time periods was converted to basal area increment (BAI). The conversion of ring widths to BAI removes variation in radial growth attributable to increasing circumference (Duchesne and others 2002). The following formulas were used to calculate pre- and post-treatment basal area increment:

\[
\text{BAI}_{\text{post}} = \pi [r^2_{2005} - r^2_{2001}]
\]

\[
\text{BAI}_{\text{pre}} = \pi [r^2_{2000} - r^2_{1996}]
\]

where \( r \) is the tree radius at the given year. Diameter at breast height (DBH) was used to determine the initial radius (\( r_{2005} \)). Since DBH includes bark, it must be adjusted in order to arrive at an initial diameter inside the bark. Diameter inside bark (DIB) was derived using simple linear regression of DIB on DBH from 136 mature lodgepole pine trees measured throughout the Inland Northwest (Flewelling and Ernst 1996). The equation used to estimate DIB for 2005 was: \( \text{DIB} = -.0853 + .954(\text{DBH}) \). \( R^2 \) was .996. Bark thickness was assumed to remain static for the ten-year growth period of interest.
Basal area increment pre- and post-treatment were incorporated into a ‘growth index’ similar to procedures used by Peterson and others (1991), where they examined the change in lodgepole pine and Douglas-fir (*Psuedotsuga menziesii*) basal area growth before and after wildfire. Growth index (GI) was the primary response variable used here to assess the degree of lodgepole pine release to the shelterwood treatments, and was calculated as follows:

$$GI = \frac{(BAI_{post} - BAI_{pre})}{BAI_{pre}}$$

where GI is growth index and $BAI_{post}$ is mean BAI growth for 2001 to 2005 and $BAI_{pre}$ is the mean BAI growth from 1996 to 2000. Because pre-treatment growth rates are accounted for in the ratio, growth index provides a reliable relative measure of release that accounts for previous growth trends and climatic variability.

**Statistical analysis**

Differences in mean growth index values were assessed using Student’s t-tests. Comparisons were made between treatments in each sub-watershed, between interior and edge trees within the group-distributed shelterwood stands, and between various subsets of trees based on size, age, and crown characteristics. One-way analysis of variance (ANOVA) tests were not employed because of non-constant variance across treatments (Figure 2) and because substantial differences in mean tree ages between the two sub-watersheds became apparent as the increment cores were read in the lab. The threshold for statistical significance was set at alpha = 0.05.
Results

There was a broad distribution of age classes in both watersheds (as well as all individual stands) (Figure 3). Mean stand ages were substantially younger in the Sun Creek stands (mean 98.0 years at breast height, standard error 1.8 years, n = 85) than in the Spring Park stands (mean 208.4 years, standard error 4.8 years, n = 70) (Table 2).
Table 2. Mean ages of lodgepole pine stands sampled in various treatment units within two separate sub-watersheds at Tenderfoot Creek Experimental Forest. ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged. ‘Age’ refers to mean breast height age. Standard errors of mean age are provided in parentheses following the associated mean value.

<table>
<thead>
<tr>
<th>Location</th>
<th>Treatment</th>
<th>Age (yrs)</th>
<th>Range (yrs)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Creek</td>
<td>SE</td>
<td>98.2 (2.70)</td>
<td>73 - 126</td>
<td>34</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>SG</td>
<td>112.5 (2.96)</td>
<td>81 - 142</td>
<td>25</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>control</td>
<td>87.0 (1.86)</td>
<td>75 - 116</td>
<td>26</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SE</td>
<td>195.5 (8.36)</td>
<td>116 - 271</td>
<td>25</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SG</td>
<td>198.0 (7.78)</td>
<td>114 - 265</td>
<td>22</td>
</tr>
<tr>
<td>Spring Park</td>
<td>control</td>
<td>232.4 (6.88)</td>
<td>149 - 276</td>
<td>23</td>
</tr>
</tbody>
</table>

Figure 3. Lodgepole pine age distributions by sub-watershed at Tenderfoot Creek Experimental Forest for trees in the dominant, codominant, and intermediate crown classes. Data is combined across treatment types.

Growth response of reserve trees to the shelterwood treatments

Mean growth index values of the evenly-distributed shelterwood treatments (SE) in each watershed were significantly higher than those of both the controls (p < 0.001 and p < 0.001) and the shelterwood with grouped reserves (SG) (p < 0.001 and p = 0.002)
Growth response to the SE treatments, as measured by growth index, was substantial in both mature (Sun Creek) and overmature (Spring Park) stands. The magnitude of the growth response was higher in the Sun Creek stands, where mean growth index for the SE treatment was 8.8 times larger than the control and 5.4 times larger than the SG treatment (Table 3). In the older Spring Park stands, mean growth index in the SE treatment was 3 times larger than the control and 3.5 times larger than the SG treatment. Mean growth index values for the group distributed shelterwood treatments (SG) were not significantly different from the controls in either watershed ($p = 0.527$ and $p = 0.805$) (Table 5). In absolute terms, growth index of the Sun Creek SG treatment was 1.6 times larger than the control, yet the Spring Park SG treatment's mean growth index was lower than the control (Table 3). For all treatment groups (including controls), basal area growth rates were higher in the most recent five year period (2001 to 2005).

