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Developing Adaptive Approaches to Forest Harvest Management in Boreal Alaska Under Rapid Climate Change

Miho Morimoto and Glenn Patrick Juday

The Alaska boreal forest has experienced some of the greatest magnitude of climate-driven change of any forest region, and adaptive management approaches are required in current management and decisions. Forest harvest management has relied heavily on natural regeneration, which generally was successful. Most harvests were small and mature white spruce near roads. Wildfires were small to very large and occurred broadly. Post-harvest regeneration is successful, but on vulnerable warm dry sites, failure is likely to occur soon. Boreal forest in some landscape positions will be resilient to additional warming or invading tundra. We offer a framework and suggest options for developing adaptive forest harvest management. The main options under climate change include (1) maintaining current species where feasible, (2) maintaining a forest landscape of any type, and (3) monitoring biome shift. We identify examples of management actions and gathered research appropriate to each of these options.

Keywords: adaptive management, climate change, forest regeneration, forest resource management planning, timber harvesting

Boreal forests provide many ecological services, including climate regulation, biodiversity, nutrient cycling (Bonan et al. 1992), and essential social and economic values for human lives, particularly for indigenous people (Nelson et al. 2008). However, the boreal forest ecosystem is now going through profound changes due to human activities and a changing climate (Gauthier et al. 2015). The key question confronting forest managers is whether the process of change has reached a point at which the traditional goal of producing or sustaining the same set of products or species is simply not feasible. In such a situation, adaptability would be fundamental to sustaining various services of boreal forests.

Adaptive management (AM) is a process of managing natural resources in which the management itself is an experiment. In AM, the success of prescribed management actions is systematically evaluated against actual outcomes, and lessons learned are applied to subsequent management. AM is an attractive approach particularly where large uncertainties exist (Stankey et al. 2005, Zhou 2015), and the desirability of using it in natural resources has been recognized since the late 1970s (Holling 1978, Walters 1986, Lee 1993). Adopting an AM approach implies the ability to actually choose different resource management scenarios. As a result, implementing AM is more feasible where a number of management options remain available to the manager rather than situations where all natural resource products and services are in high demand. The boreal forest offers examples of both situations.

Large-scale forest harvests have significantly modified forest ecosystems in many parts of the boreal region. Boreal forests in Fennoscandia and much of Canada have experienced extensive forest harvest management in the last century (Gauthier et al. 2015, Ostlund et al. 1997, Esseen et al. 1997). To maximize production, short-rotation clearcutting followed by planting of crop trees was applied widely, resulting in homogenous forest structures in terms of species, age, and genetic diversity (Ostlund et al. 1997, Esseen et al. 1997). Further development and extraction of wood from boreal forests is likely due to an increasing population (Gauthier et al. 2015). Compared to such intensively managed portions of the boreal forest, Interior Alaska has experienced only small-scale forest harvest management practices (Potapov et al.

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Affiliations: *Miho Morimoto (mmorimoto@alaska.edu), School of Natural Resources and Extension, University of Alaska Fairbanks, Fairbanks, AK 99775, USA. Glenn Patrick Juday (gpjuday@alaska.edu), School of Natural Resources and Extension, University of Alaska Fairbanks, Fairbanks, AK 99775, USA.*

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2008), and the forest harvest program has only been operating for about 40 years. The boreal forest has experienced some of the earliest and strongest effects of climate change (Juday et al. 2005), suggesting that the future is particularly uncertain. This situation provides a unique opportunity—or requirement—to consider and potentially adjust current traditional management actions using the AM approach.

The North American boreal forest is primarily a stand replacement disturbance–driven system, within which wildfire and insect damage or mortality are the dominant disturbances (Gauthier et al. 2015). Wildfires created diverse landscapes and stand structures of boreal forest in a resilient way for thousands of years (Johnstone, Chapin, et al. 2010). However, the fire regime is changing due to both climate change and human fire suppression, as well as ignition (Kasischke et al. 2010, DeWilde and Chapin 2006, Calef et al. 2015). Climate change also affects the boreal forest ecosystem directly by affecting tree growth both positively and negatively (Wilmking et al. 2004, Barber et al. 2000, Juday et al. 2015), which appears to be in the process of shifting forest composition. The Alaska boreal region is experiencing a greater amount of warming than forest regions in lower latitudes (Chapin et al. 2014). Warm season temperature in central Alaska has increased about 1.9°C during the 110 years of climate record (Figure 1a), and frost-free growing season now has expanded to 140 days (Figure 1b). As a result, Alaska's boreal forest management faces the need to implement AM sooner than other regions.

The goal of this study is to offer a general framework and suggest options for developing adaptive boreal forest harvest management by reviewing studies of the past forest harvest and regeneration management and identifying some future challenges using the example of Interior Alaska. We first evaluate forest harvest management and regeneration outcomes, including a comparison to forest disturbance by wildfire. We then identify the effects of climate change as a current challenge for forest harvest and regeneration management. Based on the findings and using the AM approach, we present flow-charts of recommended adaptive forest harvest management under conditions of the recent past which will continue to apply in some landscapes and recommended adaptive practices under continued change in landscapes with climate-sensitive forest types. While the subject of adaptation to climate change involves a vast amount of information in many different specialized fields, we believe it is useful to provide an initial synthesis of what existing information indicates for the key concerns of forest management in a place where climate change is an overriding issue and data about post-harvest regeneration has only now become available for the first time.

Interior Alaska Boreal Forest

The Interior Alaska boreal region stretches from the Alaska Range in the south to the Brooks Range in the north, and the Canadian border in the east to the Chukchi Sea in the west, covering about 47 million hectares (ha) (Figure 2a). Mean annual temperature at Fairbanks Airport (the only long-term station) is −2°C, with an annual precipitation of 270 millimeters and extreme temperatures ranging from −50°C to 35°C. However, climate in the region varies substantially according to factors such as elevation and aspect (Shulski and Wendler 2007).

Because of the extreme climate, species richness is low with six tree species, including the three main commercial species of white spruce (*Picea glauca* [Moench] Voss), Alaska birch (*Betula neoalaskana*), quaking aspen (*Populus tremuloides* [Michx]). The rest of the forest landscape includes extensive areas of black spruce (*Picea mariana* [Mill.]), generally on permafrost-covered low-productivity sites, and minor amounts of balsam poplar (*Populus balsamifera*) and tamarack (*Larix laricina*; Viereck and Elbert 1975, Labau and van Hees 1990). However, genetic diversity among some of the forest species appears to be high (Anderson et al. 2006), a consequence of a unique Alaska glacial refugium in which trees apparently survived the height of the Wisconsin glacial period (Roberts and Hamann 2015).

Cooperative Alaska Forest Inventory (CAFI) is a forest inventory project started in 1994 (Malone et al. 2009). Because of the lack of the national Forest Inventory Analysis work in boreal Alaska until 2016, CAFI is the most reliable current database of boreal forest conditions in landscapes with the greatest forest harvest potential. Productivity is relatively low compared with other forest regions, with about 90 percent of forest stands supporting basal areas lower than 40 m^2/ha (Malone et al. 2009). The most productive sites are either white spruce or balsam poplar dominated. Although black spruce—the least productive type—is the dominant species of the boreal forest, the black spruce component in the CAFI database is smaller than other forest types. Here we focus on permafrost-free sites with well-stocked stands of large white spruce, one of the most productive types that sustains most of the commercial harvest in the area.

