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Early tree regeneration is consistent with sustained yield in low-input boreal forest management in Alaska

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ABSTRACT

The boreal forest of Alaska has experienced a small area of forest cuttings, amounting to 7,137 ha out of a total of 256,284 ha of timberland in the Fairbanks and Kantishna area of state forest land. Low product values and high costs for management have resulted in a low-input type management with heavy reliance on natural regeneration. Because of increasing demand for wood biomass energy which may reduce rotation ages, understanding post-harvest regeneration is crucial. Harvested areas must meet stocking standards within seven years under the state Forest Resources & Practices Act (FRPA). We evaluated whether state forest harvest units are adequately regenerated up to 40 years following harvest based on FRPA standards in terms of stem density and biomass accumulation. We measured density of all tree size classes, and DBH and height of tree species in 726 plots from 30 representative harvest units, distributed according to harvest and treatment types, harvest year, unit size, and the geographical location of harvests. The majority of regenerated tree stems came from natural regeneration, even on planted units (77%). White spruce (*Picea glauca*) natural regeneration appears to continue for a few decades (seed crops) following harvest. Stem density was below the standard in most units surveyed during the FRPA 7-yr. period, but far exceeded the standard when resampled in this study (average 16 yrs. later), suggesting either seven years is too early to evaluate tree regeneration, or that a different standard is needed for early surveys. We found a major peak in white spruce stem density ($45,000 \text{ ha}^{-1}$) in units harvested in 1987 (an historically large spruce seed crop year), suggesting that where possible, foresters need to adjust management plans according to spruce mast years. Post-harvest and post-fire successional patterns are similar, involving rapid establishment and growth of hardwoods and slow growth of white spruce, but post-harvest white spruce recruitment appears to continue longer than post-fire. By 2014 all measured harvest units met FRPA standard under low-input management, but some issues of uniformity of regeneration may remain. Although regeneration density varied among species and by management practices, biomass accumulated steadily over time ($60 \text{ t} \cdot \text{ha}^{-1}$ after 40 years), largely composed of hardwoods, indicating that short-rotation forest management must utilize hardwoods. Our results are

46 based on relatively small harvest units within a matrix of natural forest, and similar results might not
47 occur in landscapes dominated by stands originated from more extensive and intensive management.

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49 Keywords: low-input management, stocking standards, post-harvest regeneration, biomass, white spruce,
50 hardwood

1. INTRODUCTION

Tree regeneration is an essential stage that can determine forest structure and composition for the remainder of a successional sequence, particularly for the boreal forest that is a stand replacement disturbance-driven system (Foote, 1983; Chapin *et al.*, 2006; Gauthier *et al.*, 2015). Fire is the dominant disturbance in North American boreal forest (Burton *et al.*, 2008), and numerous studies examining post-fire forest regeneration are available for Alaska and adjacent Canada (Viereck and Schandelmeier, 1980; Purdy *et al.*, 2002; Johnstone *et al.*, 2004; Johnstone and Chapin, 2006; Johnstone *et al.*, 2011; Shenoy *et al.*, 2011). However, studies of post-harvest regeneration are limited (Youngblood and Zasada, 1991; Wurtz and Zasada, 2001; Boateng *et al.*, 2009). Forest fire and forest harvest do not produce identical effects, differing in removal of coarse woody debris and the consumption of the forest organic layer (McRae *et al.*, 2001; Brassard and Chen, 2008; Ilisson and Chen, 2009), for example. Differences in successional trajectory and plant species diversity also have been detected between fire and logging disturbance (Rees and Juday, 2002; Taylor *et al.*, 2013).

The boreal forest of Alaska has experienced the smallest area or proportion of forest cuttings and regeneration management of the major forest regions of North America. Although intensive forest cutting took place locally at the time of the gold rush in the early 20th century in Interior Alaska, demand for wood declined quickly by the 1920s (Naske, 1987; Roessler, 1997). The total area harvested in the Tanana Valley State Forest and forest classified lands since record collection began in the mid-20th century is about 14,000 ha (Alaska Division of Forestry (AKDOF) Forest Management Database; Tanana Chiefs Conference Timbersale Database). This harvested area compares to a total of state timberland (USDA FIA definition) of 871,000 ha in the Tanana Valley State Forest and forest classified lands (Hanson, 2013). Since Alaska statehood in 1959, local demand for wood harvest has been relatively low in Interior Alaska, and export markets have only been profitable for limited periods of high prices (Wurtz *et al.*, 2006). In the early 21st century, annual harvested volume for spruce and birch have been about 1622 and 200 mcf (1000 cubic feet), respectively from state forest lands in the Tanana Valley (AKDOF Forest Management Database), which combined is about 20 % of the estimated annual allowable cut for

sustained yield (Hanson, 2013). In this situation, a form of forest management involving low-cost input with heavy reliance on natural regeneration has developed.

