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# Restoring Old-Growth Southern Pine Ecosystems: Strategic Lessons From Long-Term Silvicultural Research

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## ABSTRACT

The successful restoration of old-growth-like loblolly (*Pinus taeda*) and shortleaf (*Pinus echinata*) pine-dominated forests requires the integration of ecological information with long-term silvicultural research from places such as the Crossett Experimental Forest (CEF). Conventional management practices such as timber harvesting or competition control have supplied us with the tools for restoration efforts. For example, the CEF's Good and Poor Farm Forestry Forties have been under uneven-aged silvicultural prescriptions for 70 years. Monitoring these demonstration areas has provided insights on pine regeneration, structural and compositional stability, endangered species management, and sustainability capable of guiding prescriptions for old-growth-like pine forests. Other studies on the CEF's Reynolds Research Natural Area have provided lessons on the long-term impacts of fire suppression, woody debris and duff accumulation, hardwood competition, and pine regeneration failures. This experience leads us to believe the productivity and resilience of these forests can be adapted to create functionally sustainable old-growth-like stands by integrating silviculture and restoration.

**Keywords**: coarse woody debris, Crossett Experimental Forest, loblolly pine, red-cockaded woodpeckers, shortleaf pine, Upper West Gulf Coastal Plain.

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*Figure 1—Examples (a) of the presettlement pine forests that once dominated the Upper West Gulf Coastal Plain of southern Arkansas and (b) of the cutover landscapes found by the early 20th Century.*


*Figure 2—Location of the Crossett Experimental Forest (CEF) and map of the research and demonstration areas.*

## INTRODUCTION

Restoration efforts are now one of the primary driving forces in national forest management and the research programs designed to support this policy (Bosworth and Brown 2007). For many, this is a radical departure from the traditions of forestry and silviculture, in large part because of the shift in emphasis from timber harvesting to management for a variety of benefits. In reality, the emphasis on restoration shares many of the original aims of forestry. As an example, silviculture was in part designed to rehabilitate degraded forest ecosystems and renew their commercial productivity and natural resilience (Pinchot 1947). Even though the ultimate objective (timber only versus multiple use) has changed considerably, our silvicultural toolkit can still serve us well in the contemporary management of public lands (Guldin and Graham 2007). Indeed, it is the many lessons we have learned on how to manipulate the forest to yield predictable and desirable outcome(s) that permits us to attempt to restore these systems.

The establishment and operation of the Crossett Experimental Forest (CEF) in southern Arkansas is a classic example of how the implementation of science-based forestry and silvicultural research was and can still be used to restore landscapes. By the early 20th Century, decades of exploitive logging and land clearing had devastated the virgin pine forests of the region (fig. 1). As the 1920s closed, some in the local timber industry recognized the potential of their lands to sustain productive second-growth pine forests, if they only knew what to do (Reynolds 1980). Even though operations such as the Crossett Lumber Company supported the research and extension efforts of distant university academics, their work was too limited to be of much practical use. Starting in the early 1930s, the Southern Forest Experiment Station of the U.S. Forest Service offered another possibility—the establishment of permanent experimental stations staffed by federal researchers to conduct long-term research and demonstration projects and help landowners manage their properties (Bragg 2005, Demmon 1942, Reynolds 1980).

It was into this environment that Russ Reynolds, a recent graduate of the University of Michigan, came to work with Ozark-Badger, Crossett, and other lumber companies. Reynolds helped carve the CEF out of the cutover landscapes of southern Arkansas (fig. 2). When established in 1934, the CEF offered a means to design, demonstrate, and monitor the long-term response of silvicultural treatments in loblolly (*Pinus taeda*) and shortleaf (*Pinus echinata*) pine-dominated forests (Reynolds 1980) on productive sites (SI50 = 85 to 90 feet). The CEF opened for "business" on January 1, 1934, and over the next few years, Reynolds installed a number of key long-term demonstration and research areas (Reynolds 1980). During the following decades, other research was established that either continued existing projects or addressed new questions based on changing markets, utilization, silvicultural strategies, and resource interests.

As the CEF enters its eighth decade of service, a number of these long-term studies (e.g., the Good and Poor Farm Forestry demonstration areas, Reynolds Research Natural Area (RRNA), Methods-of-Cut) have had many years of detailed observations, and the silvicultural lessons learned in their implementation, maintenance, and analysis continue to develop. In this paper, we describe how information gleaned from these long-term experiments and demonstrations can be adapted to questions arising from a new silvicultural direction—the restoration of stands with old-growth-like characteristics. Unlike some existing large-scale projects in the South (e.g., Stanturf et al. 2004), these lessons are more strategic than tactical because we are still in the process of adapting our knowledge of traditionally managed southern pine to produce both old-growth attributes and commodities.

## SILVICULTURAL CONTEXT

Repeated logging and conversion to other land uses over the last 150+ years have virtually eliminated old-growth loblolly and shortleaf pine-dominated forests that once covered much of the coastal plain of the southern United

**Table 1—A sample of the desired standards and guidelines for successful restoration of old-growth-like conditions in loblolly and shortleaf pine stands of the UWGCP in southern Arkansas, adapted from Bragg (2004a)**

| Attribute | Reference target |
|---|---|
| Species composition | 50 to 60 percent loblolly pine |
| | 35 to 45 percent shortleaf pine |
| | up to 10 percent hardwoods |
| Basal area | 50 to 70 square feet per acre |
| Maximum tree DBH/age | unlimited |
| Number of big trees | 5 to 15 pines > 30 inches d.b.h. per acre |
| Reserved timber volume | 5,000 to 10,000 board feet (Doyle) per acre |
| Spatial pattern | patchy |
| Under/mid-story | open |
| Red heart | 10 to 50 percent cull in retained trees |
| Large woody debris | 5 to 10 snags (285 to 715 cubic feet) per acre |

States. Second-growth natural stands of mixed loblolly and shortleaf pine are still common, although none of them possess all of the attributes of their presettlement versions. Furthermore, naturally regenerated pine stands are under considerable pressure from commercial timber interests, land developers, and other threats to forest health (e.g., southern pine beetle (*Dendroctonus frontalis*)). For instance, although the generic "loblolly-shortleaf pine" cover type has held steady since the early 1950s at about 25 percent of the timberland in the southeastern United States, natural pine stands have declined from almost 72 million acres in 1952 to just under 33 million acres in 1999, with concurrent increases from 2 to 30 million acres of planted pine (Conner and Hartsell 2002).

There is growing interest in using silviculture to restore existing loblolly/shortleaf stands into old-growth-like conditions, especially from some national forests. A classical example of this interest is the pine-bluestem restoration project initiated in the 1990s on the Ouachita National Forest (Stanturf et al. 2004, U.S. Forest Service 1996). This large-scale project has been successful, spawning interest from other national forests desiring the same multiple-use results out of an integrated silviculture and restoration program. Success in one location, however, does not necessarily translate into acceptable results in other regions—there are enough unique attributes in any given landscape to require that every project be at least somewhat custom-designed. As an example, the management prescription for old-growth-like conditions in pine-dominated upland forests of the Upper West Gulf Coastal Plain (UWGCP) of southern Arkansas, northern Louisiana, southeastern Oklahoma, and northeastern Texas (Bragg 2004a) may not work in the shortleaf pine forests of the Ouachita or Ozark mountains, or even the hardwood-dominated forests of the UWGCP.

The successful restoration of old-growth-like forests requires the integration of historical information with lessons learned in places such as the CEF. Long-term silvicultural research and demonstration projects, some of which date back to the mid-1930s, can be modified into new strategies for multi-resource objectives. This paper provides examples taken from these projects on the CEF and related studies, and translates the lessons from conventional silvicultural treatments to the emulation of old-growth-like conditions. Ultimately, our prescriptive goal is not to reproduce an exact replica of a presettlement old-growth, but to incorporate as many of these key attributes as possible in a stand that is functionally self-supporting and actively managed.