Management and Policy Implications

Forest harvest management in boreal Alaska is concentrated on productive sites at low elevations near population and road access where fire suppression is most active. In this managed area, forest managers should identify old stands with declining health due to climate stress, insects, disease, or fire suppression. Focusing harvest in these stands will reduce risks from future fire, acute climate stress, and insect outbreaks while recovering economic value. Forest harvests should be designed to maintain mosaics of stands with a wide range of ages (including some old growth) and species that sustain ecosystem services of the boreal forest. Stand mosaics that maintain species movement within managed landscapes and between managed and adjacent unmanaged landscapes will be particularly valuable. For successful regeneration, forest harvest management needs to establish overall goals such as identifying desirable replacement stands (e.g., old-growth white spruce) and product types (e.g., biomass or sawlog). Clearcutting (with variable retention) appears to be more desirable for regeneration in most situations than partial cutting. Application of site preparation and planting need to be determined based on timing of white spruce seed crops, which greatly affects density of white spruce regeneration. Forest harvest management in boreal Alaska has been small in scale (~1 percent of productive forest to date), low-input, and concentrated near road systems. As a result, forest harvest management needs to be monitored and reevaluated as managed area expands. Adaptive management in boreal Alaska is particularly necessary because regeneration failure on vulnerable sites is likely to happen soon due to warming. Potential adaptive actions include (1) identifying climatic response zones of the major species or management actions, (2) monitoring existing post-harvest regeneration, (3) initiating studies to find adaptable tree populations or new species, and (4) accepting biome conversion and finding new product opportunities.

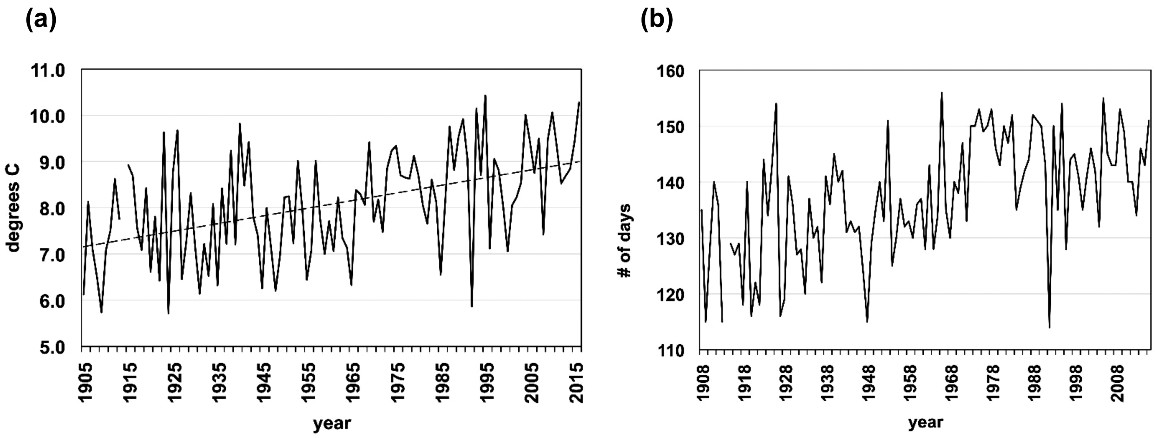

Figure 1. A, Mean daily temperature (mean of high and low) for the period April 1–October 31; linear regression for 1905–2016. B, Frost-free season length at Fairbanks, Alaska. Data are number of consecutive days with minimum temperatures above freezing. Data from National Centers for Environmental Information; 1906–1948 (1914 incomplete) University Experiment Station; 1949–2016 Fairbanks International Airport.

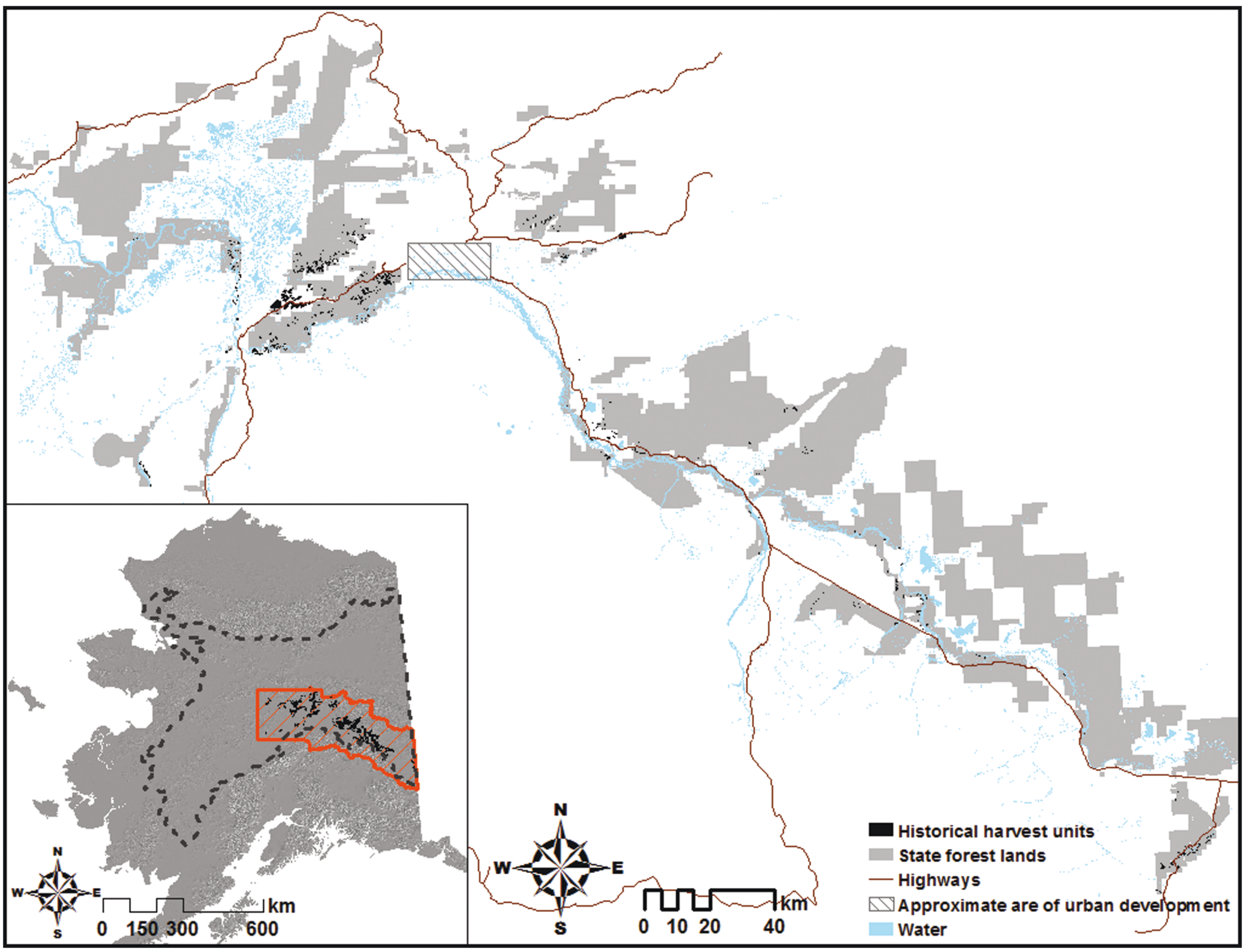

Figure 2. Map of study area. A, Study area is within the Tanana Valley (orange boundary) in Interior Alaska boreal region (dashed area). B, Most historical forest harvests occurred within the Tanana Valley State Forest and state forest classified land (state forest lands), and a few are in public lands, including Fairbanks North Star Borough, Native Allotments, and Native Corporation lands. There are other forest harvests in different ownerships which were not shown in this map because of the relatively small-scale operations.