Table 3. Lodgepole pine basal area increment and growth index means by sub-watershed and treatment type at Tenderfoot Creek Experimental Forest. ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged. Standard errors are provided in parentheses following the associated mean value.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Location</th>
<th>5-yr BAI post</th>
<th>5-yr BAI pre</th>
<th>GI</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE</td>
<td>Sun Cr</td>
<td>20.23 (2.41)</td>
<td>11.23 (0.93)</td>
<td>0.70 (.12)</td>
<td>34</td>
</tr>
<tr>
<td>SE</td>
<td>Sp Park</td>
<td>25.33 (2.95)</td>
<td>16.34 (1.91)</td>
<td>0.60 (.09)</td>
<td>25</td>
</tr>
<tr>
<td>SG</td>
<td>Sun Cr</td>
<td>11.13 (1.41)</td>
<td>9.52 (1.00)</td>
<td>0.13 (.07)</td>
<td>25</td>
</tr>
<tr>
<td>SG</td>
<td>Sp Park</td>
<td>15.19 (1.95)</td>
<td>13.05 (1.60)</td>
<td>0.17 (.09)</td>
<td>25</td>
</tr>
<tr>
<td>Control</td>
<td>Sun Cr</td>
<td>16.23 (1.93)</td>
<td>15.18 (1.69)</td>
<td>0.08 (.04)</td>
<td>26</td>
</tr>
<tr>
<td>Control</td>
<td>Sp Park</td>
<td>13.98 (1.74)</td>
<td>11.69 (1.51)</td>
<td>0.20 (.05)</td>
<td>25</td>
</tr>
</tbody>
</table>

BAI units are cm$^2$ per five-year period
Table 4. Lodgepole pine basal area increment and growth index means summarized by treatment type at Tenderfoot Creek Experimental Forest. ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged. Standard errors are provided in parentheses following the associated mean value.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>5-yr BAI post</th>
<th>5-yr BAI pre</th>
<th>GI</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE</td>
<td>22.36 (1.88)</td>
<td>13.39 (1.02)</td>
<td>0.66</td>
<td>59</td>
</tr>
<tr>
<td>SG</td>
<td>13.14 (1.23)</td>
<td>11.28 (0.97)</td>
<td>0.15</td>
<td>50</td>
</tr>
<tr>
<td>Control</td>
<td>15.11 (1.30)</td>
<td>13.47 (1.15)</td>
<td>0.14</td>
<td>51</td>
</tr>
</tbody>
</table>

BAI units are cm² per five-year period

Table 5. Differences in lodgepole pine growth index by treatment type and sub-watershed at Tenderfoot Creek Experimental Forest. ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged.

<table>
<thead>
<tr>
<th>Location</th>
<th>Null Hypothesis</th>
<th>t</th>
<th>p-value</th>
<th>CI: lower</th>
<th>CI: upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Cr</td>
<td>μSE = μcontrol</td>
<td>4.847*</td>
<td>0.001</td>
<td>0.37</td>
<td>0.92</td>
</tr>
<tr>
<td>Sun Cr</td>
<td>μSE = μSG</td>
<td>4.035*</td>
<td>0.001</td>
<td>0.29</td>
<td>0.86</td>
</tr>
<tr>
<td>Sun Cr</td>
<td>μSG = μcontrol</td>
<td>0.639</td>
<td>0.527</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sp Park</td>
<td>μSE = μcontrol</td>
<td>3.992*</td>
<td>0.001</td>
<td>0.20</td>
<td>0.61</td>
</tr>
<tr>
<td>Sp Park</td>
<td>μSE = μSG</td>
<td>3.324*</td>
<td>0.002</td>
<td>0.17</td>
<td>0.69</td>
</tr>
<tr>
<td>Sp Park</td>
<td>μSG = μcontrol</td>
<td>-0.248</td>
<td>0.805</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* indicates significance at the 0.05 alpha level, ‘CI’ is 95% confidence interval

**Evaluation of growth response for ‘edge’ versus ‘interior’ trees in reserve groups**

In attempting to compare mean growth index values for trees near the edge of reserve groups versus trees in the interior, small sample sizes were of concern because hypothesis testing requires partitioning of the available samples. While variability among the treatment groups in this study precluded ANOVA procedures, variation among the two SG treatments was similar (Figure 2). A student’s t-test for the equality of the mean growth index values for the two SG treatments did not detect a significant difference (p = 0.712). Levene’s test for equality of variances (p = 0.481) further suggested the samples from both watersheds could legitimately be combined.
Trees on the edges of the reserve groups clearly showed increased post-treatment basal area growth rates (Table 6). T-tests for differences in mean growth index were performed as the inward limits of the group ‘edge’ was defined as a progressively smaller ring (Ho: \( \mu GI_{edge} = \mu GI_{interior} \)). A positive growth response was evident for those trees located at short distances to the true group edge. When all trees located less than 10 m from the edge were compared with ‘interior trees’ (> 10 m from the group edge), the difference in mean growth index was not statistically significant. Significantly higher growth index values were found when the area considered as representing ‘edge conditions’ was reduced to 7 m. Mean difference in growth index values continued to increase for decreasing edge widths (i.e., 4 m and 2 m; Table 6).