## WHAT ARE OLD-GROWTH-LIKE CONDITIONS?

Managing for old-growth-like conditions in the pine-dominated forests of the UWGCP refers to the encouragement of forest conditions dominated by features and processes akin to old forests of the presettlement (circa 19th Century) era. In other words, we aim to duplicate many of the same structural, compositional, and functional attributes of the virgin pine forests of the region (see fig. 1a) in contemporary stands still managed for some degree of commodity production. Rather than using a fixed set of narrowly defined criteria to judge success of this restoration effort, our standards and guidelines (table 1, see also Bragg 2004a) call for a range of conditions to be emulated using conventional silvicultural tools such as thinning, reproduction cutting, competition control, and even supplemental planting.

Unfortunately, we have only spotty information on what presettlement pine-dominated forests were like in the UWGCP. According to anecdotal reports, pines in excess of 40 inches d.b.h. (diameter breast height) or greater were common, and some individuals apparently exceeded 70 inches d.b.h. and over 5,000 board feet (unless otherwise specified, all board measures are Doyle scale) of lumber (Bragg 2002, 2003). These large trees, while very noticeable, were not so numerous that stand densities or sawtimber yields were particularly high. In a review of available information, Bragg (2002) noted that stand sawtimber volumes often ran between 5,000 and 20,000 board feet per acre, with most ranging between 10,000 and 15,000 board feet per acre. Annual growth data was even spottier, although some mature- to old-growth pine stands from southern Ashley County added between 50 and 120 board feet per acre per year (Chapman 1912, 1913). Size class patterns varied, but most exhibited at least a few pines across a broad range of diameters.

Hence, when compared to modern, managed examples of uneven-aged loblolly and shortleaf pine in the UWGCP, these virgin forests grew appreciably slower, contained greater volumes of sawtimber in (typically) larger trees, and probably had considerably fewer small stems. While intensively-managed uneven-aged pine stands contain dense pockets of regeneration and thus are not relatively open, it is likely that modifications to an uneven-aged prescription can be made to develop regeneration cohorts in a more episodic manner. It is possible that they could even be treated with prescribed fire. This would eventually produce a structural effect similar to that which is reported for virgin pine forests. Both of these would have relatively open canopies with multiple size classes distributed throughout the stand. Such a functional similarity would make it possible to emulate at least some aspects of old-growth-like forests while simultaneously supporting timber production (Bragg 2004a).

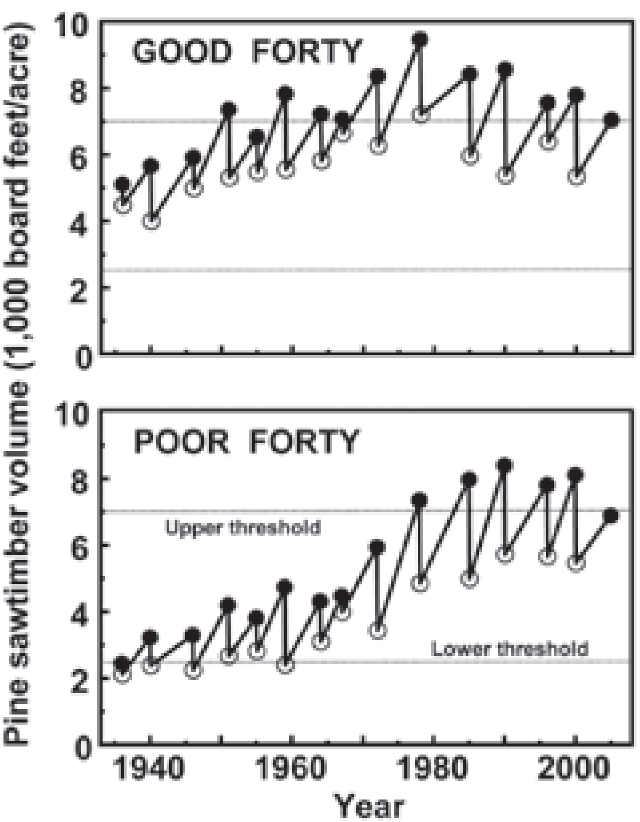


*Figure 3—Pine sawtimber volume (Doyle scale) in the Good and Poor Farm Forestry Forties on the Crossett Experimental Forest (CEF) over a 69-year period. The filled symbols are before harvest and open symbols are after harvest. The dotted lines are the upper and lower stocking thresholds recommended by Baker et al. (1996). From Guldin (2002) and unpublished data on file at CEF.*

## UNEVEN-AGED MANAGEMENT AND RESTORATION SILVICULTURE

Loblolly and shortleaf pine forests can be managed under a number of different uneven-aged silvicultural methods, using either single-tree selection or group selection (Baker et al. 1996). The silvicultural key to making these methods successful involves maintaining a critical balance in stand stocking—a sufficient overstory is retained so that growth and yield continues at high rates, but this overstory is also periodically reduced to permit pine regeneration and canopy recruitment. In addition to the generation of quality pine sawtimber, uneven-aged silviculture supports many other non-timber resources. The structure and composition of mature, uneven-aged southern pine stands are considerably better for co-managing certain types of wildlife species. The Good Forty, for example, contains two active red-cockaded woodpecker (RCW) (*Picoides borealis*) clusters. The RCW has become an endangered species in large part because the older pines suitable for nest cavities have been largely eliminated in the younger, more intensively managed forests of the South (Conner et al. 2004a, 2004b). The loss of mature, open pine woods has greatly contributed to the decline of the RCW (Saenz et al. 2001).

The Good and Poor Farm Forestry Forties on the CEF have been successfully managed using uneven-aged silviculture with single-tree selection for 70 years. Some may find the success of uneven-aged silviculture in loblolly and shortleaf pine-dominated stands surprising, due to the relative shade-intolerance of these species. However, decades of demonstration work in the Good and Poor Farm Forestry Forties have shown the efficacy of this technique, given some adjustments for species autecology and local site conditions (Guldin 2002). During these years, our monitoring of these parcels has provided critical information about pine regeneration, structural and compositional stability, and resource sustainability capable of guiding prescriptions for old-growth-like pine forests.

The initially poorly stocked Poor Forty was established to show how stands could be rehabilitated using uneven-aged silviculture, while the better-stocked Good Forty was established to document rates of growth and yield once rehabilitation had been achieved. And grow they did! Long-term records (from 1936 to 2005) have shown annual growth averages about 400 board feet per acre


*Figure 4—Contrasts in the structure and composition between the Good Forty (a) and the RRNA (b) are obvious when these stands on the Crossett Experimental Forest are compared.*

in the Good and Poor Forties. Stocking was rapidly improved in the Poor Forty by harvesting less than growth, while the well-stocked condition in the Good Forty was essentially maintained by harvesting the periodic growth (fig. 3). These cuts, now done about once every 5 years, remove mostly mature, high-quality sawtimber. Harvests over this 69-year period totaled 24,000 board feet per acre in both the Good and Poor Forties. In addition, standing pine volume in 2005 was 50 to 200 percent greater than in 1936 (fig. 3). Throughout this period, the Good and Poor Forties retained a component of big trees, averaging 5 trees per acre with d.b.h. of 20 inches and larger before the periodic harvests.

## THE HISTORICAL AGE STRUCTURE OF UNEVEN-AGED PINE STANDS

There is no reliable information on the age structure of presettlement forests of loblolly and shortleaf pine in the UWGCP. Few stands of old-growth pine or pine-hardwood timber remain, making it difficult to generalize using these remnants as models. However, if appropriately applied, some inferences can be made that have important silvicultural consequences. After examining recent stumps following salvage and limited increment coring, Bragg (2006) reported that the pine overstory in the Levi Wilcoxon Demonstration Forest (LWDF) in Ashley County, Arkansas, was uneven-aged. Overstory pines ranged from about 80 years old to as much as 300 years old, and were primarily recruited between 1800 and 1920. In a bottomland hardwood-loblolly pine stand in nearby Calhoun County, Heitzman et al. (2004) placed pine establishment during three primary periods: 1850-60; 1861-90; and 1981-90.