Most of the productive forest lands are owned by state within the Tanana Valley, which is drained by the large silt bearing Tanana River. We refer to the Tanana Valley State Forest and "forest classified" lands as "state forest lands" (Figure 2). The primary purpose of the management of state forest lands is a sustained yield of forest products. State forest lands cover 1.16 million hectares, or 2.5 percent of the total land area of Interior Alaska (Figure 2), of which ~75 percent is forested. State forest lands are representative of productive sites across this region, with particularly favorable conditions of access and proximity to population. Other major ownerships of productive forest land with harvest potential within the Tanana Valley include the Fairbanks North Star Borough, individual Native allotments, Native Corporations, University of Alaska, and Mental Health Trust land. Cooperative management across ownerships is usually a goal, because most rural villages are not on the road system and depend on local resources to meet food, shelter, and energy needs.

Overview of Forest Harvest and Regeneration Management

Interior Alaska experienced intensive but highly localized forest harvesting in the late 19th century to early 20th century as a result of development of mining and urban areas (Roessler and Packee 2000). Purposeful and silviculturally based forest management only began in boreal Alaska after statehood in 1959 and the transfer of land entitlements to the state government, Alaska Native corporations, and borough governments. Generally, databases and records of forest management activities begin only in the early 1970s. Although wood products were harvested continuously as demand increased during this time, harvest activities in the region were small due to limited access, distance from major markets, and small local demand (Wurtz et al. 2006). Recent actual annual harvest area and volume are far below annual allowable cut (harvest volumes are 11 percent, 1 percent and 0.2 percent of annual allowable cut for white spruce, birch, and aspen, respectively; Morimoto 2016), suggesting harvest could be significantly expanded sustainably (Liang 2010). White spruce has been the predominant harvested species, although harvest of birch and aspen has been increasing for wood biomass energy in the past decade (Morimoto 2016).

In Interior Alaska, clearcutting and species or diameter selection cutting have been the major harvesting methods (Alaska Division of Forestry 2013, Morimoto 2016). Clearcutting is widely used in boreal forests and is effective when applied appropriately. However, clearcutting can produce undesirable ecological outcomes in the boreal forest if it is applied without attention to the landscape context (Timoney and Peterson 1996, Ostlund et al. 1997). In Interior Alaska, some studies comparing clearcutting with partial cutting found no differences or even some positive effects of clearcutting on post-harvest regeneration (Youngblood and Zasada 1991, Wurtz and Zasada 2001, Morimoto et al. 2017). Silviculturally planned clearcutting in central Interior Alaska has been small-scale and has not created large homogenous landscapes or issues with natural regeneration caused by limited white spruce seed-dispersal ability (Morimoto et al. 2017), unlike the boreal forest of Canada and Fennoscandia, which have experienced large-scale clearcutting with short rotation periods (Ostlund et al. 1997, Boucher et al. 2014).

Following harvest, mechanical site preparation and planting of white spruce seedlings have been applied on a limited scale for successful white spruce regeneration (Morimoto 2016). Although site preparation was applied on only about 20 percent of harvest area (Morimoto 2016), site preparation appears to have the greatest effect on post-harvest regeneration in the North American boreal forest (Wurtz and Zasada 2001, Calogeropoulos et al. 2004, Boateng et al. 2009, Youngblood and Zasada 1991). Most studies from Interior Alaska have concluded that site preparation caused an increase in post-harvest regeneration by exposing mineral soil (Wurtz and Zasada 2001, Morimoto et al. 2017, Youngblood and Zasada 1991). However, following a major white spruce seed crop, site preparation can result in overstocking (Wurtz and Zasada 2001, Morimoto et al. 2017), suggesting application of site preparation needs to be decided based upon the timing of the white spruce seed crops. Planting white spruce is most likely to be needed when the probability of adequate seed crops is low for three to five years following the harvest disturbance, allowing competing vegetation to reduce seedbed receptivity. The mean interval between major seed crops is about 11 years (Roland et al. 2014, Juday et al. 2003) so that foresters can expect years with very low probability of seed crop production in advance. Reproductive bud primordia can be identified the year before the seed crop, providing a short-term predictor. The combination of these two indicators allows forest managers to anticipate where a particular year falls in general on the cycle of high to low potential for white spruce reproduction.

Notably, Interior Alaska post-harvest regeneration has relied heavily on natural regeneration. Only about half of harvested areas were planted with white spruce seedlings (Morimoto 2016). Although planting white spruce seedlings may result in greater basal area (Allaby et al. 2017), in the study region, the overall effect of planting on spruce—especially biomass—has been limited (Morimoto et al. 2017). This finding is particularly relevant for AM because planting seedlings is the most expensive post-harvest management practice in the region, and the selection of seed stock can modify or decrease genetic diversity. The expense of planting often exceeds the revenue potential of many Interior Alaska stands. AM evaluation of regeneration outcomes has confirmed that planting white spruce is not needed as a general practice for many management goals (Morimoto et al. 2017).

In sum, harvest and post-harvest practices can affect regeneration outcomes both positively and negatively in the region, depending on the context. The management practices that are applied need to be selected according to goals and specific situations. However, past management experience may not be relevant if the environment in which it occurred changes beyond conditions that generated those outcomes.

Comparison between Harvest and Wildfire

Landscape-Level Diversity

In Interior Alaska boreal forest, stand-replacement wildfire creates disturbances with specific characteristics of size, pattern, severity, and total amount (Kasischke et al. 2002, Kasischke et al. 2010). Recently, forest harvest management has begun to incorporate ecological values, and emulating natural disturbances has become the major way to achieve this goal. However, landscape patterns created by wildfire and forest harvest differ in Interior Alaska, particularly in patch size and spatial distribution.

Size of wildfire varies from smaller than one hectare to many thousands of hectares in Interior Alaska (DeWilde and Chapin 2006) ("size" is the area within the fire perimeter, some areas of which did not burn). In contrast, harvest units in Interior Alaska have been small, with a median of 4.91 ha. Nearly 87 percent of harvest blocks were smaller than 20 ha (Table 1). The largest harvests were only a few hundred hectares. During the 1969–2012 time period, approximately 13,000 ha out of 1.2 million ha (1 percent) of land in the Tanana Valley were harvested (Morimoto 2016), while approximately 16.5 million ha out of 47.1 million ha (35 percent) of total land of the Interior Alaska region occurred within a fire perimeter (AICC 2015).

Table 1. Size distribution of harvest blocks (continuous area of harvest in a given year) (Alaska Division of Forestry 2013).

Area (ha)	Density of harvest blocks ([million ha]$^{-1}$[decade]$^{-1}$)
0–10	172.7
10–20	32.9
20–30	16.5
30–40	6.7
40–50	2.7
50–60	1.9
60–70	0.2
70–80	0.2
80–90	1.0
90–100	0.2
>100	2.7

The landscape distributions of wildfire and harvest are also different (McRae et al. 2001). In the region from the Alaska Range to the Brooks Range, wildfire ignitions can occur anywhere (AICC 2015; Figure 3). Wildfire occurrence and expansion are principally affected by factors such as vegetation type, weather, and topography. In contrast, commercial forest harvesting in Interior Alaska is concentrated in a small area within a short distance from major highways near Fairbanks, the second largest city in Alaska, or rivers which freeze sufficiently to support vehicles in winter (Morimoto 2016) because of a limited road system (Wurtz et al. 2006). In addition, harvest has mainly occurred in mature white spruce forest due to its greater economic value than other local species (Wurtz et al. 2006). As a result, within managed landscapes, harvest can systematically deplete important forest structures, particularly older (productive) white spruce types that are increasingly limiting wildlife habitats (Usher et al. 2005). While this depletion can be important locally, large areas of the Alaska landscape are likely to retain significant amounts of these features. Careful layout of harvests can avoid unnecessarily disrupting continuity of older forest habitats between blocks of landscape managed for older forest values.