<table>
<thead>
<tr>
<th>Edge Defined As</th>
<th>n Edge</th>
<th>n Interior</th>
<th>t'</th>
<th>p-value</th>
<th>mean difference in GI</th>
<th>CI: lower</th>
<th>CI: upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10 m</td>
<td>33</td>
<td>17</td>
<td>1.672</td>
<td>0.101</td>
<td>0.18</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>&lt; 7 m</td>
<td>27</td>
<td>23</td>
<td>2.310*</td>
<td>0.026</td>
<td>0.25</td>
<td>0.03</td>
<td>0.47</td>
</tr>
<tr>
<td>&lt; 4 m</td>
<td>20</td>
<td>30</td>
<td>2.656*</td>
<td>0.013</td>
<td>0.33</td>
<td>0.07</td>
<td>0.58</td>
</tr>
<tr>
<td>&lt; 2 m</td>
<td>14</td>
<td>36</td>
<td>2.705*</td>
<td>0.015</td>
<td>0.39</td>
<td>0.09</td>
<td>0.69</td>
</tr>
</tbody>
</table>

*equal variances not assumed, ** indicates significance at the .05 alpha level, ‘CI’ is 95% confidence interval.

A peculiar artifact of the modest number of sample trees evaluated in this study is that mean growth index for those trees \( a priori \) considered interior trees (> 10 m from the group edge) were much lower (0.03) than the mean growth index of the two controls (0.14). Because the interior tree basal area growth rate estimates were so small, the trees near group edges within each sub-watershed’s SG treatment were separately compared to that sub-watershed’s control growth index values (Table 7). Statistically significant
differences were found only within the Sun Creek watershed, for those trees within 2 m of the group edge (p = 0.002). In absolute terms, however, t-values and mean differences in growth index generally increase with closer proximity to the group edge (Table 7).

Table 7. Comparison of mean growth index value differences for lodgepole pine near the edges of reserve groups (SG) versus controls at Tenderfoot Creek Experimental Forest.

<table>
<thead>
<tr>
<th>Location</th>
<th>Edge Defined</th>
<th>n Edge</th>
<th>n Control</th>
<th>t^1</th>
<th>p-value</th>
<th>mean GI difference</th>
<th>CI lower</th>
<th>CI upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Cr</td>
<td>&lt; 10 m</td>
<td>17</td>
<td>26</td>
<td>1.216</td>
<td>0.237</td>
<td>0.11</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Sp Park</td>
<td>&lt; 10 m</td>
<td>16</td>
<td>25</td>
<td>0.230</td>
<td>0.821</td>
<td>0.03</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Sun Cr</td>
<td>&lt; 7m</td>
<td>13</td>
<td>26</td>
<td>1.750</td>
<td>0.099</td>
<td>0.17</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Sp Park</td>
<td>&lt; 7m</td>
<td>14</td>
<td>25</td>
<td>0.504</td>
<td>0.621</td>
<td>0.08</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Sun Cr</td>
<td>&lt; 4m</td>
<td>9</td>
<td>26</td>
<td>2.025</td>
<td>0.07</td>
<td>0.23</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Sp Park</td>
<td>&lt; 4m</td>
<td>11</td>
<td>25</td>
<td>0.925</td>
<td>0.374</td>
<td>0.18</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Sun Cr</td>
<td>&lt; 2 m</td>
<td>6</td>
<td>26</td>
<td>4.721*</td>
<td>0.002</td>
<td>0.42</td>
<td>0.21</td>
<td>0.62</td>
</tr>
<tr>
<td>Sp Park</td>
<td>&lt; 2 m</td>
<td>8</td>
<td>25</td>
<td>0.722</td>
<td>0.463</td>
<td>0.18</td>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>

^1 equal variances not assumed, **' indicates significant at the 0.05 alpha level, 'CI' is 95% confidence interval

Factors related to individual tree growth response

At the treatment-level, significantly higher mean growth index values were observed for reserve lodgepole pine where a sufficient reduction in competition had occurred (SE treatments and trees along the edges of SG treatments). While the shelterwood treatments provided release potential for individual reserve lodgepole pine, variability was high, particularly in the case of the SE treatments (Figure 2). This variation in observed basal area growth response may be explained, in part, by observable individual tree characteristics. What follows is an examination of growth response as related to tree age, diameter, crown class, and live crown ratio.