Hence, it appears that many (if not most) of the presettlement pine forests of the UWGCP were at least broadly uneven-aged, with periodic small- and large-scale distur-

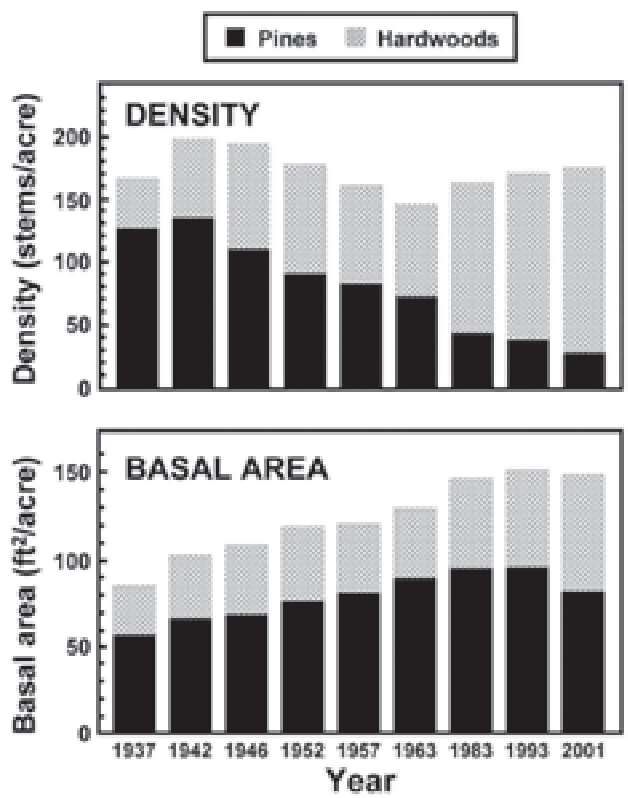


*Figure 5—Successional changes in pines and hardwoods 4 inches d.b.h. and larger over a 64-year period in the Reynolds Research Natural Area on the Crossett Experimental Forest (CEF). Adapted from Cain and Shelton (1996) and updated with unpublished data on file at CEF.*

bances allowing for the establishment of new cohorts of regeneration (Bragg 2006, Heitzman et al. 2004). This produced scattered individuals or patches of older "veteran" trees intermingled with more extensive areas of maturing timber (Bragg 2002). This pattern is consistent with stand maps made in southern Ashley County from Chapman (1912) that distributed large, decadent old pines in a matrix of maturing trees. Areas of even-aged stands arising from natural disturbances were also noted elsewhere in Arkansas (Turner 1935), and probably comprised a significant portion of the presettlement landscape. From a restoration perspective, this distribution implies that at least some degree of age variation should be present for old-growth-like conditions. This, in turn, suggests that the stands be treated in a manner capable of producing multiple age classes.

Even though fire was an important dynamic in the presettlement pine forests of the UWGCP, conventional wisdom holds that intensively managed uneven-aged pine stands are best managed without fire. However, work on the CEF has shown that fire can be compatible with uneven-aged mixed pine forests. A 19-year study of different burning regimes showed that, though not very efficient at producing large numbers of saplings, low- to moderate-frequency dormant season fires did not completely eliminate them from the treatment areas (Cain and Shelton 2002). Regularly applied dormant season fires were found to only temporarily suppress competing hardwoods, and the fires also killed much of the pine regeneration. Thus, the authors suggested that fires be applied in conjunction with herbicide use, which would allow pine regeneration to more quickly reach fire-tolerant size (Cain and Shelton 2002). Another adaptation using fires to control species composition in uneven-aged pine stands would involve an interrupted burning cycle. Repeated dormant season prescribed fires would be used to control competing hardwoods, but this burning cycle would be interrupted long enough for pine seedlings to become established and to grow to fire-tolerant sizes. After a brief interval, the burning cycle would then be reestablished (Cain and Shelton 2002).

Residual old trees are also important for the restoration of old-growth-like conditions. Unlike most pine plantations in the UWGCP, which are generally harvested after 30 to 35 years when the pines have just reached reasonable sawlog size, uneven-aged stands will frequently have trees greater than 70-years old, and often these trees are of considerable diameter and height (Guldin and Fitzpatrick 1991). The older component of uneven-aged pine stands often possesses a greater incidence of red heart fungus (***Phellinus pini***), an attribute critical to RCW nest cavity excavation (Conner 2004a, 2004b). Since the current managing for old-growth-like condition strategy calls for the retention of some of the oldest and largest pines regardless of how old they may be (Bragg 2004a), these trees provide attributes such as RCW cavities and aesthetics without excessively compromising fiber production.

## LESSONS FROM UNMANAGED STANDS OF LOBLOLLY AND SHORTLEAF PINE

The dynamics and long-term composition of the RRNA have also taught us much about the behavior of unmanaged forests in the UWGCP. This research natural area, an 80-acre no-harvest reserve on the CEF, has been sheltered from fire and logging for over 70 years. When established, the RRNA was intended to showcase stand development in an unmanaged parcel compared to the adjacent managed Good Forty (fig. 4). The long-term dynamics of the RRNA have vastly differed from those of the Farm Forestry Forties. Even though some structural elements of the unmanaged RRNA are similar to the virgin forests of the region (for example, older pines, large quantities of dead wood), others are more comparable to managed stands.

For instance, after decades of stable stocking, net growth, and increasing yields, pine mortality rates in the RRNA have recently increased considerably, while growth has slowed and pine recruitment dropped to virtually nothing (fig. 5). Pine no longer dominates the overstory or understory composition of the RRNA, while the Farm Forestry Forties are heavily pine dominated in all age and size classes (figs. 4 and 5). This disparity is largely the result of lower over- and midstory density and the use of herbicides to control competing vegetation in the Farm Forestry Forties. Presettlement UWGCP forests typically had a variable and potentially significant component of hardwoods (Bragg 2002), but pine would have been very prominent, and its gradual disappearance in the RRNA does not bode well for the sustainability of conifers in this formerly pine-dominated tract.

Over the last half-decade, pine basal area in the RRNA and the nearby LWDF has continued to decline precipitously (Bragg 2006). Mortality is a natural component of any stand of timber, managed or otherwise, but it must be carefully regulated when restoring old-growth-like conditions so as not to lose the key overstory component that defines the type—pine. At times, preemptive harvests of pine beetle spots, storm damaged timber, or even large-scale salvage logging may be necessary to ensure that the overall health of the pine overstory is maintained. However, it is also important to ensure that at least some accumulation of dead wood is allowed, as this is a critical ecological attribute of old-growth (see later section).

Net pine growth in the first half of the 1990s became negative for the RRNA, with mortality losses double that of survivor growth and zero contribution from recruitment (Shelton and Cain 1999). While growth does not need to be maximized or optimized in a silvicultural strategy focused on restoring old-growth-like stand conditions, there is need for positive increment in at least some of the merchantable size classes. Presumably, the relatively open stand conditions and continual recruitment of young pines to the overstory will ensure that there is enough fiber production to support periodic harvests to regulate overstory density. The long-term regenerative success of the Farm Forestry Forties, coupled with their high-value sawtimber yield, suggest that it should be possible to maintain desired structures within these old-growth-like stands by encouraging vigorous smaller classes, even if mortality in the largest classes (retained for their contributions to stand structural complexity) is high at times.

## RETAINING A PINE OVERSTORY VIA NATURAL REGENERATION

The failure of pines to replace themselves in the RRNA and the LWDF is a clear lesson on how not to perpetuate a pine-dominated canopy. Pine regeneration is a complicated process, involving the impacts of stand conditions, fire suppression, hardwood competition, and woody debris and duff accumulation. The presettlement pine-dominated forests were typically self-replacing, propagated by frequent fire and other large-scale, intense perturbations that produced adequate pine regeneration conditions while simultaneously restricting the success of competing hardwoods. For our old-growth restoration efforts to be successful, we must be

**Table 2—Quantitative expression of some factors affecting the success of establishing pine regeneration and providing for its development in the Reynolds Research Natural Area (RRNA) and the Good Farm Forestry Forty on the Crossett Experimental Forest (CEF)**

| Factor[a] | RRNA | Good Forty |
|---|---|---|
| Mean seed production per acre | 503,000 | 418,000 |
| Median seed production per acre | 60,000 | 195,000 |
| Litter depth: inches | 1.0 | 1.1 |
| Light intensity near ground: percent of full sunlight | 4 | 66 |
| Pine basal area, trees ≥ 4 inches d.b.h.: $ft^2$/acre | 82 | 63 |
| Hardwood basal area, trees ≥ 4 inches d.b.h.: $ft^2$/acre | 68 | 1 |

[a] Compiled from several published sources providing data and/or background information on methods (Cain and Shelton 1995, 2001; Guo and Shelton 1998; Shelton and Cain 1999) and unpublished data on file at CEF. Seed production was for 16 years (1991 through 2006); tree inventories were from 2000; litter depth was determined in 1994, about 4 years after the Good Forty was last harvested.

able to emulate this result without investing heavily in artificial regeneration or competition control. After all, low-cost, low-impact, self-replacing pine stands can produce both environmental complexity characteristic of presettlement old-growth and make it much easier to convince landowners to sustain their efforts over the long run.