In terms of direct human dependency of forest resources, the provisioning of food through wildlife harvest is one of the most critical outcomes of forest management. Landscape-scale forest age class and type diversity contributes to maintaining diverse wildlife species in Interior Alaska (Nelson et al. 2008). Moose, one of the most important subsistence species in Interior Alaska, use both early- and late-successional forests for different purposes (Nelson et al. 2008, Lord and Kielland 2015, Balsom et al. 1996). Moose use recently burned forest (up to a few decades post-fire) as feeding habitat because of the higher food availability (Nelson et al. 2008, Lord and Kielland 2015). But moose also select and use mature spruce stands, especially in winter, because of the shallow snow cover, greater seasonal

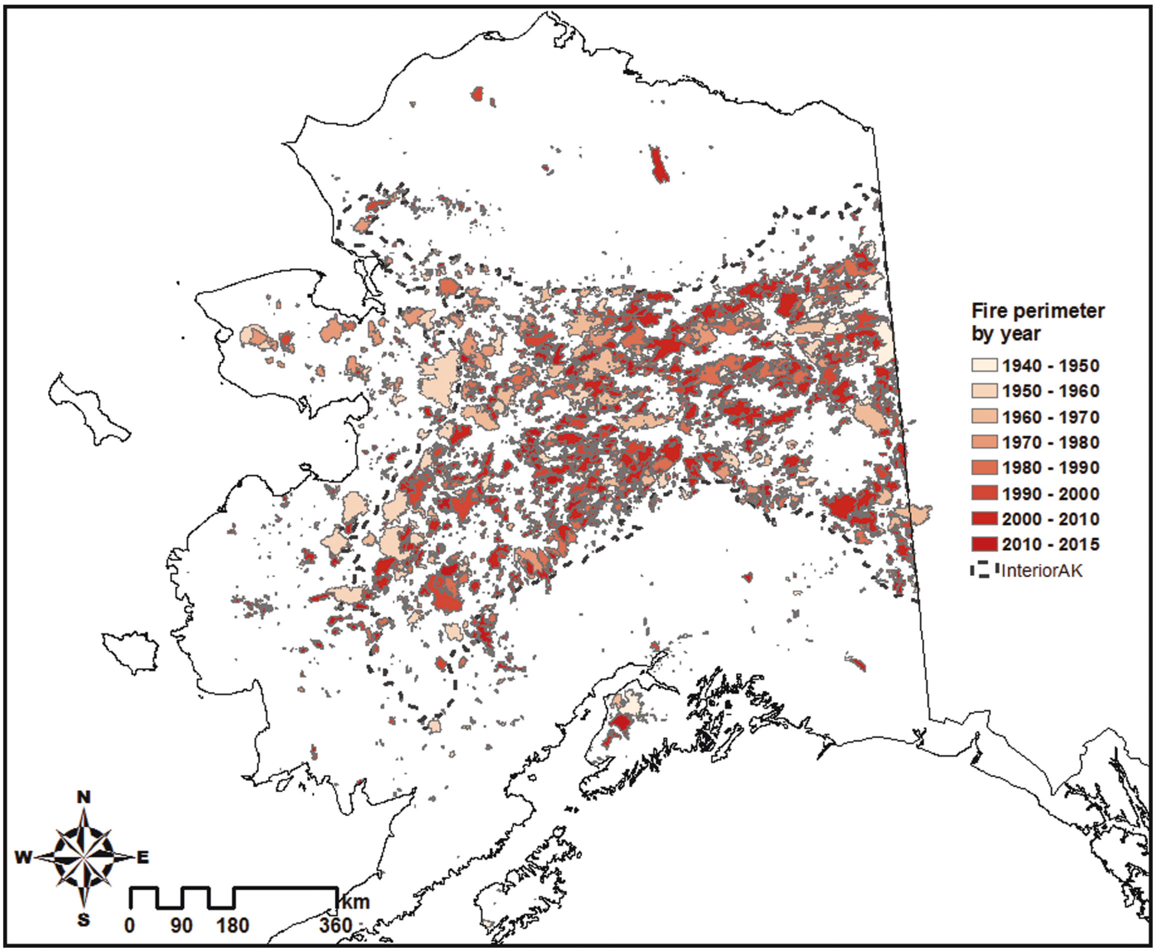

Figure 3. Map of perimeters of historical wildfires in Alaska from 1940–2015 (AICC 2015).

browse availability, protection from heat and cold, and cover from predators (Balsom et al. 1996). Despite the abundance of browse in young post-fire sites, moose density decreases with distance into burned sites, largely because of the lack of mature forest cover from predators (Weixelman et al. 1997). As a result, a mosaic of various age classes and forest types is important in maximizing moose populations on a landscape.

The boreal forest is distinctive among the major ecological regions of the earth for being dominated by conifer (Gauthier et al. 2015). Older conifer forests on more productive sites are the source of a significant share of biodiversity conservation issues across the boreal region for several reasons. For example, caribou depend heavily on the lichens in mature spruce-lichen forests as a source of food (Joly et al. 2003). Such stands are particularly rich in canopy lichens, mosses, and bryophytes. Old conifer forests are also rich in fungi responsible for decomposing wood and in specialized wood-boring and foliage-consuming insects, which are consumed by woodpeckers and other cavity nesting animals and insectivorous songbirds (Esseen et al. 1992, Berg et al. 1994).

However, during the period that fire records have been maintained or reconstructed (1943 onward), the fire regime which affects older conifer types in particular has been shifting. One of the biggest causes is human activities, particularly fire suppression (Kasischke et al. 2010). All of Alaska has been placed into fire management zones, and the greatest area (90 percent) falls within zones three and four ("modified" and "limited"), in which ignitions are not automatically suppressed. By contrast, most state forest lands (92 percent) fall within zones one and two ("critical" and "full") in which fire suppression occurs (AICC 2015). Large-scale wildfires (>400 ha) were more common in remote areas where fires are not automatically suppressed by fire management policy (DeWilde and Chapin 2006; Figure 3).

If the fire regime in areas under forest harvest management in the future were similar to the past 70 years, areas with a strict suppression policy would experience fewer large-scale fires than before suppression began (Figure 4), resulting in increased average stand ages. Some mature forests which have passed their most productive stage begin to lose ecological and economic values and add a higher risk of future large-scale fires because of higher flammability (Chapin et al. 2003). This projected increase in mature forest near populated and roaded areas would also reduce the availability of habitats for early successional wildlife species.