Age
A relatively broad range of lodgepole pine tree ages were present within both watersheds. In Sun Creek, breast height ages ranged from 73 to 142 years. In Spring Park Creek, the breast height age ranges were broader still: 114 to 276 years (Table 2). Pearson’s simple correlation coefficient denotes the strength of the linear association between two continuous variables. The simple correlation coefficient (r) was calculated for growth index as a function of age for all treatment combinations (Figure 4). As evident in the scatter plots of Figure 4, there was only a weak relationship between growth index and age (r values range from -0.168 to 0.207). Mean growth index values were investigated to compare basal area growth patterns for trees younger or older than the mean age within each treatment combination (Table 8).

![Figure 4. Growth index/age correlations for lodgepole pine at Tenderfoot Creek Experimental Forest. ‘SE’ refers to shelterwood with evenly-distributed reserves,](image-url)
‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged.

Table 8. Mean growth indices for lodgepole pine at Tenderfoot Creek Experimental Forest: trees younger versus older than the stand’s mean. ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged.

<table>
<thead>
<tr>
<th>Location</th>
<th>Treatment</th>
<th>mean $Gl_{younger}$</th>
<th>$n$</th>
<th>mean $Gl_{older}$</th>
<th>$n$</th>
<th>$t^1$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Creek</td>
<td>SE</td>
<td>0.60 (0.18)</td>
<td>20</td>
<td>0.84 (0.16)</td>
<td>14</td>
<td>-0.969</td>
<td>0.340</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>SG</td>
<td>0.04 (0.10)</td>
<td>12</td>
<td>0.21 (0.10)</td>
<td>13</td>
<td>-1.244</td>
<td>0.226</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>Control</td>
<td>0.07 (0.05)</td>
<td>13</td>
<td>0.08 (0.06)</td>
<td>13</td>
<td>-0.134</td>
<td>0.895</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SE</td>
<td>0.57 (0.14)</td>
<td>12</td>
<td>0.63 (0.11)</td>
<td>13</td>
<td>-0.313</td>
<td>0.757</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SG</td>
<td>0.25 (0.15)</td>
<td>10</td>
<td>0.22 (0.14)</td>
<td>12</td>
<td>0.177</td>
<td>0.861</td>
</tr>
<tr>
<td>Spring Park</td>
<td>Control</td>
<td>0.24 (0.06)</td>
<td>11</td>
<td>0.16 (0.09)</td>
<td>12</td>
<td>0.740</td>
<td>0.468</td>
</tr>
</tbody>
</table>

$H_0: \mu Gl_{younger} = \mu Gl_{older}$, equal variances not assumed, standard errors in parentheses

Age does not appear to have deleterious influence on basal area growth response ($p$ values range from 0.226 to 0.895). In most instances, the mean growth index values and $t$-values are negative, suggesting that older trees may have had a tendency toward higher basal area growth increments in the past five years as compared with younger trees (Table 8).

**Diameter**

The simple correlation coefficient ($r$) was calculated for growth index as a function of 2005 diameter at breast height for all treatment combinations (Figure 5).
There is high variability in growth index values among trees of a given size, and the correlations are weak (coefficients range from -0.024 to 0.390). However, with the exception of the Spring Park Creek control, all associations are positive. For evenly-distributed reserve trees, post-treatment basal area increment generally declined with age among trees of similar diameter (the large diameter trees in Spring Park are the exception), though this relationship was highly variable (Figures 6 and 7).
Figure 6. Post-treatment basal area increment by age and diameter class among evenly-distributed reserves in Sun Creek sub-watershed at Tenderfoot Creek Experimental Forest.

Figure 7. Post-treatment basal area increment by age and diameter class among evenly-distributed reserves in Spring Park sub-watershed at Tenderfoot Creek Experimental Forest.
Crown class

Of the 160 total trees sampled in this study, the majority were judged to be codominant (69%), with approximately one quarter intermediate (27.5%), and less than 4 percent classified as dominant. The stands in this study had broad age ranges, such that viewing crown position differentiation as a result of competition is somewhat confounded by tree age. Crown position tended to follow a pattern such that the upper canopy layers were primarily made up of the older trees in the stand (Table 9).

Table 9. Mean lodgepole pine tree ages by crown class sampled in two separate sub-watersheds at Tenderfoot Creek Experimental Forest. Crown classifications are described in the text. Standard errors of the mean estimate are provided in parentheses following the associated mean values.