In Alaska, a mandate for sustainable yield was adapted within Article VIII of the State's Constitution. Elaboration of the sustainable yield mandate in the context of forestry was developed in the Alaska Forest Resources & Practices Act (FRPA)¹. This was followed by the establishment of FRPA regulations². According to these regulations, reforestation is required for all forest harvests in the State with stocking levels dependent on the exact location of the harvest. Additional regeneration efforts are required in Interior and South-central Alaska, when more than 10% of the harvest area fails to meet State regeneration standards within seven years following harvest (Table 1). The Alaska Division of Forestry (AKDOF) is required by the FRPA³ to conduct regeneration surveys within seven years after harvest to ensure the stand is adequately regenerated. However, because forest regeneration in Interior Alaska may take place over an extended period of time following disturbance (Viereck and Schandelmeier, 1980), it is impractical to determine if natural regeneration has been successful based on these short term surveys. Therefore, a comprehensive, long-term investigation of tree establishment and post-harvest growth is necessary to determine whether low-cost forest management with heavy reliance on natural regeneration has met at least the first requirement for sustained yield, which is successful tree regeneration.

More recently, the demand for wood products from state land is evolving from sawlogs to woody biomass (AKDOF, 2013). As of 2015, nine wood biomass energy facilities have been built, 10 are under construction, and more than 11 are in design or feasibility status in Interior Alaska (AEA, 2015). As the new wood energy facilities begin to operate, demand for wood will increase in this region (Fresco and

¹AS 41.17

² Alaska Forest Resources and Practices Regulations (11 AAC 95) implement and interpret FRPA (AS 41.17). The requirement of regeneration survey is mentioned in section 385 of the regulations. Booklets of FRPA and the regulations are available at <http://forestry.alaska.gov/forestpractices>.

³FRPA 11 AAC 95.385

Chapin, 2009). The increased wood biomass energy demand will require expanded forest harvest and a change in product emphasis from large-dimension white spruce to additional species at smaller diameters. Increased birch harvest for use as firewood has already occurred (AKDOF Forest Management Database). In addition, the harvest cycle may become shorter for biomass harvest than for large-dimension wood products, requiring more frequent regeneration (Janowiak and Webster, 2010). In order to meet the needs of this evolving forest management situation on the sustained yield basis, it is crucial to understand post-harvest regeneration of all the woody species that could meet the new biomass demand.

Although the total area harvested is small, Interior Alaska boreal forest has experienced 40 years of varying harvest and regeneration practices. Forty years is too short a period to address all the issues associated with sustainable harvest through an entire rotation, but may be sufficient to address critical questions of forest regeneration. The objective of this study was to evaluate success of post-harvest regeneration up to 40 years in terms of stem density and biomass accumulation. To achieve this objective, we evaluated whether harvest units are adequately regenerated up to 40 years following timber harvest based on current yield standards set forth in FRPA. Ours is the first broad scale study in Interior Alaska to examine, across time and space, the effects of mature forest harvest on regeneration in an operational context in which low-input management is characteristic of the region.

2. METHODS

2.1. Study area

The study was conducted within the Fairbanks and Kantishna Management Areas of the Tanana Valley State Forest and forest classified lands ("state forest lands"; Figure 1) which covers 348,178 ha. The study area is within the Alaska boreal forest which is primarily composed of white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.)), Alaska birch (*Betula neoalaskana* Sarg.), quaking aspen (*Populus tremuloides* (Michx)), with minor amount of balsam poplar (*Populus balsamifera*), and tamarack (*Larix laricina*) (Labau and van Hees, 1990). Tree cover of the state forest lands is composed of black and white spruce/hardwood forest, white spruce/hardwood forest, birch forest,

white spruce forest, and white spruce/birch (Hanson, 2013). Total net cubic volume is greatest for the white spruce/hardwood and lowest for the black and white spruce/hardwood cover types (Table 2). Soils are mostly silt loams formed from loess parent material (Ping *et al.*, 2006) and elevations range from 100 m to 600 m. The climate of the study area is strongly continental, but long-term climate data are primarily available for low elevation sites. Data from Fairbanks International Airport indicate a mean annual temperature of -2°C and annual precipitation of 270 mm, with extreme winter temperatures as low as -50°C. The growing season is approximately 123 frost-free days in Fairbanks since the late 20th century (Wendler and Shulski, 2009).

2.2. Silvicultural systems

The two primary commercial harvest methods used during the period of this study on the Fairbanks and Kantishna areas of state forest lands were clearcutting and partial cutting systems. Both of these systems were utilized for green wood and post-fire salvage harvests. The clearcut system as utilized in Interior Alaska ranged from a conventional clearcut, to a clearcut with reserves (The Society of American Foresters, 1994). Partial cuts typically involved one of two types: the removal of a single species from mixed stands, either white spruce or birch, or an intermediate harvest with diameter limits. Regardless of the harvest system, only whole tree harvesting was performed. At the time of harvest, all sampled units used in this study were dominated by the mature white spruce type which originated from fire. This study examined only units that were either clearcut or partial cut for spruce, and excludes harvest units of partial cutting for birch or post-fire salvage logging. All sampled units were harvested once between 1975 and 2004 and were not burned following the harvest.

In order to enhance seedbed quality for white spruce germination, mechanized site preparation is often applied in Interior Alaska following harvest (Youngblood and Zasada, 1991; Youngblood *et al.*, 2011). The site preparation treatments used in this study involved mechanical scarification using either a bulldozer blade or a disk trencher. We categorized units that received any site preparation as scarified regardless of the method used.