First, to sustain the pine overstory for the foreseeable future, conditions must permit the recruitment to the canopy. For naturally regenerated pine stands, the key factors to ensure adequate regeneration include an ample seed supply, an acceptable seedbed, and sufficient amounts of limited resources such as light, water, and nutrients (Shelton and Cain 2000). Seed production and seedbed conditions generally affect the initial establishment of regeneration, while its subsequent development is largely determined by the amount of limited resources that are available to established seedlings. These regeneration factors are also under a varying level of silvicultural control. For example, both loblolly and shortleaf pine tend to experience a bumper seed crop, a seed crop failure, and three average seed crops during a 5-year period (Cain and Shelton 2001). Although silviculturists can do little to modify this natural variation, they can determine the number, size, vigor, and quality of the seed-producing trees that occupy the site. In contrast, seedbed conditions and the resources available to the species targeted in regeneration are more easily modified by tools such as site preparation, competition control, and harvesting.

Some of the factors that our silvicultural experiences have found to affect pine regeneration can be contrasted for the RRNA, where the pine component is not being sustained (Cain and Shelton 1996), and the adjacent Good Farm Forestry Forty, with its stable pine dominance. These differences did not arise from seed limitations. Pine seed production was ample in both areas (table 2). Historically, seed production in the unmanaged RRNA has exceeded that of the Good Forty by an average of about 25 percent. This difference was mainly due to exceptionally high production in the RRNA during bumper years. The effects of stand management are more apparent by considering the median value for seed production, where the Good Forty exceeded that of the RRNA by three times.

**Table 3—Density of pine regeneration in the Reynolds Research Natural Area (RRNA) and Good Farm Forestry Forty on the Crossett Experimental Forest**

| | Seedlings[b] | | Saplings | |
|---|---|---|---|---|
| Year[a] | RRNA | Good Forty | RRNA | Good Forty |
| | *per acre* | | *per acre* | |
| 1982 | 8[c] | 1,210 | 0 | 80 |
| 1993 | 733 | 6,920 | 0 | 480 |
| 2001 | 110 | 825 | 0 | 239 |

[a] Sampling methods vary from sixty 0.002-acre subplots to one hundred 0.001-acre subplots.

[b] Seedlings have d.b.h. <1 inch; saplings have d.b.h. of 1 to 3 inches.

[c] Does not include seedlings <0.5 feet tall.

Likewise, seedbed conditions in the two areas also were found to be similar. Both areas consisted of a litter seedbed with a depth of about 1 inch (table 2). However, the litter depth reported for the Good Forty in table 2 was measured 4 years after the most recent harvest. Logging has both positive and negative effects on the germination of pine seeds. Harvesting creates favorable conditions by displacing forest floor litter and exposing mineral soil, but it also creates an unfavorable seedbed in certain areas covered by logging debris. Shelton and Cain (2000) reported that typical seedbed conditions following harvesting of the Good Forty was 40 percent undisturbed litter, 30 percent disturbed litter, 25 percent logging debris, and 5 percent exposed mineral soil.

The biggest difference in the conditions for regeneration between the RRNA and Good Forty was expressed in light levels near the ground, which averaged 4 percent of full sunlight in the RRNA compared to 66 percent in the Good Forty (table 2). Even though loblolly and shortleaf pine seedlings are moderately shade-tolerant during their first few years, seedlings become more intolerant to shade as they develop. Thus, the low light environment under the relatively continuous, dense canopy of the RRNA strongly limits pine regeneration. Pulses of pine seedlings can establish in the RRNA during years with high seedfall and ample summer moisture, but these seedlings die long before reaching sapling size (table 3). In contrast, pine canopy recruitment is continuous in the Good Forty, where enough seedlings grow into saplings and saplings grow into merchantable trees to sustain the pine overstory.

The favorable light environment for the overstory recruitment of pine was maintained in the Good Forty by periodic harvests and repeated control of non-pine competing vegetation, principally using selective herbicides. These silvicultural activities have virtually eliminated merchantable hardwoods in the Good Forty, while the RRNA in comparison had 68 square feet per acre of hardwood basal area (table 3). Due to their broad leaves and large crowns, hardwoods generate about twice the level of shade as do pines per unit of basal area (Guo and Shelton 1998), so the acceptable level of hardwoods dispersed amongst the pines is inherently low. A basic tenet regarding competition control is that as site quality increases, the aggressiveness of competition control must also increase (Shelton and Cain 2000).

In addition to its impact on pine regeneration, the dense hardwood under- and midstory of the RRNA has affected other ecosystem properties. Traditionally, uneven-aged stands have a much more open canopy structure than plantations because uneven-aged stands are managed at lower stocking levels. This openness, once prevalent in the presettlement landscapes, permits certain ecosystem attributes not possible in intensively managed stands. For instance, with some minor modifications to traditional uneven-aged practices (for example, retention of large red heart infected pines, reducing the density of the midstory near cavity trees), sustainable RCW clusters can be incorporated. While the RRNA contains some of these attributes (for example, widespread occurrence of red heart in large pines), there are no active nest clusters in this stand. Even though it can be argued that the perpetuation of the RCW clusters in the Good Forty has been made possible, in part, by the use of nest box inserts, without the open nature of the uneven-aged stands of the CEF, these clusters would not have been able to persist.

Because management for old-growth-like conditions in pine-dominated forests implies the direct manipulation of the physical environment, there is considerable flexibility in how regeneration is achieved. As an example, the successful regeneration of pine in the Good Forty involves regulation of the overstory pine through volume-guided harvests typically conducted about every 5 years. Ideally, harvests are scheduled so that the volume in merchantable trees does not exceed 7,000 board feet per acre, which is the observed threshold level at which the overstory competition begins to unacceptably suppress recruitment (Baker et al. 1996). Without the ability to recruit new pines to the canopy, any uneven-aged silvicultural system intended to perpetuate a pine overstory would quickly fail. Harvesting, seedbed disturbance, and chemical and/or fire-based competition control are necessary to ensure viable pine recruitment. Even supplemental planting may prove to be the best strategy under certain conditions.

## DEAD WOOD MANAGEMENT

Overstory attrition, whether in intensively managed seed-tree or uneven-aged stands or unmanaged old-growth, is a continual process. Under most circumstances, large crop trees are very exposed, and hence particularly susceptible to mortality agents such as ice storms, lightning, or windthrow. Losses to bark beetles and other insect pests, disease, wildfire, and logging damage further reduce the number of canopy pines that must eventually be replaced. While it is possible to mitigate these losses with well-planned harvest entries, salvage of dead or declining trees, and other protective techniques, there is no way to eliminate tree mortality.

To some degree, mortality losses are more than just a cost of doing business, they are an ecological necessity. For instance, without dead trees (or the loss of large parts of live trees), it is impossible to accumulate coarse woody debris (CWD), a critical habitat element that serves many vital ecosystem functions (Harmon et al. 1986, Spetich et al. 1999, Van Lear 1996). CWD volumes tend to be higher in unmanaged forests. When last measured, the RRNA exceeded 1,700 cubic feet per acre of CWD, compared to 470 cubic feet per acre in the occasionally salvaged LWDF and only 214 cubic feet per acre in managed stands on the CEF (Bragg 2004b, Zhang 2000). Conceivably, an intensively cultured stand with continual salvage and high rates of product utilization may have almost no CWD. This is a desirable outcome when fiber production is the primary goal, but an unwanted simplification when managing for old-growth-like conditions (Harmon et al. 1986, Spetich et al. 1999).