Wildfire across North America—but particularly Alaska—has become more severe, intense, and frequent in recent decades during a time of climate warming and drying (Calef et al. 2015). Particularly under this changing fire regime, wildfire is almost impossible to control for the creation of an optimum wildlife habitat mosaic in the landscape. In contrast, forest harvest

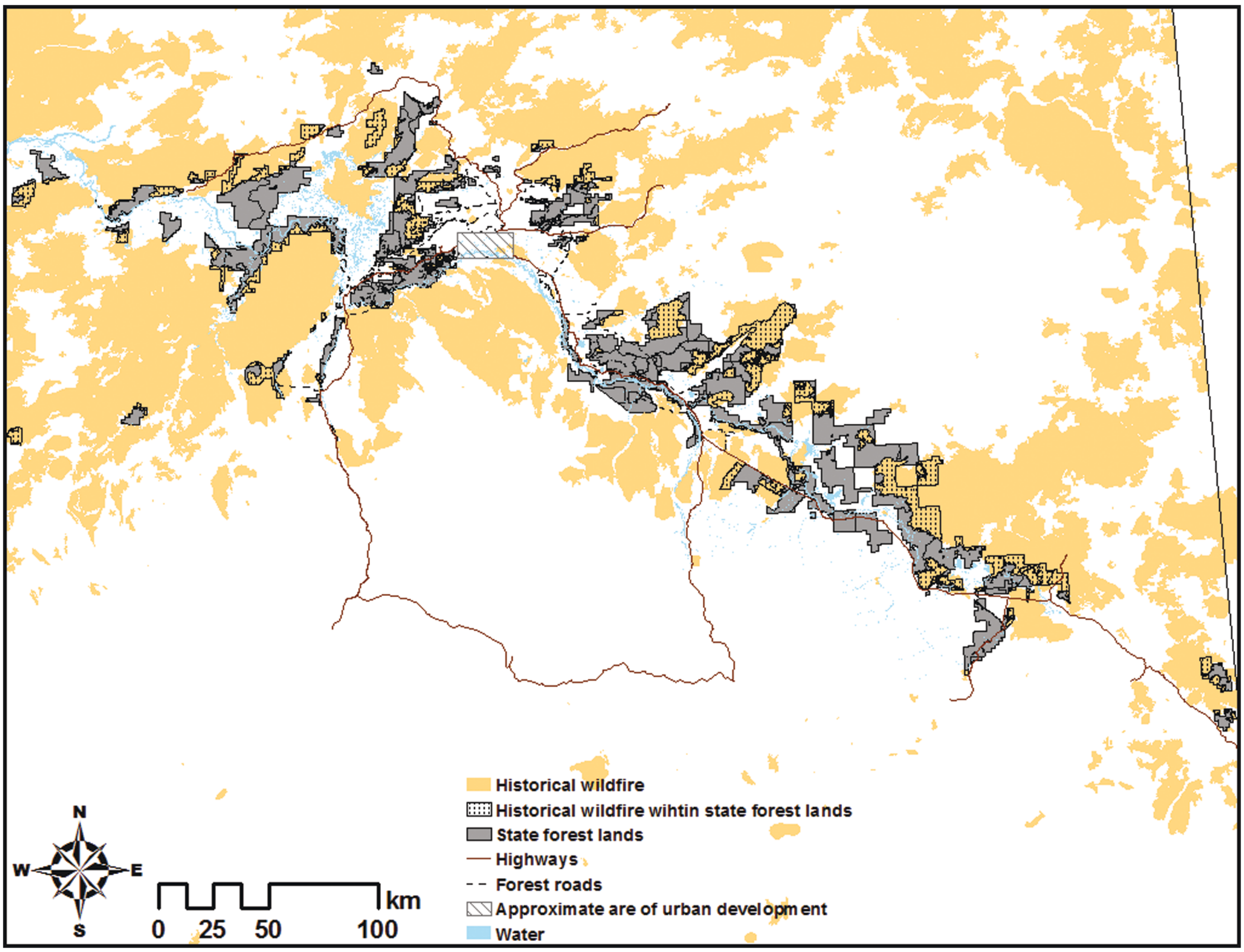

Figure 4. Historical wildfire perimeters within state forest lands and outside of state forest lands in the Tanana Valley (AICC 2015).

management can create desirable landscape patterns at a useful scale if planned appropriately. Under rapid climate change, with its large uncertainties, adaptive forest harvest management appears to be an essential tool to sustain diverse landscape patterns, particularly where public safety requires fire suppression.

Stand-Level Diversity

Within-stand biodiversity increases resilience of the boreal ecosystem to a changing or variable climate. As a result, sustaining biodiversity is usually an important goal of adaptive management. The general relationship between species richness (density) and forest productivity is positive (Liang et al. 2016). In the Alaska boreal forest, an empirically calibrated relationship suggests that a reduction in plant diversity of 1 percent could reduce individual tree productivity by 0.23 percent (Liang et al. 2015). The management tools available to most directly influence species diversity generally involve management of coarse woody debris (CWD), the soil organic layer, and disturbance regime.

Stand-level biodiversity is promoted by heterogeneous forest structures, which are typically produced by wildfires that initiate early-successional stands. Snags and CWD have been identified as two of the critical structures promoting biodiversity, as they provide various types of soil substrate and habitat for a wide range of species and play an essential role in nutrient cycling. The amount of CWD increases considerably after natural disturbance (Brassard and Chen 2006). However, forest harvesting in general reduces the amount and types of CWD compared with wildfire (Pedlar et al. 2002, Brassard and Chen 2008). Coarse woody debris left after fire primarily consists of standing dead trees of all sizes, while CWD left after harvest is mostly made up of small logs and stumps (Pedlar et al. 2002). In addition, whole-tree harvest, the predominant harvest method in Interior Alaska, creates less CWD than other types of harvesting (Zimmerman 2004). Finally, forest harvesting leaves more CWD of hardwood species than conifers, because the greater economic value of conifers is a greater incentive for removal and utilization (Brassard and Chen 2008).

A management tool to deal with these problems is variable retention harvest, which leaves large live trees and snags. This technique increases the use of harvested areas by old-growth forest bird species compared to complete tree removal (Schieck and Song 2006). Retaining the full range of sizes and species of residual stems on harvested sites provides both wood harvest and specialized wildlife habitats, although it can decrease revenue from harvest. Few studies of CWD following either fire or harvest have been conducted in Interior Alaska (Alexander et al. 2012, Paragi and Haggstrom 2005). In order to manage for such multiple simultaneous goals for CWD, it will be essential to understand the amount, type, and distribution of CWD and their dynamics, and the effects of the presence or absence of CWD on forest ecosystems, including both plants and wildlife.

Wildfire also creates a mosaic of high and low fire severity conditions within the burn perimeter, which allows establishment of a variety of both pioneer and residual species on diverse seedbed conditions (Van Cleve et al. 1996). Depth of organic layer is one of the most important variables determining the post-fire regeneration trajectory (Shenoy et al. 2011; Johnstone, Hollingsworth, et al. 2010). In Interior Alaska, a thick organic layer tends to accumulate because the rate of organic matter decomposition in soils, particularly in spruce stands, is very slow due to cold temperatures (Valentine et al. 2006). When fire consumes only a small amount of the organic layer, regeneration is dominated by previous vegetation that survived belowground and can regenerate asexually from remaining plant parts. In contrast, when fire largely consumes the organic layer, burned sites promote establishment of early-successional species that germinate from seeds on exposed mineral soil (Johnstone and Chapin 2006).

This same principle applies to soil organic layer management for post-harvest vegetation (Rees and Juday 2002, Haeussler and Bergeron 2004, Peltzer et al. 2000). In general, high-severity ground disturbance which exposes mineral soil promotes establishment of pioneer species, whereas low-severity disturbance results in a greater cover of residual vegetation and nonvascular species (Haeussler and Bergeron 2004). While some levels of ground layer disturbance favor tree recruitment, disturbance can also stimulate dense cover of *Calamagrostis canadensis* (Wurtz and Zasada 2001, Youngblood et al. 2011), which is a major problem for post-harvest tree regeneration in Interior Alaska (Peltzer et al. 2000). Aside from herbicide treatment (Youngblood et al. 2011), which has been too controversial for widespread use, site preparation is the main practical option to reduce *Calamagrostis* (Lieffers et al. 1993). It is apparent that site preparation should be applied with caution and good knowledge of the likely effects to achieve management objective.