All harvest units on state forest lands relied either on natural regeneration, white spruce artificial regeneration, or small amounts of planted exotic conifers. On the Fairbanks and Kantishna areas of state forest lands the two most common artificial regeneration techniques included direct seeding or planting of container stock. For both of these methods, seeds were typically collected from local sources. In this study, we included only harvest units that experienced natural regeneration or planting of white spruce seedlings from container stock.

Historical harvest units on the Fairbanks and Kantishna areas of state forest lands varied in size from ~ 1 to a few hundred ha (Figure 2a). The size distribution of the harvest units was positively skewed, with a median of 4.66 ha and a mean of 10.89 ha. We excluded the smallest units (< 1 ha) and extremely large units (> 40 ha). The harvest units included in this study ranged from 1.4 – 30.3 ha in size (Figure 2b). The total area of sampled harvest units is 269 ha, which is about 3.5% of total harvested area (about 7,000 ha) on the Fairbanks and Kantishna areas of state forest lands.

2.3. Sampling layout

We chose 30 harvest units on the Fairbanks and Kantishna areas of state forest lands from the Alaska Division of Forestry (AKDOF) Forest Management Database (D. Hanson personal communication). The AKDOF Forest Management Database is a GIS-based database collection of records of the location and type of all management activity that has occurred on state forest lands within the Fairbanks and Kantishna areas since 1972 archived in Microsoft Access (see Figure 1). Using this database, we selected representative harvest units that were evenly distributed according to harvest and treatment types, the year of timber sale, size of harvest units, and the geographical location across the study area (Table 3). Sampled harvest units are located in both upland and floodplain sites. To compare our results to operational regeneration surveys conducted within 7 years following a harvest, we used the same plot size for sampling as AKDOF surveys, 1.69 m radius circular plots (AKDOF, 2008). We chose sampling intensity of four plots ha⁻¹, which was generally lower than the AKDOF surveys' 12.4 to under 3 plots ha⁻¹ depending on the size of the harvest unit (AKDOF, 2008). However, a preliminary test of

sampling efficiency of the selected number of plots ha^{-1} using a censused population of white spruce in the study region demonstrated that it was adequate to obtain valid tree density data (Juday, 2012). To determine the placement of plots, we created a virtual 50 m $\times$ 50 m grid with points at the center of each cell over the entire study area using the fishnet tool in ArcGIS version 10.1 (Esri, 2012; Figure 3). ArcGIS points falling within the selected harvest units represented the center of the plots. The number of plots in each unit varied between 7 and 120 due to the size and geographic configuration of the harvest units (Table 3). Because we prioritized sampling a large number of harvest units over intensive sampling in a single harvest unit, the sampling intensity was truncated in larger units. When the standard of four plots ha^{-1} totaled more than 50 plots, we sampled only every other plot, or every third plot when the unit was larger than 100 plots at the four plots ha^{-1} standard. In units where only every other or every third plot was sampled, plots were selected to evenly distribute them starting from the first plot (Figure 3). The coordinates of the plots ($\pm$ 1m) were exported to a Trimble Pro XT GPS unit (Trimble Navigation, California) and were used to navigate to the sample plot centers.

2.4. Data collection

Field sampling was conducted during the summer of 2013 and 2014. Within each plot, we counted and recorded all tree species presented in the plots including, white spruce, birch, aspen, balsam poplar, and black spruce. All woody stems in each plot were counted by size class and origin. Stems were categorized into small (< 2.5 cm DBH) and large (≥ 2.5 cm DBH). When a live white spruce was 30 cm or taller, we measured total height and basal diameter, unless the tree was ≥ 1.37 m in height in which case we measured height and DBH. For live birch, aspen, balsam poplar, and black spruce > 1 cm DBH, we measured DBH and height. The origin of all stems was classified into, a) natural regeneration, b) planted (only for white spruce), or c) residual stems from pre-harvest. Planted white spruce seedlings were distinguished from seedlings of natural origin based on age, growth pattern in early age, and alignment in planted rows with other white spruce stems when visible. Residual stems were distinguished from regeneration based on estimated age of the tree. In this study, we considered only actual

regeneration following harvest. The sampling protocol for this study will be made available at Bonanza Creek Long Term Ecological Research Site website (<http://www.lter.uaf.edu/>).

We also used data of regeneration within 7 years post-harvest collected by AKDOF operational surveys (early surveys). Early surveys were available for 13 of our harvest units. The data are available in the AKDOF Forest Management Database (D. Hanson personal communication).

2.5. Evaluation of regeneration success

The regeneration stocking standard currently in place within the Alaska state forest for sustainable management is based on the minimum tree stem density that must be present within seven years following harvest. Tree stems that count toward meeting the stocking standard are weighted by size classes, with fewer larger stems required and greater numbers of small stems required (Table 1). For purposes of meeting the requirements of FRPA regulations, a 1.69 m radius circular plot is evaluated as meeting the stocking standard if it contains a sufficient number of stems, when expanded to per hectare values, to equal or exceed 100% of the minimum stem density. The minimum stem density can be met by stems from any of the size classes, or a sufficient weighted combination of stems from all of the size classes (Table 1).