In the end, a stand managed for old-growth-like conditions needs to retain a large quantity of CWD—perhaps not to the extent seen in the RRNA, but more than that found in conventionally managed stands of mature pine timber. Salvage operations to remove dead and dying trees should be limited to circumstances where either an insect or disease outbreak threatens management objectives, or where safety factors override environmental goals (for example, along roads, trails, campsites, near buildings). Otherwise, moribund trees should be left to expire on their own accord. Snags should be allowed to accumulate and fall. The less than complete utilization of all the trees on these sites is not necessarily a bad thing.

## ANTICIPATED CHALLENGES

Even though we expect this silvicultural system to work, a number of challenges in its implementation and long-term success are expected. Certainly, total fiber and sawlog volume production will be lower under this strategy when compared to more conventional treatments such as uneven-aged silviculture. Logistical issues will also arise. For instance, marking the appropriate pines for removal in harvests will take additional training to ensure that the desired ecosystem attributes are retained. We also expect there to be some difficulty in getting loggers to harvest the stands without excessively damaging some of the residual trees and the pine regeneration, as most are no longer accustomed to cutting uneven-aged stands.

While these challenges can be addressed through additional training and discussions (coupled with close monitoring), other factors are harder to control and may require modifications to management strategies over time. As an example, shortleaf pine is noticeably harder to regenerate than loblolly on the UWGCP. This tendency is likely due to long-term decreases in shortleaf pine overstory density from discriminatory harvesting and shifts in disturbance regimes from one driven by fire (favoring shortleaf) to one influenced primarily by logging and land clearing, which favors the reproductive proclivity of loblolly. Hence, it may be necessary to facilitate shortleaf pine during the canopy recruitment stages of stand development by discriminating against loblolly. Even this may still not produce the desired outcome of significantly greater shortleaf canopy representation.

## CONCLUSIONS

Using these lessons, we believe the productive potential and resilience of mixed loblolly/shortleaf pine forests can be adapted to create functional examples of old-growth-like stands capable of sustainably producing both timber and non-timber outputs. Although considered shade-intolerant, both loblolly and shortleaf pine possess characteristics that make them conducive to the creation and maintenance of old-growth-like conditions. These include their moderately long-lived nature, adaptations for fire, rapid growth on a wide range of soils and sites, favorable timber characteristics, an ability to recover well from logging and weather damage, response to release following suppression, and the ease in which loblolly and shortleaf pine regeneration is secured. Fortunately, our conventional silvicultural tools are exactly the instruments of change required to take advantage of these characteristics.

In addition to the conduciveness of the primary overstory species involved, there are less direct lessons from our long-term silvicultural research that can be adapted for more successful restoration projects. For instance, we have found that managing for a particular ecosystem element, such as the stand openness required to regenerate a pine overstory in uneven-aged stands, also encourages structural and compositional characteristics that can contribute desirable habitat for wildlife species (Conner et al. 2002, Thill et al. 2004). Translated to old-growth-like stand management, this suggests that more of the physical and biotic environments will be restored, furthering the value of the ecological rehabilitation of the landscape.

A tentative blueprint for the implementation of restoration silviculture in pine-dominated forests in the UWGCP proposes to use a combination of timber harvesting, competition control, and adaptive management to restore existing stands into a similar composition, structure, and dynamics as the old-growth stands that once characterized the region (Bragg 2004a). Any such design would not have been possible without the decades of long-term experiments and demonstrations to illustrate how these forests behave under certain controlled conditions. This is a powerful argument for the continuation of the use of experimental forests and long-term projects in the U.S. Forest Service's research and development program.

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# Adaptive Management of Young Stands on the Tongass National Forest

*Michael H. McClellan*


## ABSTRACT

The idea of adaptive management as a means of improving natural resource management has been around since the 1970s, but to date there have been relatively few examples of fully successful adaptive management efforts in forest management. In 2001, the Tongass National Forest and the Pacific Northwest Research Station began a series of adaptive management studies aimed at improving the management of young, even-aged conifer stands for multiple values: the Tongass-Wide Young-Growth Studies, or TWYGS. This effort is notable both for its scale and for its successes to date—the Tongass devoted its entire timber stand improvement program for two years to the establishment of the first three operational scale experiments, each replicated widely across southeast Alaska, and a fourth experiment has subsequently been implemented. The experiments are continuing, but the successes to date in assessing the problem, and designing and implementing the studies are largely due to capitalizing on the respective strengths of management and research, and could serve as a model for answering important management questions elsewhere.


**Keywords**: adaptive management, young growth, silvicultural treatments, wildlife habitat

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# INTRODUCTION

The 17-million acre Tongass National Forest is our nation's largest national forest and it includes over 85% of the forest land in southeast Alaska. In the past five years, the Tongass has embarked on an ambitious adaptive management program to improve its management of young stands for wood production and wildlife habitat. It is too early to judge the full success of this program, but the early steps in the adaptive management cycle have been successfully completed and they provide useful examples of adaptive management at work at a regional scale.

Large-scale timber harvesting on the Tongass began in the 1950s and created 430,000 acres of young, even-aged stands. This is a relatively small part of the total area of the Tongass, but harvesting tended to be focused on the more productive and accessible stands along shorelines, valley bottoms, and gentle, lower elevation slopes. Old-growth stands in these areas have high value for wildlife species such as the Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) because they have an abundance of understory forage plants and in winter they have less snow cover than higher elevation or more open sites. The dense, even-aged conifer stands that typically develop after clearcut logging, however, are recognized as having negative consequences for wildlife and fish (Wallmo and Schoen 1980; Schoen et al. 1988; Thedinga et al. 1989; Hanley 1993; Dellasala et al. 1996), primarily due to the loss of understory plants. The moderate temperatures and abundant rainfall of southeast Alaska foster abundant natural regeneration of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and other conifers following clearcutting. Within ten years of clearcutting, newly established conifers begin to overtop the shrubs and crown closure may be complete by 25 years. Few understory plants can survive in the low light levels of this stem-exclusion stage, and this condition may persist until the stand reaches 120-150 years of age (Alaback 1982, 1984; Hanley 2005).

Throughout the 1990s, land managers on the Tongass implemented a variety of silvicultural treatments in an attempt to promote the growth of understory plants. Their motivation was to improve habitat conditions for the Sitka black-tailed deer, a species valued as a game animal, subsistence food source, and prey for large carnivores such as the Alexander Archipelago wolf (*Canis lupus ligoni*) and bears (*Ursus americanus* and *U. arctos*). Most of the treatments were variations of precommercial thinning and they often included wide or variable spacing, unthinned patches or corridors, and sometimes gaps where all trees were cut. These operational field trials rarely followed the principles of experimental design and lacked appropriate controls, replication, and random assignment of treatments. Each ranger district worked independently and there was no forest-wide coordination of testing. Follow-up monitoring, evaluation, or reporting of these trials was done in only a few cases. By the end of the 1990s, it was apparent that this approach was not working and that reliable information would come only from a more organized and coordinated effort. The Tongass consulted with researchers from the Pacific Northwest Research Station and representatives from other federal and state agencies, and they decided to use forest-wide adaptive management studies to evaluate their young-growth silvicultural options. This action was aided by two developments in the late 1990s. First, the Tongass transformed its organizational structure from three areas—Chatham, Stikine, and Ketchikan, each having a Forest Supervisor—to a single administrative unit with one Forest Supervisor. This made it much easier to apply a uniform approach forest wide. Second, there was significant scientist involvement in the revision of the Forest plan from 1995 to 1997 (Everest et al. 1997).