<table>
<thead>
<tr>
<th>Location</th>
<th>Crown Class</th>
<th>Age (yrs)</th>
<th>Range (yrs)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Creek</td>
<td>Dominant</td>
<td>124.0 (15.0)</td>
<td>109 - 139</td>
<td>2</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>Codominant</td>
<td>101.5 (2.1)</td>
<td>75 - 142</td>
<td>59</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>Intermediate</td>
<td>90.5 (2.9)</td>
<td>73 - 119</td>
<td>24</td>
</tr>
<tr>
<td>Spring Park</td>
<td>Dominant</td>
<td>239.5 (12.0)</td>
<td>211 - 263</td>
<td>4</td>
</tr>
<tr>
<td>Spring Park</td>
<td>Codominant</td>
<td>211.6 (6.0)</td>
<td>116 - 273</td>
<td>47</td>
</tr>
<tr>
<td>Spring Park</td>
<td>Intermediate</td>
<td>194.0 (8.6)</td>
<td>114 - 276</td>
<td>19</td>
</tr>
</tbody>
</table>

The relationship between growth index and crown class did not show consistent trends across treatments. The few trees that were classified as overstory dominants within the evenly-distributed shelterwood treatments had greater mean growth index values than did codominant and intermediate trees (Figure 8). Sample sizes were more equitable for codominant and intermediate trees, allowing for comparison of mean growth index values (Table 10); however no clear trends were apparent between these two crown classes.
Figure 8. Multi-aged lodgepole pine growth index data by crown class, treatment type, and sub-watershed at Tenderfoot Creek Experimental Forest. ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged.

Table 10. Mean growth indices for lodgepole pine in codominant and intermediate crown classes by treatment and sub-watershed at Tenderfoot Creek Experimental Forest. ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged. Standard errors of the mean estimate are provided in parentheses following the associated mean values.

<table>
<thead>
<tr>
<th>Location</th>
<th>Treatment</th>
<th>mean Glc</th>
<th>n</th>
<th>mean Gli</th>
<th>n</th>
<th>t^1</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Creek</td>
<td>SE</td>
<td>0.80</td>
<td>24</td>
<td>0.34</td>
<td>9</td>
<td>1.807</td>
<td>0.090</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>SG</td>
<td>0.23</td>
<td>15</td>
<td>-0.04</td>
<td>9</td>
<td>1.901</td>
<td>0.072</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>control</td>
<td>0.05</td>
<td>20</td>
<td>0.15</td>
<td>6</td>
<td>-1.143</td>
<td>0.285</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SE</td>
<td>0.54</td>
<td>16</td>
<td>0.65</td>
<td>7</td>
<td>-0.534</td>
<td>0.604</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SG</td>
<td>0.18</td>
<td>17</td>
<td>0.15</td>
<td>8</td>
<td>0.136</td>
<td>0.894</td>
</tr>
<tr>
<td>Spring Park</td>
<td>control</td>
<td>0.22</td>
<td>18</td>
<td>0.16</td>
<td>5</td>
<td>0.509</td>
<td>0.620</td>
</tr>
</tbody>
</table>

‘C’ is codominant, ‘I’ is intermediate, Ho: μGl_c = μGl_i, ‘equal variances not assumed
Live crown ratio

Three live crown ratio (LCR) classes were distinguished to facilitate comparison. These were: less than 30 percent ('low'), between 30 and 50 percent ('medium'), and greater than 50 percent ('high'). The majority of the subject trees (about 71%) had live crown ratios between 30 and 50 percent. In all partially harvested treatments, mean growth index values increased with higher LCRs (Table 11, Figure 9).

Table 11. Lodgepole pine mean growth index for trees classified as having “low”, “medium”, and “high” live crown ratio values two separate sub-watersheds within the Tenderfoot Creek Experimental Forest. Live crown ratios (LCR) were classified as follows: ‘low’ = <30% LCR, ‘med’ = 30 to 50% LCR, and ‘high’ = >50% LCR. Treatment abbreviations are as follows: ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged.

<table>
<thead>
<tr>
<th>Location</th>
<th>Treatment</th>
<th>μ GI low</th>
<th>n</th>
<th>μ GI med</th>
<th>n</th>
<th>μ GI high</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Creek</td>
<td>SE</td>
<td>-0.08 (.18)</td>
<td>4</td>
<td>0.77 (.73)</td>
<td>26</td>
<td>1.05 (.33)</td>
<td>4</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>SG</td>
<td>-0.13 (.07)</td>
<td>9</td>
<td>0.20 (.09)</td>
<td>13</td>
<td>0.59 (.06)</td>
<td>3</td>
</tr>
<tr>
<td>Sun Creek</td>
<td>control</td>
<td>0.18 (.15)</td>
<td>3</td>
<td>0.07 (.04)</td>
<td>21</td>
<td>-0.04 (.02)</td>
<td>2</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SE</td>
<td>0.50 (.31)</td>
<td>4</td>
<td>0.62 (.11)</td>
<td>17</td>
<td>0.64 (.07)</td>
<td>4</td>
</tr>
<tr>
<td>Spring Park</td>
<td>SG</td>
<td>-0.15 (.07)</td>
<td>5</td>
<td>0.25 (11)</td>
<td>20</td>
<td>x</td>
<td>0</td>
</tr>
<tr>
<td>Spring Park</td>
<td>control</td>
<td>-0.02 (.12)</td>
<td>5</td>
<td>0.26 (.06)</td>
<td>17</td>
<td>0.16 (.06)</td>
<td>3</td>
</tr>
</tbody>
</table>

Standard errors of the mean growth index (GI) values are provided in parentheses following the associated mean.
Figure 9. Lodgepole pine growth index data by live crown ratio class, treatment, and sub-watershed at Tenderfoot Creek Experimental Forest. ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged.