In this study, we calculated the percent stocking standard achieved on each plot, and the percent of plots that met or exceeded the standard (AKDOF, 2008). Percent stocking standard achieved on each harvest unit as a whole was calculated as the mean of plot percentages (AKDOF, 2008). We were also interested in determining whether harvested units met the standard without planted seedlings, so we calculated the percent stocking standard contributed by naturally regenerated trees separately.

We calculated the proportion of plots meeting the standard in each unit, both for combined natural and planted regeneration, and for natural regeneration alone. In order to examine the effects of year since harvest on achievement of the stocking standard, we divided the harvest units into young (logged up to 20 years ago or post-1994) and old (logged 21-40 years ago or pre-1994) harvest units. Pre-1994 harvest units include 416 plots from 19 units. Sampled post-1994 harvest units include 310 plots

from 11 units. We calculated the difference between the proportion of plots meeting the standard through the combination of natural and planted regeneration versus natural regeneration alone both for pre-1994 and post-1994 harvest units, and tested for significance of difference using a t-test in R (R Core Team, 2014). We used significance level of $\alpha = 0.05$.

We compared the stem density obtained from AKDOF operational regeneration surveys (early surveys) conducted within 7 years after harvest (one unit was surveyed after 10 years) with our results (2013 survey) in 13 harvest units. We could not directly calculate percent stocking standard from the early regeneration surveys because tree size was not recorded in those surveys. However, because operational surveys were conducted in earlier stages of regeneration, we assumed that the stems would be in the smallest size class (Table 1). We compared our results with the early survey by assuming that if units did not contain 1,112 seedlings per hectare or greater at the time of the early surveys, they had not achieved the stocking standard.

We evaluated biomass accumulation up to 40 years following harvest. For biomass calculation, we used biomass equations established using samples from Interior Alaska (Yarie *et al.*, 2007). The equations follow the form:

$$Y = \alpha_1 * DBH + \alpha_2 * DBH^2 + \alpha_3 * height$$

where Y is the total above ground biomass (grams), and α_1 , α_2 , and α_3 are specific coefficients for each species (for more details refer to Yarie *et al.*, 2007).

3. Results

3.1. Stocking density

White spruce and Alaska birch are the most abundant regenerating (non-residual) tree species (Figure 4ab). Apart from a peak in units harvested in 1987-88, stem density appears to generally decrease with time since harvest (Figure 4a). White spruce contributes disproportionately to the 1987-88 peak in density of stems of all sizes (Figure 4a). However, the 1987-88 peak in large regenerating stems is composed primarily of birch (Figure 4b). As expected, the younger units supported high absolute

densities of regenerating birch and aspen. When considering stems of all sizes, the proportion of white spruce in older units was higher than in the younger units (Figure 4a). However, for large stems, the proportion of white spruce in younger vs. older units did not increase to the same degree (Figure 4b).

Overall, 53% of the units were planted and 47% were solely naturally regenerated. Proportions of planted vs. naturally regenerated units in the first half vs. second half of the period of analysis are roughly similar (Table 3). Even when planted seedlings are excluded, all units met or exceeded the established numerical goal of the state's stocking density standard when considered as a whole (Table 1 and 4). The contribution of planted white spruce seedlings toward the stocking standard decreased through time. The difference in percent stocking standard contributed by combined natural and planted seedlings compared to natural seedlings alone was lower in the older harvested units than the younger units, demonstrating that planted seedlings were less important in older units (Table 4; *pre-1994 difference*, mean = 2.4%; *post-1994 difference*, mean = 6.0%; $t = -2.60$, $p = 0.010$).

All units had a considerably (about 14-fold) greater stem density in our study (2013/14) than in the early operational regeneration survey conducted by AKDOF (Figure 5ab). Although 6 out of 13 units did not meet the stocking standard in the early survey, in our study all the units exceeded the standard (Figure 5a). Density of larger stems in our 2013/14 study was about 50% greater than density of stems of any size in the early surveys (Figure 5b).

Although all units met or exceeded the standard as a whole, not all the plots within units met the standard (Table 4). Overall, 87.5% of the plots met or exceeded the standard when natural and planted regeneration were combined, and 81.8% with natural regeneration alone. The proportion of plots meeting the standard was substantially greater in our 2013/14 study than in the early survey ($2013/14 = 90.4 \pm 4.2\%$ (mean ± 1 SE); early survey = $46.1 \pm 5.5\%$). In the early survey, the proportion of plots meeting the standard through the combination of natural and planted regeneration was much higher than through natural regeneration alone (difference = $26.6 \pm 6.0\%$). In contrast, in our 2013/14 study, the proportion meeting the stocking standard by the combination of natural and planted seedlings was almost the same as the proportion meeting the standard by natural regeneration alone (difference = $3.7 \pm 3.7\%$).

3.2. Accumulation of biomass in harvested units

The amount of biomass accumulated in the harvest units was variable, with biomass accumulation below 5 t·ha⁻¹ in the youngest units and a peak value of about 95 t·ha⁻¹ in the older units (Figure 6). Despite the variability, biomass accumulation was smaller in the younger units than in older units in general (Figure 6). Birch and white spruce, with aspen in some years, constitute a great portion of biomass accumulation (Figure 6). Birch was the most abundant regenerating tree species in terms of total biomass for the entire study period, except for units harvested in 1983-84 (total biomass accumulation: birch = 63%, white spruce = 18%, and aspen = 13%).