Adaptive management is more than simply learning from experience or trial and error. It is a formalized, systematic, and deliberate approach to learning from management actions (Nyberg 1999). The concept was developed during the 1970s (Holling 1978) and 1980s (Walters 1986), and there have been attempts to develop these concepts and apply them to forest management questions in the Pacific

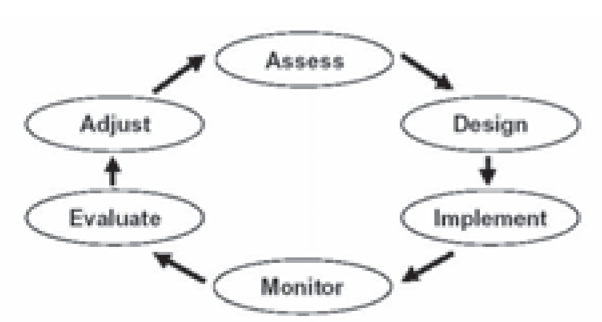


*Figure 1— The adaptive management cycle of activities (from Nyberg 1999).*

Northwest and elsewhere (Bormann et al. 1994, Stankey et al. 2005). The system of adaptive management can be viewed as a continuous evaluation of management alternatives based on a repeating cycle of activities (Figure 1): assess the problem, design a management experiment, implement the experimental treatments, monitor the response to the treatments, evaluate the monitoring data, and, finally, adjust management policy and actions in line with the adaptive management findings (Nyberg 1999). There have been many attempts to apply adaptive management approaches to forest management issues, not always successfully (Nyberg 1999, Stokstad 2005, Marmorek et al. 2006).

The process of adapting management activities in light of new knowledge may proceed in three ways (Walters and Holling 1990): (1) an evolutionary or trial-and-error pathway; (2) passive adaptive management, where existing knowledge is used to select a single "best" treatment to test; or (3) active adaptive management, where uncertainty regarding outcomes is recognized and a range of alternative treatments are tested concurrently. The second, passive, approach is institutionalized in the concept of "best management practices." The Tongass chose to use the active approach, even though it would require more resources to implement multiple treatments.

There are other means of learning new ways to manage. Historically, most silvicultural studies have employed relatively small plots (0.1 to 1 acre) and focused on a small group of resource values—an example of this on the Tongass would be the Cooperative Stand-Density Study (DeMars 2000). More recently, silvicultural studies worldwide have addressed a broader range of resource management objectives, and in doing so, have typically employed operational scale treatment units (Peterson and Monserud 2002, Szaro et al. 2006). An example of this approach on the Tongass would be the Alternatives to Clearcutting study (McClellan et al. 2000). Both of these approaches contain elements of the adaptive management approach, but they differ in that they are typically researcher-driven and are implemented generally outside of the day-to-day operations of the land management agency. The present study, and adaptive management studies in general, can be distinguished by the fact that learning as an objective is incorporated into the normal program of work.

## FIRST STEP: ASSESSMENT OF YOUNG-GROWTH MANAGEMENT OPTIONS

A significant body of scientific research has documented the negative effects of the stem-exclusion stage on understory plant communities (Alaback 1982, 1984; Hanley 2005). What has not been clear is the best method of mitigating ill effects, either by shortening its duration or lessening its intensity. Managers and researchers discussed various options in a series of workshops, white papers, and field trips during 2000-2001, culminating in an interagency meeting in November 2001 attended by representatives from the Tongass, the Alaska Region of the Forest Service, the PNW Research Station, the U.S. Fish and Wildlife Service, and the Alaska State Department of Fish and Game. The group was asked to:

1) prioritize young-growth management information needs
2) develop standardized young-growth silvicultural prescriptions for evaluation
3) develop implementation protocols for each prescription that were practical from a management viewpoint as well as being consistent with good experimental study design (i.e., including controls, randomization, and replication)
4) develop a plan for peer review of prescriptions and protocols

As part of this process, the group reviewed the existing silvicultural information, including new results regarding precommercial and commercial thinning, pruning, and the development of mixed stands of red alder (Alnus rubra Bong.) and conifers. Since 1950, precommercial thinning has been performed on approximately 204,000 acres of young-growth stands on the Tongass, roughly one-third of the available acres (McClellan 2005). Typically, thinning was used as a method to increase merchantable wood outputs, but other possible benefits include delaying the onset of the stem exclusion stage, increasing understory plant diversity, and improving wildlife habitat. Attempts to reestablish understory herbs and shrubs through thinning young-growth conifer stands have met with mixed success, however. For example, Deal and Farr (1994) found that thinning of young even-aged stands promoted tree growth but not herbaceous colonization, and that wide spacing resulted in a second episode of western hemlock regeneration.

As part of the Alaska Region's Second-Growth Management Program (SGMP), five demonstration sites in southeast Alaska were commercially thinned in 1984-85. The purpose of the study was to evaluate the ability of commercial thinning to enhance wood production, the development of understory vegetation, and the availability and quality of Sitka black-tailed deer forage. When the SGMP sites were examined in 1998, researchers found that the strip and strip + individual tree selection treatments had the highest total understory biomass, but most of the biomass consisted of conifer regeneration (Zaborkske et al. 2002). The individual tree selection treatment had less understory biomass per acre but over half the biomass was shrubs, ferns, and forbs which had greater nutritional value for deer. Estimates of deer-forage availability showed that this treatment created better forage resources for deer than did the other treatments and that summer forage availability was similar to the values estimated for old-growth forest (Zaborkske et al. 2002).

In the early 1990s, five field trials were established in southeast Alaska to monitor the response of western hemlock and Sitka spruce to thinning and pruning (Petruncio 1994). Follow-up monitoring showed that developing clear wood in Sitka spruce was doubtful due to epicormic branching (Deal et al. 2003). Although pruning may not fully achieve wood-quality objectives, it may have added value for habitat objectives. Recent observations of Petruncio's field trials suggest that pruning was more effective than thinning alone in promoting understory diversity and abundance (unpublished data on file at the Juneau Forestry Sciences Laboratory). Understory response was not an objective of this study, so we can draw only limited inferences from it, but it is reasonable to conclude that the pruning increased understory vigor by admitting increasing sidelight from low sun angles.

Recent studies of mixed red alder-conifer stands have indicated that successional pathways alternate to the stem exclusion stage (i.e., loss of understory vegetation) are possible following clearcutting in southeast Alaska. Logging practices used after 1970 consisted of high-lead log yarding in which trees are carried through the air and soil is not disturbed. After this type of logging, a dense, uniform conifer stand lacking understory plants develops. Earlier methods of logging (prior to 1970) resulted in considerable soil disturbance which made excellent seed beds for red alder to colonize (Ruth and Harris 1979). In contrast to the dense, uniform conifer stands created following high-lead logging, alder-conifer mixed young-growth stands have a species-rich and highly productive understory with a biomass similar to that found in old-growth stands. This species-rich understory has been found to persist for as long as 45 years after logging. Understory richness has been shown to be highest in stands with 18-51% alder and lowest in pure conifer or pure alder stands (Hanley 1996; Hanley and Hoel 1996; Deal 1997; Hanley and Barnard 1998).

## SECOND STEP: DESIGN OF THE TONGASS-WIDE YOUNG-GROWTH STUDIES (TWYGS)

The interagency group of scientists and managers that met in 2001 designed three experiments to test the treatments suggested by their assessment. The primary research objectives set by the group are to assess the response of understory plants (herbs and shrubs), overstory trees, and slash loading to several silvicultural treatments, including altering stand composition by artificially regenerating red alder, pruning, and precommercial thinning. A fourth experiment was added later to compare thinning by conventional methods and by girdling. The fourth experiment was designed more informally than the first three, largely through discussions between PNW researchers and Tongass managers.

All the experiments share a common set of guidelines. First, the group decided that the treatments would lend themselves to practical application within the Tongass stand improvement program. Second, the treatments within an experiment should differ sufficiently to yield widely differing treatment effects—the designers frequently stated they were looking for "bushel basket" differences among treatments. Third, the treatments would be applied at an operational scale, generally ten acres or more per experimental unit. Fourth, the experiments would be widely replicated across the Tongass, twenty being the target number of replicates. This study is intended to last a minimum of 20 to 30 years in order to adequately assess long-term responses to silvicultural treatments and responses will be assessed at five-year intervals after treatment.