Within the shelterwood treatments, reserve trees with LCRs of at least 30% in many instances had significantly higher mean growth index values than trees with LCRs below 30% (Table 12). In the evenly-distributed treatments, trees with live crowns ratios of less than 30% had significantly lower mean growth index values than trees with longer crowns in Sun Creek (p = 0.006 and p = 0.004). Though a similar trend was observed in absolute terms for Spring Park, the comparisons were not statistically significant (Table 12). In the grouped reserves, trees with lesser LCRs had significantly smaller mean growth index values than trees with longer crowns in all instances (p values range from < 0.001 to 0.008) (Table 12). In the controls, the relationship between growth index and
live crown ratios was less clear, and in one instance (Sun Creek) growth index appeared to decline with increasing LCRs (Table 11, Figure 9).

Table 12. Comparison of mean growth indices for three live crown ratio classes by treatment type and sub-watershed at Tenderfoot Creek Experimental Forest. Live crown ratios (LCR) were classified as follows: ‘low’ = <30% LCR, ‘med’ = 30 to 50% LCR, and ‘high’ = >50% LCR. Treatment abbreviations are as follows: ‘SE’ refers to shelterwood with evenly-distributed reserves, ‘SG’ refers to shelterwood with grouped reserves, and ‘Control’ refers to unmanaged.

<table>
<thead>
<tr>
<th>Location</th>
<th>Treatment</th>
<th>Null Hypothesis</th>
<th>t</th>
<th>p</th>
<th>CI: upper</th>
<th>CI: lower</th>
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<tr>
<td>Sun Creek</td>
<td>SE</td>
<td>$\mu GI_{low} = \mu GI_{med}$</td>
<td>-3.751* 0.006</td>
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<td>-0.33</td>
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<tr>
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<td>SE</td>
<td>$\mu GI_{low} = \mu GI_{high}$</td>
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<td>-1.73</td>
<td>-0.54</td>
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<tr>
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<td>SE</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>SG</td>
<td>$\mu GI_{low} = \mu GI_{med}$</td>
<td>-2.925* 0.008</td>
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<td>-0.51</td>
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<td>1.483 0.272</td>
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<td>2.479* 0.027</td>
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<td>0.21</td>
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<td>-0.358 0.739</td>
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<td></td>
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<td></td>
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<tr>
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<td>-0.13</td>
<td></td>
</tr>
<tr>
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<td>$\mu GI_{low} = \mu GI_{high}$</td>
<td>x x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring Park</td>
<td>SG</td>
<td>$\mu GI_{med} = \mu GI_{high}$</td>
<td>x x</td>
<td></td>
<td></td>
<td></td>
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<td>control</td>
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<td></td>
<td></td>
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<tr>
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<td>control</td>
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<td>1.316 0.233</td>
<td></td>
<td></td>
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</tbody>
</table>

‘CI’ = 95% confidence interval, and ‘x’ = no trees in the >50% class

Discussion

Effects of alternative shelterwood treatments on reserve tree growth response

At the treatment level, both mature and overmature lodgepole pine reserve trees in the study area responded to release by accelerating basal area growth rates following
shelterwood harvesting. The level of growth response, however, was dependent on the spatial arrangement of the reserve trees. Treatments with evenly-distributed reserves showed more dramatic basal area growth increases, presumably because individual reserve trees were given greater reduction in competition from neighbors (Tables 3 and 5). Variability was also highest among the evenly-distributed reserves (Figure 2, Table 3). At the stand level, wider spacing appears to be the dominant factor in explaining the substantially larger basal area growth response of reserve trees in the evenly-distributed treatments as compared to the grouped reserves and controls.

The mature and overmature central Montana lodgepole pine stands sampled in this study showed slower basal area growth prior to treatment than has been reported for unmanaged stands elsewhere in the west. Pre-treatment average annual basal area increment for lodgepole pine in this study ranged from about 1.9 to 3.3 cm²/yr (Table 3, where ‘BAI pre’ is divided by 5). Peterson and others (1991) found lodgepole pine average annual basal area increment (in the years preceding a major wildfire disturbance) of about 9 cm²/yr in the Bitterroot National Forest in western Montana, and about 4 cm²/yr in Yellowstone National Park. Mainwaring and Maguire (2004) found average annual basal area increment for lodgepole pine in mixed species stands in central Oregon ranging from 5.0 to 16.3 cm²/yr. The apparently slow pre-treatment basal area growth rates observed in this study may be related in part to the older ages of the stands. Kashian and others (2005) found average annual basal area increment on a per hectare basis in Yellowstone National Park lodgepole pine stands to be significantly higher in younger stands (aged 50 to 100 years) growing on similar sites as compared to stands aged 125 years and older. Such a pattern did not occur in this study, as the older Spring
Park stands had higher mean basal area increments. However, in absolute terms, Kashian and others (2005) also found higher average annual basal area increments in 300 to 350 year old stands than in stands 200 to 250 years old also growing on similar sites, suggesting that growth did not decline with age in a linear fashion.