3.3. Tree diameters

Maximum DBH of white spruce was greatest in the units harvested about 25 years earlier (1987-88 harvests), but was not markedly different in units harvested in the decade before compared to after (Figure 7a). After the earliest phase of regeneration (up to 15 years), mean and maximum DBH of white spruce fluctuate by year of harvest (Figure 7a). No plots contained white spruce saplings (>2.5 cm) until about 15 years after harvest. After 1987 the proportion of plots with sapling white spruce was about the same among year of harvest, except for a peak in stands harvested in 1987-88.

For the first 25 years following harvest, birch mean and maximum DBH, and the proportion of plots containing birch saplings showed an increasing trend (Figure 7b). After that, birch mean and maximum DBH, and the proportion of plots containing birch saplings did not show a clear trend and varied greatly by years (Figure 7b). Mean DBH in units 40 years after harvest was about 3 cm (Figure 7b). Overall, birch DBH was greater than white spruce DBH (Figure 7ab).

4. Discussion

Sustainability is a vague but widely accepted concept in forest management, and regeneration following disturbance plays an essential role in sustainable forest yield, particularly for stand replacement

disturbance-driven system such as the boreal forest (Rowe and Scotter, 1973; Foote, 1983; Chapin *et al.*, 2006; Gauthier *et al.*, 2015). However, until this study, the Alaska FRPA regulations stocking standards (Table 1) have not been empirically tested either for achievability or for their contribution to sustainability. As a result, the lessons of 40 years of operational tree regeneration experience reported here can serve as a principal point of reference for assessing the relevance of FRPA regulations to sustainability.

The success of all our study harvest units in meeting the State stocking density standard is notable (Table 1, 4), particularly given the heavy reliance on natural regeneration. However, an average of about 20% of our plots within harvest units did not meet the standard, indicating that some issues of heterogeneity of regeneration may remain. Planting might be desirable in those areas with low natural regeneration. In younger units (< 20 years), planted seedlings appear important in supplementing natural regeneration to meet the standard, while in older units (> 20 years), natural regeneration alone was sufficient to meet the standard (Table 4). Unlike early successional hardwood species, such as birch and aspen, which establish most seedlings or asexually reproducing stems in the earliest phase of regeneration, white spruce recruitment may continue for a more extended time after disturbance, mostly with sporadic mast events (Rossi *et al.*, 2012). In our study area, white spruce natural regeneration appeared to continue to fill up (or expand within) unregenerated areas in harvest units at least until 40 years post-harvest (Figure 4). Our results may include a small amount of bias against the recognition of planted white spruce seedlings. It was harder to distinguish planted from naturally regenerated white spruce in units that were logged in earlier years compared to units harvested more recently. However, planting was not widely used in the early period of analysis.

Early regeneration surveys conducted by AKDOF (≤ 7 years after harvest) found that about half of our sampled units did not meet the State stocking standard (Figure 5). However, apparent stem density, and obviously the density of larger stems, increased substantially between the early survey and the time of our sampling (Figure 5). All units exceeded the standard in 2013/14, which was ten years or more following harvest (Figure 5). There are two likely explanations for this increase in stem density. First,

herb and grass cover may have dominated the site immediately after harvest to such a degree that the time required for tree regeneration was prolonged. Such herb and grass dominance in our study region is well-known in the initial stage of regeneration following disturbance (Rydgren *et al.*, 2004; Chapin *et al.*, 2006). This suggests that either seven years after harvest might be too early to evaluate tree regeneration as a contributor to sustainable yield, or that a different standard is needed for early surveys. The second likely explanation for the increase in stem density involves the different sampling protocols used in the two evaluations. Stem density was most likely underestimated in AKDOF surveys due to the quick, and sometimes simplified stem counting by using category, such as “10-20 stems”. By contrast, our protocol involved a careful search for and a count of all tree stems present. However, particularly because of the magnitude of the difference in stem density between the two evaluations, we believe that stem density did actually increase over time, and that this mostly accounts for the increase in units meeting the standard.

Sustainable forest management in North American boreal forest is often evaluated by comparing the consequence of management to that of wildfire (Attiwill, 1994; Bergeron *et al.*, 2002). We found that post-harvest natural regeneration, in general, follows a similar successional pattern to that seen following high severity fire, but white spruce recruitment following harvest may take place for a longer time. Regeneration following high severity fire is dominated by deciduous trees in a great majority of cases (Bergeron, 2000; Chen *et al.*, 2009; Johnstone *et al.*, 2010). Most white spruce recruitment is limited to a few years after fire, because seedbed quality declines rapidly as post-fire succession advances (Purdy *et al.*, 2002). However, post-fire white spruce recruitment could occur after the initial recruitment phase if there is a suitable substrate for spruce germination, such as partially decomposed logs (Peters *et al.*, 2006). Over time, white spruce established early in the process of stand development become a more prominent part of the stand, especially those trees that find a favorable canopy position (Youngblood, 1995; Chapin *et al.*, 2006). Generally, hardwood species have advantages in the early phase of post-fire regeneration over white spruce for several reasons. Although white spruce regenerate only from seed (Nienstaedt and Zasada, 1990), birch and aspen regenerate both sexually and asexually (Perala, 1990; Safford *et al.*, 1990). Birch and aspen vigorously sprout from stumps and roots, respectively, when mature trees are cut (Perala,