At present TWYGS includes four experiments:

1. A test of mixed hardwood/conifer stands, created by planting red alder at low (20 TPA) and high (80 TPA) densities in 0 to 5 year-old stands.
2. A test of moderate (222 TPA) and heavy (135 TPA) precommercial thinning of 15 to 25 year-old stands;
3. A test of moderate (170 TPA) precommercial thinning combined with two pruning treatments (25 or 50% of the trees were pruned), in 25 to 35 year-old stands;
4. A test comparing girdling and conventional thinning, with and without slash treatment, in stands over 35 years-old.

The 0-5 year age class was chosen for experiment 1 because conifer regeneration was assumed to be small enough to allow for the successful planting and survival of red alder seedlings. The 15-25 year age class was chosen for experiment 2 because this age is the normal precommercial thinning period. The 25-35 year age class was chosen for experiment 3 because this is the typical age for pruning—with or without additional precommercial thinning. Unthinned stands over 35 years-old were chosen for experiment 4 because they frequently occur in areas where commercial wood-production is not allowed, such as in beach-fringe stands. These stands have developed past the normal precommercial thinning stage and the large tree size and dense, interlocking crowns make it difficult

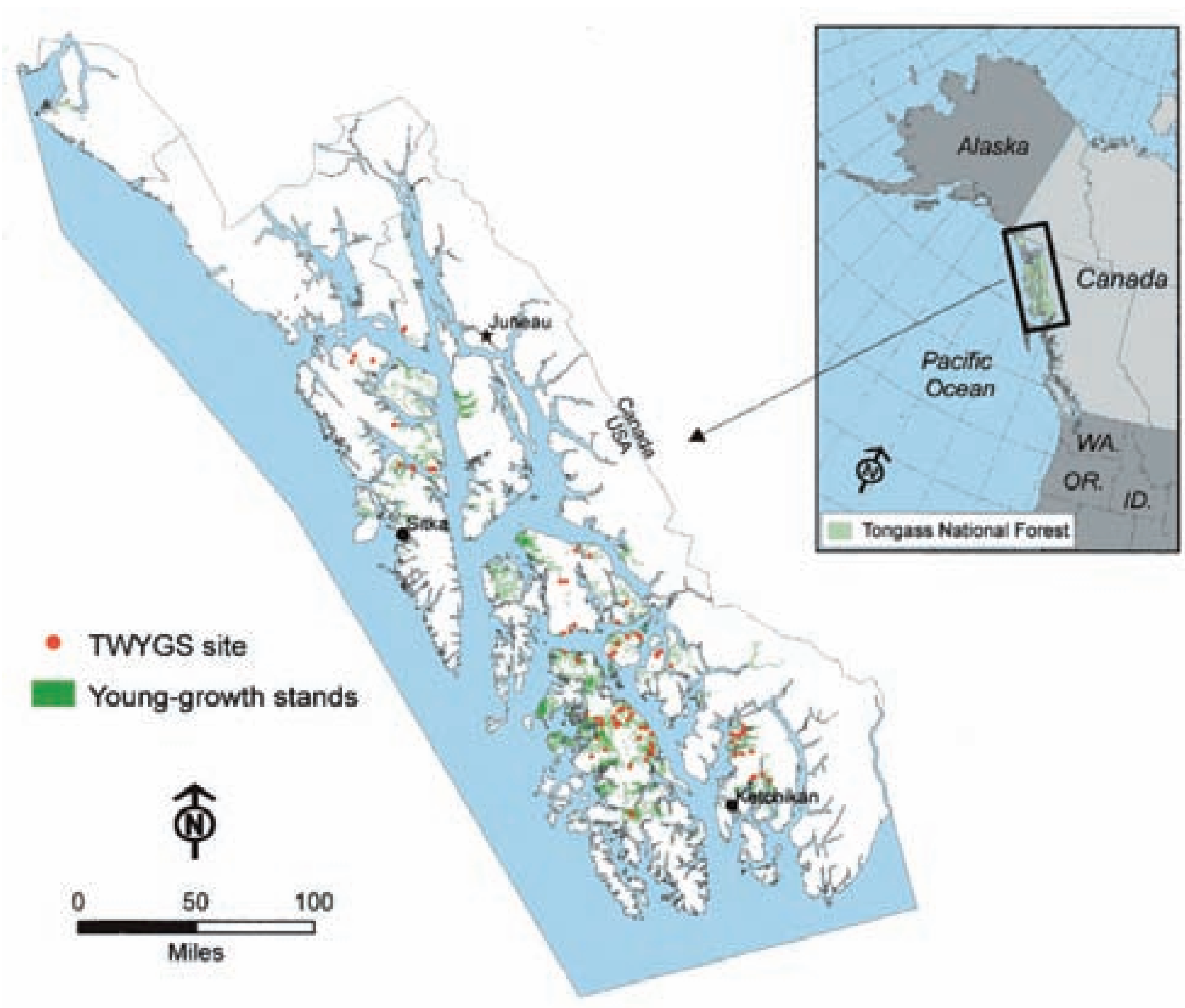


*Figure 2— Map of southeast Alaska showing distribution of young-growth stands and TWYGS experimental sites.*

to fell the cut trees and the thinning generates enormous slash loads. Girdling may avoid the operational and safety issues associated with cutting and may deliver slash to the forest floor over an extended period, thus reducing peak slash loads.

Each of the four existing experiments uses a randomized complete block design, with a target of 20 blocks (replicates) per experiment, distributed across the Tongass (figure 2). An untreated experimental unit is included in each block.

## THIRD STEP: IMPLEMENTATION OF TWYGS

Tongass personnel screened and selected sites based on criteria developed by the design group. Candidate sites needed to be in the target age range, of moderate to high productivity, and at elevations below 1200 ft. Stands selected for treatment were to have relatively uniform productivity, stand density, and stand composition within the stand, but this was not always the case. Ranger district crews laid out the experimental units, typically dividing a single harvest unit into three to five experimental units. The scale of each experiment is impressive: because each experimental unit has a minimum of five to ten acres. The four experiments have from 17 to 23 replicates (blocks) and each of the four experiments covers 520 to 1773 acres in total. Once the units were laid out and the treatments were assigned randomly, Tongass personnel prepared and administered the treatment contracts necessary for the treatments to be applied by private silvicultural contractors. Treatments began in 2002 and all were completed by 2006. The silvicultural treatments were applied within the forest's normal program of work and it has been estimated that the adaptive management approach increased administrative costs by less than five percent[1].

[1] Russell, J.M. 2007. Personal communication. Silviculture Program Manager, Tongass N.F., Sitka, AK.

## FUTURE STEPS: MONITOR, EVALUATE, AND ADJUST

The Tongass young-growth studies have passed through the first three of Nyberg's (1999) stages—assessment, design, and implementation—and are now entering the monitoring stage. PNW researchers have the primary responsibility for monitoring and evaluating treatment responses, including the design of measurement protocols, hiring and managing field data collection crews, managing data, and analyzing and reporting results. Most of the funding for these efforts, however, is provided by the Tongass. Just as the implementation phase took advantage of the experience and skills of NFS managers in working with private contractors to accomplish targets, the monitoring and analysis of responses relies on the traditional strengths of researchers to produce scientifically credible results. Once results are available and evaluated, the Tongass will have an opportunity to adjust its management at both the project and forest-plan levels. Based on our past experience, we expect that future adjustments will be made through a collaborative process involving NFS managers, PNW researchers, and interested parties from other state and federal agencies.

During the 2007 field season, we began monitoring with the measurement of responses in experiment 2, the precommercial thinning study. This is a critical point in this study, because effectiveness monitoring is often a low priority for land managers—there is an institutional bias to treat acres and meet targets, but when funds are limited, monitoring may be seen as expendable. By including researchers in the TWYGS program, the Tongass has gained a partner strongly motivated to monitor, evaluate, and report results, and we expect that researchers will be strong advocates for completing the adaptive management cycle.

The TWYGS treatments were designed to produce large differences in response between treatments—differences that should be readily perceived by an observer in the field—so it is possible that the success or failure of the treatments could be judged by a qualitative, anecdotal approach. A quantitative, statistically defensible assessment of the treatment responses, however, will better provide a sound, scientific basis for young-growth management in southeast Alaska, and will provide land managers with critically needed information on the relative costs and benefits of these treatments.