The Effects of Recent Climate Change

High latitude regions such as Alaska are experiencing the greatest temperature increases in the recent period of global climate change (Chapin et al. 2014). As a result, climate change in the region is now one of the major challenges for sustainable forest management. Climate warming is causing changes in the physical environment, including longer growth seasons and warming or thawing permafrost (Wolken et al. 2011). Temperature increases have begun affecting Interior Alaska boreal forest both directly and indirectly, including changing tree growth both positively and negatively (Barber et al. 2000, McGuire et al. 2010, Juday et al. 2015), advancing tree lines into tundra (Wilmking et al. 2004), and modifying wildfire behaviors (Johnstone, Chapin, et al. 2010).

Studies of climate warming in relation to tree growth have focused on mature or crop trees and found that drought stress has reduced growth of mature white spruce to near survival limits on vulnerable sites in Interior Alaska (Barber et al. 2000, McGuire et al. 2010, Wilmking et al. 2004, Beck et al. 2011). However, climate sensitivity of trees depends on age, species, and site (Szeicz and Macdonald 1994, Mamet and Kershaw 2013). To date, the effects of climate warming on early regeneration on potentially vulnerable sites appear to be minor, based on adequate levels of tree density observed up to 40 years following harvest (Morimoto et al. 2016). Post-harvest regeneration has developed entirely within the warmer conditions that have prevailed in Alaska since the climate regime shift of the mid-1970s (Barber et al. 2004). By contrast, mature trees 100–200 years old that are the basis for findings of temperature-induced growth stress (Barber et al. 2000) originated in cooler climates. As a result, young trees of today have had the opportunity to compete and adjust under the new climate regime. However, the effects of climate warming are likely to appear in a later phase of forest succession, when such trees have grown lager, root biomass in relation to leaf biomass is lower, and the efficiency of water translocation has decreased (Szeicz and Macdonald 1994)—or once a temperature threshold is reached (Costantini et al. 2014). In an empirically calibrated scenario study of post-harvest regeneration in central Interior Alaska, the success of post-harvest regeneration decreased under a modest climate warming scenario (IPCC 2014, A2 scenario), and the effects were more profound on birch and aspen than white spruce (Morimoto 2016).

The more intense fire associated with increasing temperatures has converted a significant amount of old-growth to early successional stands (Kasischke et al. 2010). Fire and insect disturbance often involve mature conifer types and reduce not only the current inventory of these stands but also the prospects for their replacement on the sites where they have typically occurred in the past. As a result, timber production systems based on white spruce are likely to face sustained yield challenges unless intensive practices, such as fire protection and repeated planting, are applied. Recent severe warm and dry episodes in Interior Alaska appear to have made flammable even the traditionally relatively fire-resistant hardwood types (Barrett et al. 2016), and portions of the boreal forest appear to be converting to nonforest with completely different fire regimes (Johnstone et al. 2011).

Adaptive Forest Management in Interior Alaska

A Suggested Boreal Forest Harvest Management Decision Process under Conditions of the Recent Past

Assuming that the northern boreal environment remains similar to the recent past, results from recent forest management and studies provide a sound basis for successful forest harvest management. Recent small-scale, low-input management appears to have had limited adverse effects on the forest ecosystem. Continuing this regime would represent sustainable forest management under stable to moderately changing environmental conditions. In areas where fire has been suppressed strictly, forests continue to age. In such areas, forest harvesting can be used to improve forest health, provide moose browse (contribute to food security), recoup economic values, and reduce fire risks in the areas near community and roads. However, fire suppression is not likely to be as effective in the future, since fire intensity, severity, and frequency have been increasing due to climate warming (DeWilde and Chapin 2006)

It should also be noted that the current apparent success of post-harvest regeneration is partly a result of very small areas of harvest within a vast and relatively intact forest and the legacy effects of a climate regime that is increasingly not present and not likely to persist. Successful management in the future will require monitoring, and adjustment as climate continues to change, the total managed area expands (scale-dependent effects emerge), and a second harvest begins in managed forest.

In order to be successful, any forest management program must align specific stand-level practices to the overall goals of management (Smith et al. 1997). We offer a flow chart of management decisions and actions considering ecological factors: the timing of white spruce seed crops (Figure 5) for the region based on the recent studies and an assessment of recent literature. It is important to note that this management decision process applies only to white spruce harvest (great majority of harvested area) and considers only within-stand outcomes, but not between-stand influences (landscape spatial component). It also assumes that climate or environmental conditions roughly similar or only moderately different to the historical period will persist over the projected forest rotation.

In order to maximize post-harvest regeneration, cost efficiency, and structural diversity, clearcutting with reserves appears to be the most effective harvest method (Figure 5). Retention of various sizes and species of residual trees can increase structural diversity that will sustain a broad range of wildlife species, some of which play important functional roles in the stand such as insect predation or seed dispersal, and some of which (e.g., moose) benefit from a mosaic that includes mature forest cover. However, retaining more large trees in harvested stands will decrease harvesting efficiency and revenue. One approach that can minimize these disadvantages is to retain patches of unharvested areas within clearcuts, allowing efficient harvest while retaining the desired wildlife habitat. Another appropriate technique would be to shift from whole-tree removal to partial stem retention to increase CWD on the forest floor, sustaining soil nutrients and habitat for small mammals and insects.

Following harvest, if a large white spruce seed crop is present or expected, neither site preparation nor planting seedlings is necessary, because either would likely result in overstocking (Figure 5). Foresters can check for the indicators of a white spruce seed crop (predictable a year in advance) shortly before and after harvest and then make appropriate adjustments to the regeneration plan. Relying on natural regeneration has the obvious advantage of cost savings and other advantages, particularly retaining native genetic diversity on managed sites.

However, if a white spruce seed crop is not present or expected, specific post-harvest reforestation practices may be required to achieve desired management outcomes. First, if large dimension white spruce production is a critical management goal, planting white spruce seedlings may be desirable in order to obtain trees that achieve and sustain canopy dominance from the earliest possible time following harvest (Figure 5). Second, if wood biomass production is the management goal, target species need to be specified. When white spruce is the target species, planting seedlings might be necessary (Figure 5). In contrast, where hardwood material is suitable for wood biomass products, short-rotation forest management would be possible without the strenuous efforts often needed to establish white spruce (Figure 5). In any case, site preparation following harvest will enhance seedbed quality for tree establishment and growth (Figure 5), except that aspen density can be reduced by site preparation when the soil organic layer is already thin (Allaby et al. 2017).