1990; Safford *et al.*, 1990). As a result, regeneration of birch and aspen is denser and more vigorous than white spruce from the earliest life of the stand. In addition, most white spruce seed falls within 100-150 m from the seed source (Youngblood and Max, 1992), so the species is frequently limited by seed dispersal distance. Competition with hardwoods and early-successional vegetation is also an issue for white spruce early growth, because of its generally slower rate of early growth (Youngblood and Zasada, 1991; Youngblood and Max, 1992; Youngblood, 2012). Therefore, post-fire regeneration usually begins with dense hardwood regeneration, followed by a rapid decline in stem density due to competition. White spruce with poor canopy position grow slowly and, if they can persist, require several decades to a century to enter the canopy (Chapin *et al.*, 2006).

These same limitations and patterns are present in our post-harvest units. Birch dominated in the early phase of regeneration, but the overall birch density was lower in older compared to younger units, apparently due to self-thinning, while stems that survived the competition grew larger (Figure 4ab). The same patterns to a lesser degree occurred in aspen (Figure 4ab). White spruce recruitment appears to continue for a few decades (Figure 4ab). The overall density of white spruce was relatively low in units at the early phase of regeneration and increased gradually in older units up to the 40-year maximum in our study (Figure 4a). Although the overall density of white spruce was similar to the density of other tree species at 40 years following harvest, smaller numbers of spruce saplings (> 2.5 cm DBH) were present compared to hardwood species in the oldest units due to slower rate of spruce growth, particularly compared to birch (Figure 4).

White spruce regeneration density is also affected greatly by sporadic seed production (Juday *et al.*, 2003; Roland *et al.*, 2014). White spruce is a masting (Kelly, 1994) species and produces large seed crops only about every 10 years in boreal Alaska (Juday *et al.*, 2003; Roland *et al.*, 2014). We observed a major peak in established stem density in units harvested in the 1987-88 time period, which was an historically large white spruce seed crop year (Juday *et al.*, 2003; Roland *et al.*, 2014). White spruce contributed substantially to the apparent 1987-88 density peak, when considering all trees (Figure 4a), as well as saplings (> 2.5 cm DBH; Figure 4b). Despite the high competition among trees due to the high

density, birch regeneration appeared to be successful in this time period as birch sapling density in units harvested in that time period was the highest observed (Figure 4b). Two possible explanations may have contributed to this result. First, the high density of both white spruce and birch might have been the result of particularly favorable environmental conditions and/or a favorable growth period in those years. Alternatively, only one sampled unit was harvested during 1987-88 (unit NC-305) suggesting that lack of sample depth may have influenced the result. However, we believe the 1987-88 result is real. Other mast years occurred during the period of analysis, but none produced an equivalent amount of white spruce recruitment in the harvest units. The 1987 white spruce seed crop is unsurpassed during the period of analysis in terms of the combination of volume of seeds and seed viability across a broad area of Alaska (Roland *et al.*, 2014). The density peak of white spruce in units harvested in the mid-1980s (Figure 4a) represents strong evidence that units harvested in the mid-1980s provided suitable seedbeds for the exceptional 1987 seed crop.

Other years that are reported to have either moderate to high seed fall and/or high seed viability between 1975-2004 include 1983, 1990, 1997-98, and 2000 (Zasada, 1985; Roland *et al.*, 2014). A modest recruitment peak does appear to be present in units harvested in the early and late 1990s (Figure 4ab), which would correspond to the 1997-98 modest seed crops and seedbed availability. Determining the influence of smaller white spruce seed crops is more challenging than for exceptional seed crops because abundant seedling establishment is generally associated only with a major mast year that exceeds a threshold amount of seed fall (Rossi *et al.*, 2012). Nevertheless, foresters need to keep in mind the influence of periodic white spruce seed crops as they plan future harvests, and where possible adjust management plans according to actual or anticipated white spruce mast years. This might include reducing seedbed preparation in mast years to avoid overstocking or applying site preparation to enhance seedbed quality in years with no/low white spruce seed crop.

As expected, biomass accumulated steadily over time, and the total accumulation was between 40-100 t·ha⁻¹ after a little less than 40 years post-harvest. Although the change of regeneration density varied among species and site or management variables, apparently regeneration success did not change

markedly through the period of analysis nor did mortality of newly established trees. Biomass accumulation overall was largely composed of hardwoods, including birch, aspen, and balsam poplar (Figure 6). As a result, it seems obvious that a short-rotation forest management system in this part of the boreal forest must be prepared to utilize primarily woody materials from hardwood species, unless strenuous efforts are made to establish white spruce. Where forest management goals can be met largely by hardwood material, the management regime applied in our study area would be successful.