The positive growth response to release among evenly-distributed reserve lodgepole pine in this study is consistent with what might be expected following thinnings and what has been observed in previous studies of different reserve tree spacing. Mata and others (2003) analyzed diameter growth of mature reserve lodgepole pine in several locations in the central Rockies following thinnings of varied intensity designed to make stands less susceptible to mountain pine beetle attack (residual trees were left roughly evenly-distributed). Results showed that the diameter growth of reserve trees increased following thinning and that diameter growth increases were more pronounced at wider residual spacings (Mata and others 2003). Amman (1989) analyzed radial growth of mature residual lodgepole pine following diameter limit and evenly-spaced thinnings to varying residual stand basal areas in western Montana and northwest Wyoming. Trends showed increased radial growth among reserve trees five years after thinning treatments, and relative increases in radial growth generally were greatest in stands where a greater reduction in density had occurred (Amman 1989).

*Evaluation of growth response for ‘edge’ versus ‘interior’ trees in reserve groups*

Mean growth index for trees within grouped reserves were not significantly different from the controls. However, trees located in closer proximity to the reserve group edge did show higher mean growth index values than interior trees. Significantly
larger growth index values for ‘edge’ versus ‘interior’ trees were found when the reserve group ‘edge’ zone was considered to be a band as wide as 7 meters, and this difference became progressively more pronounced as the width of this outer edge zone was reduced in the analysis (Table 6). The relatively small and uneven sample sizes available for comparison in this study make it difficult to assess critical distances from group edges where meaningful release might be expected. However there was strong evidence that closer proximity to the group edge had a positive effect on the growth of both mature and overmature lodgepole pine in this study, and further investigation of this matter may help clarify the extent to which varying the shape of reserve groups may have a significant influence on stand level basal area growth increment.

Effects of crown size and position and tree age on reserve tree growth response

Apart from the level of competition reduction (i.e. treatment effects), the live crown ratio of individual reserve trees appeared to have the greatest direct influence on basal area growth response to partial harvesting. Reserve trees that had longer crowns (higher live crown ratios) generally showed higher basal area growth following partial harvesting (Figure 7). In older stands of high density, such as the pre-treatment conditions in this study, it is unlikely that many lodgepole pines will display live crown ratios exceeding half of their total height (only about 10% in this study). A higher proportion of trees may retain crown ratios between 30 and 50 percent (about 70% in this study), and such trees were generally vigorous enough to respond positively to release. Trees with live crown ratios less than 30 percent (which accounted for about 20% of the trees in this study) showed little ability to respond positively to release.
Advanced age, by itself, did not appear to have a negative influence on the likelihood of release for reserve lodgepole pine at Tenderfoot Experimental Forest. At the treatment level, the magnitude of the basal area growth response among evenly-distributed reserves and among trees near the edge in reserve groups was greatest in the younger Sun Creek stands (Tables 3, 5, 7). However, age may not be a dominant factor in this discrepancy between sub-watersheds given that reserve tree age was poorly and generally positively correlated with growth index within individual stands (Figure 4, Table 8). In absolute terms, mean incremental growth among reserve trees following treatment was higher in the older Spring Park stands. Though all stands were classified as subalpine fir / grouse whortleberry habitat types (Pfister and others 1977) on similar aspects, pre- and post-treatment mean basal area increments were higher for the treated stands in Spring Park than in Sun Creek (Table 3).

Among individual reserve trees within the same stand, it was somewhat unexpected that age was poorly and generally positively correlated with growth index. All else being equal (i.e. crown position, amount of foliage), it would generally be assumed that younger trees have higher growth rates and greater potential for release. However, within the broad-aged stands of this study, the older trees tended to occupy higher positions within the canopy (Table 9). Comparisons of mean growth index among crown classes did not show clear trends or yield statistically significant differences (Figure 6, Table 10). In Sun Creek it appeared that dominant and codominant trees showed greater release following treatment than intermediate trees, yet this was not the case in Spring Park. This lack of observed differences may be related to small sample sizes in both the dominant and intermediate crown classes. The effects of age on reserve
trees within the same stand are thus obscured because of its relationship with crown class. Similarly, reserve tree diameter is reflective of both age and crown class. As was the case with age, diameter was poorly but positively correlated with growth index (Figure 5). Both growth response and variability was highest within the evenly-distributed reserves. It appeared that the variables age, crown class, and diameter were interrelated yet imperfect surrogates for one another, such that none of the variables individually offered clear relationships with growth index. Scatterplots of post-treatment basal area increment, however, did reveal trends suggesting that basal area growth generally increases with tree diameter (and more dominant crown classes) yet may decline with age for trees within a given size class (Figures 6 and 7).