If a management goal is to sustain habitat diversity for a full range of boreal species, the specific forest type to be developed needs to be identified. When a canopy dominant white spruce component is to be sustained, planting seedlings may be necessary or desirable (Figure 5). When producing an abundant early successional hardwood component is the goal, natural regeneration would very likely be adequate (Figure 5). In both cases, the severity of ground disturbance needs to be kept low or moderate to avoid extensive dominance by

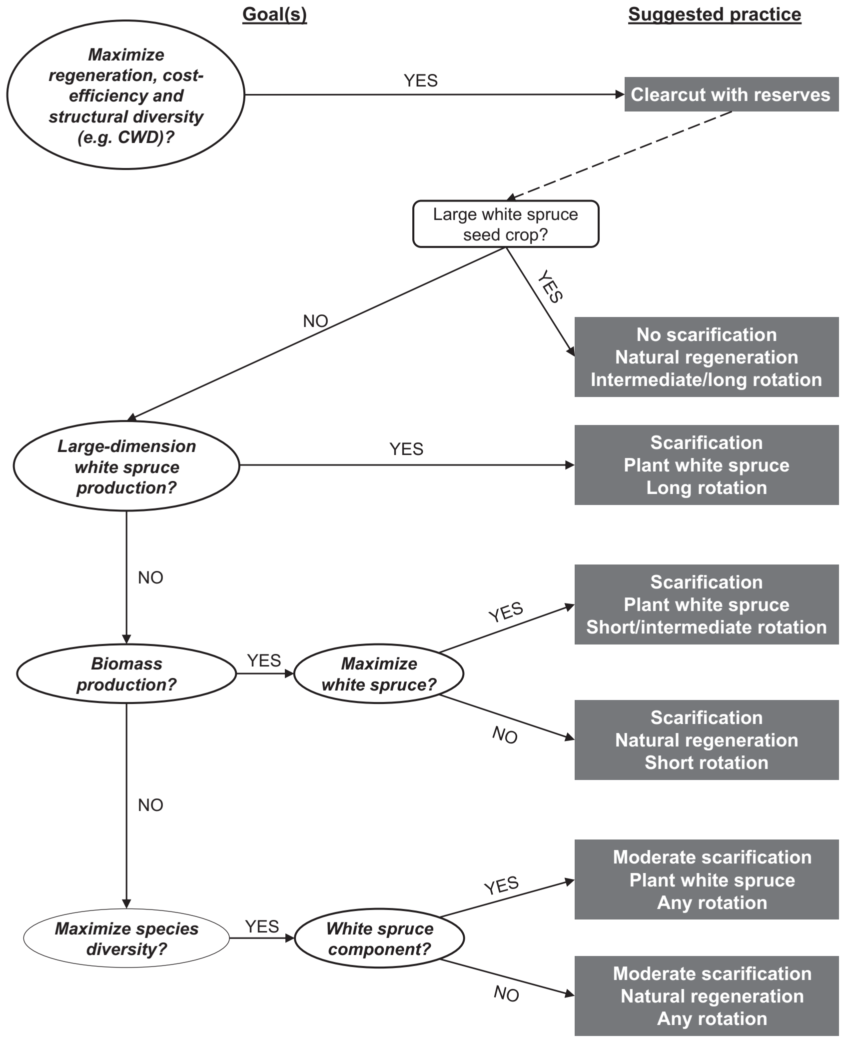

Figure 5. Adaptive decision flow-chart for stand-level white spruce harvest management developed from 40+ years of experience. This applies only to harvest of existing white spruce stands, assumes a boreal forest environment similar to recent past, and does not consider landscape-level outcomes.

pioneer species and to maximize diversity of understory vegetation.

Adaptive Management Options and Practices for Future Environments

Although post-harvest regeneration appears to be successful under recent boreal conditions, the landscape patterns and stand compositions created by forest harvest management cannot be assumed to be the same as those created by natural disturbances of wildfires and insect outbreaks. Harvest at the same rate as natural disturbances would have minimal effects on the abundance of desirable harvestable stands, particularly on older, large conifer communities, but more rapid removal would not. In addition, a changing climate will be a major influence on the development of post-disturbance forests of the future. An increase of global mean surface temperature is highly likely by the end of the 21st century and would exceed 1°C under all but the lowest emission scenarios. Warming in the Arctic is almost certain to be greater than the global mean (IPCC 2014) and has already exceeded that level in the past century (Figure 1a). A climate-sensitive matrix modeling driven by forest inventory data indicates that at the whole stand level, predicted greater precipitation cannot offset growth reduction from drought stress (Liang et al. 2011). The unprecedented rate of temperature increase is likely to start causing failure of post-harvest regeneration on vulnerable, warm, low elevation sites in the near future (Morimoto 2016).

As a result of these processes of change, it is clear that forest management, and especially forest harvest regeneration management, needs to incorporate adaptive approaches today. The main options for adaptive boreal forest management practices under a regime of increasing temperatures appear to fall into three categories (Figure 6): maintaining current species (P1), maintaining a forest landscape of any type (P2), and supervising biome shifts from forest to other biome types (P3). Each of these adaptive management approaches will require supporting information and investigations.

In order to maximize the potential of sustaining current forest products and species while increasing the potential of new products under a warming climate, sites and regions suitable for each option need to be identified. Boreal Alaska comprises diverse landscapes, regional climate gradients, and areas of complex topography. The first option (P1: maintaining current species) is feasible in the cooler end of the climate gradient where trees will experience sustained or enhanced growth potential under increased temperatures. In contrast, the third option of biome shift (P3) will be required in the hottest and driest end of the climate gradient where tree growth is not likely to be feasible under a future warmer climate. The second option (P2) is available in the middle of the climate gradient.

Clear goals for the spatial arrangement of different stand types at a landscape scale is also essential when developing management options. In order to sustain current species in the landscape, connectivity is critical for dispersal of current forest propagules and wildlife mobility (Millar et al. 2007). Connectivity also promotes natural migration of species under changing environments (Noss 2001). Landscape arrangement of stand types is also crucial to reduce the risk of intense, wide-spreading wildfire under an amplified fire regime. To a limited degree, forest managers can create forest landscape types. But under climate warming, resilience and natural redistribution of stand types will be important constraints to management created landscape patterns.

Current species patterns can be maintained on resilient sites that experience sustained or enhanced forest growth potential under continued temperature increases. These include higher elevations (Wilmking et al. 2004), aspects with less than full south exposure, and locations in western Alaska (e.g., Juday, Alix, and Grant 2015). On such sites, the suggested forest harvest