White spruce DBH and the proportion of plots that contain white spruce saplings appeared to increase only for the first 15 years after harvest, and growth might slow down substantially after that time period (Figure 7a). White spruce that fail to achieve unobstructed canopy position grow slowly under hardwoods for decades, until the hardwood component starts declining (Chapin *et al.*, 2006). It appears that white spruce diameter growth in the early phase of regeneration is not necessarily associated with time since harvest but may be more influenced by variability in environmental conditions, especially the degree of hardwood competition, among units. The historical seed crop in 1987 not only increased stem density of white spruce but also associated with a period of favorable growth (Figure 7a). Birch DBH increased more steadily in older harvest units compared to white spruce (Figure 7ab). As some stems grow larger, mortality of the other, suppressed stems increases. As a result, the proportion of plots that contain birch saplings can vary by year of harvest (Figure 7b) due to the degree of local competition and dominance. Birch DBH and the proportion of plots that contain birch saplings was very small in 1983-84 period (Figure 7b), while white spruce regeneration during those years was as successful as units harvested in other time periods. This suggests that weather was not poor then for tree growth in general. Instead, it may be that birch experienced low seed production during this time period, and was outcompeted by white spruce during the early phase of regeneration. We have only one harvest unit sampled in this time period, and thus further investigation could help determine whether birch regeneration was actually less successful during this time period. In any event, birch generally grows faster than white spruce (Figure 7ab; Safford *et al.*, 1990), suggesting that birch would be a more suitable species for short-rotation biomass harvest if the products were equally usable.

The thirty harvest units in this study, evaluated 10-40 years following harvest and distributed across an area of 8,400 km², all met State stocking density standards at the time of our evaluation despite the heavy reliance on natural regeneration. All the harvest units analyzed in this study were originally mature stands dominated by white spruce and, to date, have regenerated into mixed forest, suggesting that sustaining white spruce would take longer than sustaining total wood biomass. It is important to note that we analyzed a set of relatively small harvest units within a matrix of natural forest, and similar results might not occur once the area of stands originated from management became a greater portion of the total landscape. For example, white spruce might gradually decrease in managed forests if a short-rotation, hardwood focused management with a heavy reliance on natural regeneration becomes the major type of management. A number of issues relating to sustainability also remain, even with a better assessment of regeneration than has been available before.

The history of 40 years of forest development in harvest units still represents only one-half to one-third of rotation age assumed when these stands were initiated (Hanson, 2013). Looking forward, issues of the risks of tree and stand mortality will play an increasingly important role in the questions of long-term succession. Moreover, there are other important factors that need to be considered when thinking about sustainable forest management, such as biodiversity and provision of wildlife habitats. Forest harvest can supplement natural disturbance to create diverse landscape patterns and valuable habitats for wildlife if it is applied skillfully. It is apparent that further research is necessary to understand and implement sustainable management, but we believe the results of this study provide a useful starting point. Considering all of our findings, it appears desirable to evaluate whether the State stocking standard is effective in assessing post-harvest regeneration, particularly within the seven year time frame. Partly as a result of this study, a formal FRPA Science and Technical committee review process of reforestation was launched. In particular, more systematic and frequent post-harvest surveys will be required to remain confident of sustainable yield.

5. Acknowledgement

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Figure 1. Maps of study area. (a) Management areas of state forest (dashed polygon) and the Tanana Valley State Forest and forest classified lands (black polygons; 1,162,000 ha) within the Tanana Valley which is drained by the large silt-bearing Tanana River in Interior Alaska boreal region (dashed boundary; Hanson, 2013). (b) Fairbanks and Kantishna areas of Tanana Valley State Forest and forest classified lands. NC- followed by number represents the ID label of a sampled harvest unit.

Figure 2 Histogram of harvest size of (a) historical harvest units, and (b) sample units in the Fairbanks and Kantishna areas of Tanana Valley State Forest and forest classified land.

Figure 3. Example of plot placement and selection. The size of the grid is 50 m. Dots represent plots and the numbers above them represent plot labels. In units with more than 50 plots, every other plot was selected (shaded cells).

Figure 4. Stem density (ha^{-1}) by two-year classes of period of harvest (beginning year) by species for (a) all diameters and (b) large stems ($\text{DBH} \geq 2.5$ cm).

Figure 5. Comparison of stem density of (a) all sizes between early survey conducted by AKDOF within 7 years of harvest and our 2013/14 study and (b) all sizes in early survey to stems ≥ 2.5 cm in our 2013/14 study. Error bars represent 1SEs.

Figure 6. Biomass of regenerated stems post-harvest by two-year classes of period of harvest (beginning year).

Figure 7 Proportion of plots that contain saplings, and mean and maximum DBH by two-year classes of period of harvest (beginning year) of (a) white spruce, and (b) birch.

625 Table 1. Post-harvest stocking standard established by the State of Alaska

DBH in cm	Minimum Stocking Standard (trees per ha)
Seedlings	1112
2.5-15.2	495
15.2-22.9	420
>22.9	297

626 Note: Example of calculation of percent stocking for seedlings

627 $\% \text{ stocking} = (d/1112) \times 100$

628 where d is the stem density ha^{-1} measured in each plot. Percent stocking standard was calculated similarly
629 for the other three size classes for their minimum density values.

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632 Table 2 Tree cover of the Tanana Valley State Forest. MCF = 1000 cubic feet, and MBF = 1000 board
 633 feet (Hanson, 2013).