Though relatively weak, patterns observed in this study, i.e., trees with higher amounts of foliage (live crown ratio) and higher crown position tended to benefit most from release, is consistent with studies of tree vigor in older unmanaged lodgepole pine stands based on sapwood-leaf area relationships. Kollenberg (1997) found that ‘growing space efficiency’ (volume growth per amount leaf area) was higher for upper canopy and older cohort trees in multi-aged lodgepole pine stands in western and central Montana. Kaufmann (1995) found continued increasing trends in volume increment over decades for dominant lodgepole pine in Colorado that were over 250 years old but had retained high leaf area.

**Implications for Two-aged Management of Lodgepole Pine**

Where growth performance of reserve trees following partial harvest is an important management goal, the shelterwood with evenly-distributed reserves method
may be a viable option in the northern Rocky Mountains, even in older lodgepole pine stands. Average growth within the residual overstory will be enhanced if reserve trees are selected on the basis of visually adequate pre-treatment vigor, i.e. live crown ratios of at least 30% and favored retention of dominant and codominant trees. The evenly-distributed reserve trees in this study averaged a 66% increase in basal area growth rate in the five years post-treatment relative to pre-treatment growth rate. It is likely that similar treatments may result in greater growth response if applied in younger lodgepole pine stands. The wider spacings created by the even distribution as compared to the grouped arrangement may increase windthrow risks. If reserve losses to windthrow are high, benefits of increased individual tree growth may be offset. Within the shelterwood with evenly-distributed reserves treatments at the Tenderfoot Creek Experimental Forests, however, reserve losses to windthrow were modest, averaging less than 5 percent (Ward McCaughey, personal communication).

An additional benefit of the evenly-distributed reserve arrangement is the potential for improved resistance to mountain pine beetle. Increased basal area growth is reflective of generally improved vigor because diameter growth occurs only after trees have allocated resources to maintenance respiration and new fine roots and foliage (Barnes and others 1998). The improved vigor among evenly-distributed reserves along with the reduction in stand density meets common objectives of management actions designed to reduce stand susceptibility to mountain pine beetles (Amman 1989). However, this potential for improved resistance within these treatments remains hypothetical because there is little evidence of beetle activity in the study area and
because of uncertainty regarding growth rate thresholds for determining susceptible/non-
susceptible trees (Mata and others 2003).

At the stand level, growth rates among grouped reserves were not significantly
different from uncut controls. However, reserve trees along the edges showed improved
growth in response to release. Further research may help clarify whether increased stand
level growth rates could be promoted by designing reserve groups in long, relatively
narrow strips or in irregular shapes that provide a greater proportion of ‘edge’ conditions.
The findings of this study suggest that trees further than two crown widths (> 7 m) from
the group edge are not experiencing release. Apart from consideration of reserve tree
growth, the grouped reserve arrangement may offer important advantages over the even
distribution such as more favorable conditions for the development of a new cohort
within the cleared openings and easier access for future entries into the stand. In
addition, following mixed severity wildfires in lodgepole pine, the spatial arrangement of
surviving trees has been reported as highly variable (Tande 1979, Arno 1976, Barrett
1993). While the retention patterns in the study area attempt to emulate a range of
possible structures, the grouped arrangement may more closely resemble structures that
result from fires of irregular and patchy intensity.

Growth response of reserve lodgepole pine is only one of many aspects of interest in
determining the success of two-aged management treatments such as those employed at
the Tenderfoot Creek Experimental Forest. Other important objectives include adequate
regeneration establishment and development, economics of the harvesting, and the effects
of the treatments on aesthetics, wildlife habitat, water yields, and wildfire risk. It should
also be made clear that the TCEF had important attributes that made it attractive to experimentation with two-aged management of lodgepole pine, these included an absence of recent mountain pine beetle activity, very little dwarf mistletoe, and scarce evidence of significant wind events (Hardy and others 2000). Though the lodgepole pine forests of the TCEF are similar to those in many other locations throughout the northern Rocky Mountains, the types of treatments considered here may not be suitable given constraints due to localized mountain pine beetle activity, high mistletoe infection rates, or landscape locations prone to higher winds (Alexander 1986).


**Literature Cited**


Barrett, S.W. 1993. Fire history of Tenderfoot Creek Experimental Forest, Lewis and Clark National Forest. RJVA internal report on file with Rocky Mountain Research Station, Research Work Unit 4151, Missoula, MT.


Appendix A. Diameter Inside Bark Equation

Original diameter data (136 mature lodgepole pine) obtained from:


![Graph showing Diameter Inside Bark vs Diameter Outside Bark with Rsq = 0.9958](image)

<table>
<thead>
<tr>
<th>Model</th>
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<th>Standardized Coefficients</th>
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<th>Sig.</th>
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<td>Std. Error</td>
<td>Beta</td>
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a. Dependent Variable: DIB