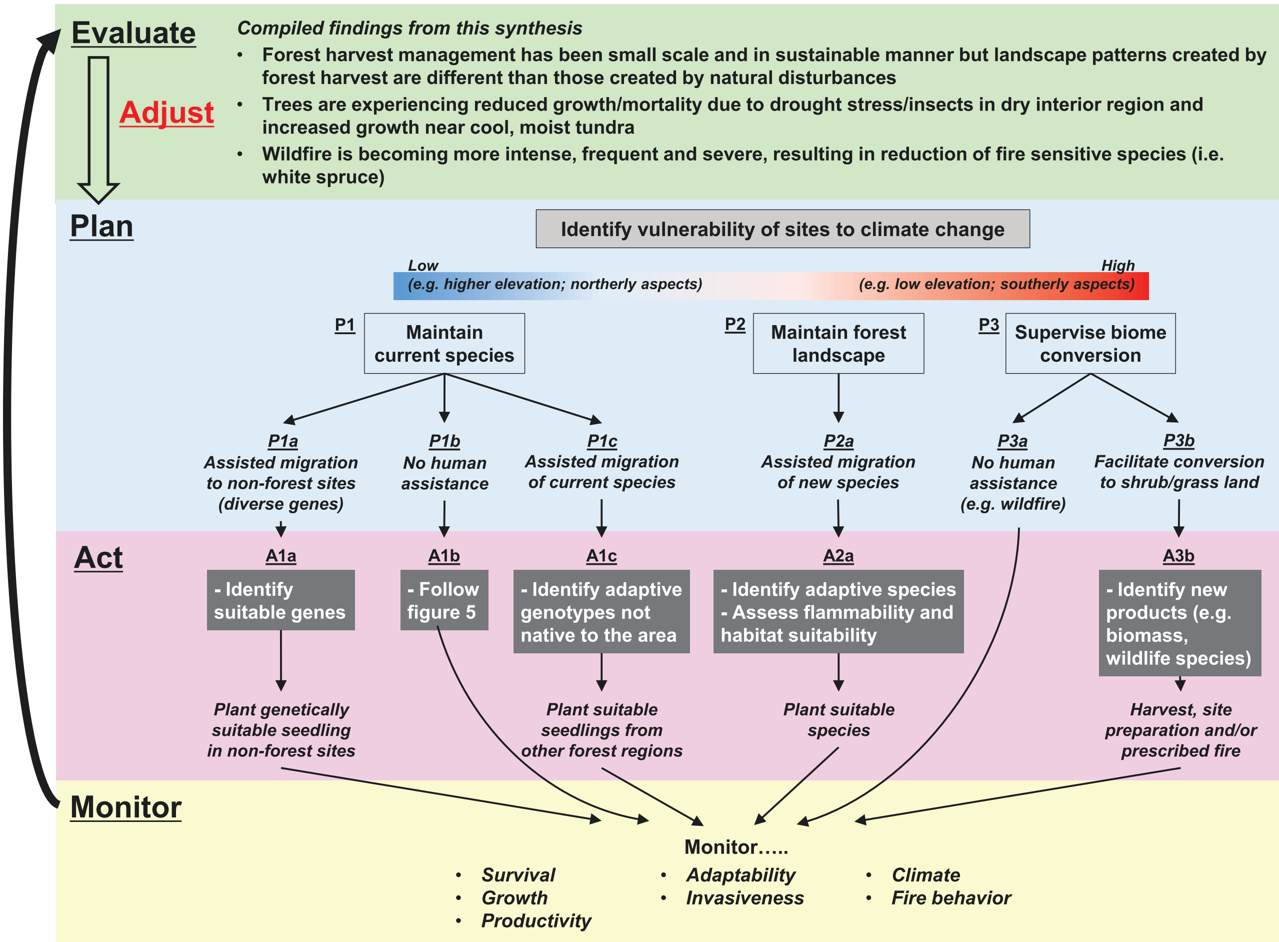

Figure 6. Evaluation flow-chart of suggested adaptive management options and practices under a warming climate relevant to the boreal forest.

management decision process, based on past management success, will be useful (Figure 5). These sites do not require assisted migration (P1b).

However, intensive fire management may be critical to maintaining the most valuable, productive native species on resilient forest landscapes that have traditionally not experienced frequent fire. The Alaska boreal forest has the potential to be a significant offset resource in the context of emerging carbon markets, and fire management on resilient forest landscapes is particularly relevant to this goal (Liang and Zhou 2014). Old-growth stands require priority attention to issues of harvest, wildlife, and ecological goals within a regional context. In some cases, initially reducing large legacy accumulations of soil organic layer depth through wildland fire may be appropriate, and in others, fire suppression may be appropriate.

Sites that can maintain current species under additional warming are prime locations for considering the introduction of southern genotypes of the dominant species not currently occurring in the area (Figure 6 A1c). In any event, forest management will need to incorporate genetic studies (e.g., Alden 1991) to a degree well beyond what has occurred to date in order to identify the specific gene types best adapted to the new and emerging environmental conditions.

Nonforest sites becoming newly suitable for tree growth should be carefully evaluated for their potential contribution to future forest productivity. Tree establishment on tundra is already occurring (Suarez et al. 1999, Dial et al. 2007, Harsch et al. 2009), and current tundra, especially near treelines, is likely to eventually support full canopy forests under warmer conditions, as long as moisture is not limiting (Ohse et al. 2012, Wilmking et al. 2006). Forest displacement of tundra can result in a net decrease in habitat suitability for caribou. Resource managers will need to carefully evaluate the relative gains and losses of forest expansion versus nonforest habitat loss. Due to the unprecedented rate of warming, adaptive human-supervised or assisted migration of genetically diverse tree populations, which happened as a natural process in the past (Roberts and Hamann 2015), is likely to be necessary in some current nonforest areas (Figure 6 A2a). A number of these areas of enhanced and new forest potential are not near current infrastructure and essentially do not have a history of forest management. Monitoring the growth and health of post-harvest regeneration in areas of presumed improved forest growth potential will be a critical verification step (Figure 6).

Recent warming is producing environments beyond the optimum for existing tree species in Alaska but possibly capable of supporting well-adapted species from elsewhere. If maintaining a forest landscape of any type is a future goal, then conceivably the introduction of species that grow better under the new, warmer climate regime might be an option (Figure 6, P2a; Hagman 1993). Introduction of exotic, non-native species poses a number of well-recognized risks (Pimentel et al. 2000). However, the concept of "non-native" itself may need to be reconsidered, at least in the context of managed landscapes, under the magnitude of climate change now emerging in the far north. Despite the generally low species richness of the far north, nearly 30 tree species capable of stand dominance are adapted to extreme cold temperatures and high latitude locations, 15 of which are native North American species (Nikolov and Helmisaari 1992). Native North American boreal tree species have migrated north and south across much of the continent in response to past climate changes (Anderson et al. 2006). A conservative management approach would be to begin now to examine the genetic adaptability of North American tree species populations that, under continued warming, would arrive in northern Alaska simply given enough time (Figure 6, A2a). A further step would be to screen the most adaptive species of any origin while carefully examining invasive potential (Alden 2006). The potential new species may be either fire-promoting (e.g., lodgepole pine) or vulnerable to fire (*Abies* spp.), so the landscape context of the introductions in relation to fire will need to be carefully considered. The new forest types also need to be assessed for their habitat suitability for the current or potential new wildlife species. Species introductions need to be arranged spatially so that wildlife species have access to a full range of habitat types they require. Few exotic tree plantations exist yet in Interior Alaska, which can be used to assess these critical questions.

Finally, in the areas most vulnerable to climate warming, monitoring or even facilitating biome conversion of boreal forest to shrubland or grassland (Hogg and Hurdle 1995) might be an option (Figure 6, P3). In such areas, the fire regime may shift to frequent light ground fires, and fire planning and management would need to adjust accordingly. Opportunities on the converted lands need to be assessed, such as new plant products or potential subsistence wildlife species (Figure 6, A3b). In Interior Alaska, wood bison (*Bison bison athabascae*) have been reintroduced (Alaska Wood Bison Management Planning Team 2015) as one part of a comprehensive conservation recovery strategy (e.g., Sanderson et al. 2008) that will very likely produce harvestable products as the population increases enough to be de-delisted under the Endangered Species Act. However, the interactions and conflicts between new and existing species need to be monitored and assessed to minimize the risk of reduction or loss of current wildlife populations. Landscape arrangement of forests near shrubland or grassland is critical for fire management to reduce the risk of wide-spreading fire. Hardwood stands or fire-resistant new tree species might be an option for the surrounding areas to reduce large-scale fires. Fuel breaks might be desirable in some areas to prevent spreading fire to adjacent forests, especially to old-growth white spruce forests, which will be among the most limiting and vulnerable stand type under climate change (Usher et al. 2005). Mosaics of diverse land cover types will be key to produce and maintain habitat for a full range of species. For example, wood bison prefer grassland as foraging habitat, but they also use forests for shade in summer, shelter in winter, and travel between foraging habitats.

Conclusion

By its very nature, forest management has always confronted uncertainties about the future. In many ways, the forestry profession has developed as a response to the need to make decisions, provide for human needs from forest lands, and sustain the forest ecosystem in the face of uncertainty (e.g., Smith et al. 1997). Climate change as an issue confronting forest management has evolved from a distant prospect to an unfolding reality as it is being experienced in boreal Alaska. We have offered here a framework to build on the knowledge and practices of the past, meet the needs and challenges of today, and demonstrate an approach to prepare for the challenges of the future in one of the most rapidly changing forest regions of the world.

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