Vegetation Type Class	Area (ha)	% of area	Total Net Volume		
			Cubic Foot (MCF)	Cubic Meter (m ³)	Board Foot (MBF)
Aspen	32,682	4	169,723	4,806	178,742
Birch	88,299	10	354,235	10,031	407,868
Black and White Spruce/Hardwood	314,153	36	206,781	5,855	188,124
Hardwood	35,758	4	151,681	4,295	235,158
White Spruce	67,679	8	419,564	11,881	1,344,723
White Spruce/Balsam poplar	11,033	1	45,692	1,294	88,061
White Spruce/Birch	58,530	7	245,802	6,960	761,953
White Spruce/Hardwood	263,128	30	479,282	13,572	852,877

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636 Table 3. List of sampled harvest units

Unit	Size (ha)	# plots (calculated)	# plots (sampled)	Logged year	Harvest type	Site preparation	Reforestation
NC-120	10.4	41	41	1975	Partial cut	None	Plant
NC-93	17.9	76	35	1975	Partial cut	None	Natural
NC-190	5.1	22	22	1977	Clearcut	Scarify	Natural
NC-126	5.7	22	22	1978	Partial cut	None	Natural
NC-140-17	2.5	8	8	1979	Clearcut	None	Natural
NC-249	5.0	22	22	1980	Clearcut	Scarify	Natural
NC-362	4.4	15	15	1981	Partial cut	None	Natural
NC-140-38	1.5	7	7	1982	Clearcut	Scarify	Natural
NC-395	5.1	21	21	1983	Clearcut	None	Natural
NC-490	8.4	32	32	1985	Clearcut	None	Natural
NC-556	6.6	26	26	1986	Clearcut	None	Plant
NC-305	3.5	11	11	1987	Partial cut	Scarify	Plant
NC-705	11.0	44	44	1989	Clearcut	Scarify	Plant
NC-454	20.4	87	44	1991	Clearcut	Scarify	Plant
NC-740	1.9	8	8	1991	Clearcut	None	Plant
NC-709	17.2	71	35	1991	Clearcut	Scarify	Plant
NC-842	2.1	7	7	1992	Partial cut	None	Natural
NC-733	30.3	120	44	1992	Clearcut	Scarify	Plant
NC-702	2.0	9	9	1993	Clearcut	None	Plant
NC-747	8.0	31	31	1994	Clearcut	None	Plant
NC-750	9.8	41	41	1995	Clearcut	Scarify	Plant
NC-1085	22.6	94	47	1996	Partial cut	Scarify	Plant
NC-1137	13.5	55	29	1997	Clearcut	None	Plant
NC-927	22.5	90	43	1998	Partial cut	None	Plant
NC-760	3.4	13	13	1998	Partial cut	None	Natural
NC-1129	6.0	22	22	1999	Partial cut	None	Plant
NC-1090	1.4	7	7	1999	Partial cut	None	Natural
NC-1135	11.7	49	49	2002	Partial cut	None	Plant
NC-1116	2.4	9	9	2003	Partial cut	Scarify	Natural
NC-1143	6.7	28	28	2004	Partial cut	None	Natural

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638

639 Table 4 Percent stocking standard and percentage of plots meeting the standard. Natural = natural
640 regeneration

Units	Year of harvest	Density ha ⁻¹		% plots stocked		
		Natural & Planted	Natural	Natural & Planted	Natural	Diff.
NC-93	1975	5824	5824	-	90%	-
NC-120	1975	4622	4556	56%	56%	0%
NC-190	1977	9726	9726	-	95%	-
NC-126	1978	6396	6396	-	87%	-
NC-140-17	1979	1393	1393	-	75%	-
NC-249	1980	15451	15451	-	86%	-
NC-362	1981	10428	10428	-	71%	-
NC-140-38	1982	5732	5732	-	86%	-
NC-395	1983	9181	9181	-	86%	-
NC-490	1985	9632	9632	-	82%	-
NC-556	1986	15770	15770	85%	85%	0%
NC-305	1987	46505	44174	100%	100%	0%
NC-705	1989	21809	21530	82%	82%	0%
NC-740	1991	14648	14329	100%	100%	0%
NC-709	1991	8981	8457	76%	74%	3%
NC-454	1992	11580	10846	93%	90%	2%
NC-733	1992	12445	11543	98%	93%	5%
NC-842	1992	4140	4140	-	71%	-
NC-702	1993	23900	23652	89%	78%	11%
NC-747	1994	17943	17943	90%	90%	0%
NC-750	1995	20573	20452	81%	76%	5%
NC-1085	1996	15793	15295	94%	89%	4%
NC-1137	1997	8147	7417	100%	86%	14%
NC-760	1998	11753	11753	-	64%	-
NC-927	1998	12482	11758	98%	95%	3%
NC-1090	1999	9712	9712	-	71%	-
NC-1129	1999	4693	4458	79%	74%	5%
NC-1135	2002	19770	19213	80%	70%	11%
NC-1116	2004	38311	38171	-	63%	-

641	NC-1143	2004	11434	11434	-	89%	-
642							

fig 1a

fig 2a

fig 2b

fig 3

fig 4a

fig 4b

fig 5a

fig 5b

fig 6

fig 7a

fig 7b