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# Yellow-Cedar Decline: Conserving a Climate-Sensitive Tree Species as Alaska Warms

*Paul E. Hennon, David V. D'Amore, Dustin T. Wittwer, and John P. Caouette*

## ABSTRACT

Yellow-cedar is a valuable, long-lived tree species that has been dying in concentrations on 500,000 acres of forest land for about 100 years in southeast Alaska. Recent research implicates climatic warming, specifically warmer springs and reduced insulating snow pack, which initiates premature dehardening and predisposes trees to spring freezing injury and death. Knowledge of the likely mechanism and spatial occurrence of the decline informs decisions about where on the landscape to favor active cedar conservation and management. Scientists and managers are devising a conservation strategy for yellow-cedar in the context of this decline problem. The strategy involves shifting more timber harvesting to the dead yellow-cedar forests, where most wood properties are maintained even 80 years after tree death, and then favoring other tree species on those sites. The strategy also includes restoration and facilitated migration of yellow-cedar to cooler sites where decline is not predicted to occur as the climate warms. These cooler areas of favorable habitat are where spring snow is consistently present or in well-drained soils where deeper roots escape freezing injury. Because of yellow-cedar's low reproductive capacity, silvicultural practices such as site preparation, planting, and thinning are being used on favorable sites to maintain populations of this valuable tree species.

**Keywords**: Chamaecyparis, yellow-cedar, forest decline, snow, climate change, conservation.

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# INTRODUCTION

Yellow-cedar (***Chamaecyparis nootkatensis (D. Don) Spach)***[1], is a commercially, ecologically, and culturally important tree species in Alaska and British Columbia. The species range extends from the California-Oregon border in forested montane areas to Prince William Sound in Alaska. It is limited to high elevation throughout most of its range, except in Alaska where yellow-cedar grows from near timberline down to sea level (Harris 1990). It is these lower elevation forests in the northern portions of it's range where extensive mortality exists (Fig. 1).

Yellow-cedar is a defensive, slow-growing tree with few natural enemies and is capable of achieving great longevity (Jozsa 1992). The chemical deterrents to pathogens and insects in the foliage and heartwood are examples of this defensive nature. Reproduction capacity is low, leading to poor natural regeneration in some areas. The tree's resources are routed to chemical defenses rather than rapid growth or prolific reproduction. The extensive mortality problem in Alaska poses challenge of discovering some unique vulnerability of this tree species.

The landscape of southeast Alaska has complex geologic origins (Conner and O'Haire 1988) where accreted terrain and faults created many islands and deep fjords that bisect the mountainous mainland. The current climate of southeast Alaska is hyper-maritime, with abundant year-round precipitation, no prolonged dry periods, and high summer temperatures mediated by abundant rain and cloud cover. Winter temperatures average near freezing for the winter months at many weather stations, creating widely variable amounts of winter snow. This near-freezing threshold winter temperature regime suggests that modest changes in climate could dramatically influence snow deposition and accumulation.

*Figure 1— Intensive yellow-cedar decline on Chichagof Island near sea level in southeast Alaska.*

Without fire as a disturbance factor, the region supports the largest temperate rainforest in the world, which extends south through British Columbia. Cool temperatures, short growing seasons, and saturated soils slow decomposition of plant material, resulting in peat formation. Slope and soil properties, including peat accumulations, produce gradients of soil drainage that are largely responsible for driving forest productivity from large-stature, closed canopy forests on well drained soils to stunted, open canopy forests on saturated organic soils (Neiland 1971). Yellow-cedar has been competitive on these latter wet soils, typically reaching its greatest abundance here relative to other trees.

This paper represents a continuing effort to update and synthesize knowledge on yellow-cedar decline relevant to forest management by building from ongoing studies, published research, and previous summaries (Hennon and Shaw 1994, Hennon and Shaw 1997, Hennon et al. 2006). In this paper, we illustrate the probable mechanism leading to tree death, supply evidence at different scales supporting the rationale, and provide conservation suggestions to maintain the species in southeast Alaska.

[1] The taxonomic status of yellow-cedar is in question because of the discovery of a tree species with close phylogenetic affinity in northern Vietnam, ***Xanthocyparis vietnamensis*** Farjon & Hiep. (Farjon et al. 2002). Yellow-cedar joins the Vietnamese tree in this newly erected genus as ***Xanthocyparis nootkatensis*** Farjon & Hiep. Whether that name, or the older name ***Callitropsis nootkatensis*** (D. Don) Örest. (Little et al. 2004), is adopted will be determined at the next International Botanical Congress in 2011 (Mill and Farjon 2006).

## YELLOW-CEDAR DECLINE

Yellow-cedar decline occurs at several thousand locations, that total approximately 200,000 hectares (1/2 million acres), in southeast Alaska (Wittwer et al. 2004) and a smaller amount in nearby British Columbia (Hennon et al. 2005). Yellow-cedar mortality far exceeds that of other tree species. In these forests, approximately 70 percent of yellow-cedar mature trees are dead, but some areas (e.g., Fig. 1) have even more intensive tree death (Hennon et al. 1990b, D'Amore and Hennon 2006). Most of the forest decline is on wet soils (Johnson and Wilcock 2002) where yellow-cedar was previously well adapted and competitive (Neiland 1971, Hennon et al. 1990b).

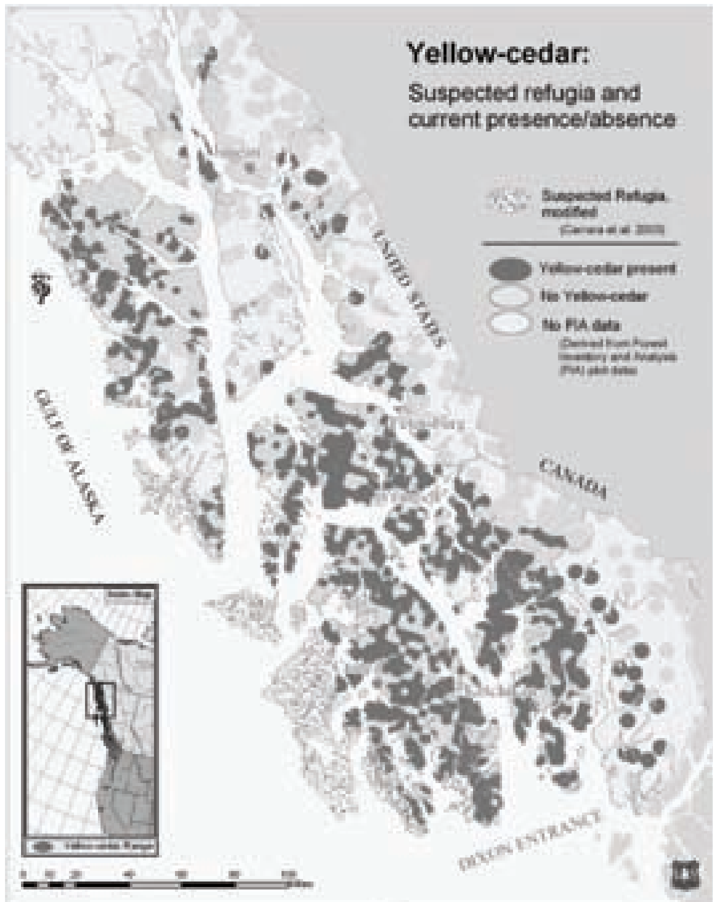


*Figure 2— The occurrence of yellow-cedar (dark polygons) in southeast Alaska based on Forest Inventory and Analysis plot data. Areas where yellow-cedar was absent are depicted with lighter polygons; unsampled areas shown as very light grey. Also represented are areas of suspected refugia (stippled) (Carrarra et al. 2003), which may represent seed sources for post-glacial migration and colonization.*

We examined trees in varying stages of dying by evaluating tissue death in their roots, bole, and crown to develop a general sequence of these symptoms (Hennon et al. 1990d). Initially, fine roots died, then small diameter roots died, followed by formation of necrotic lesions on coarse roots, and finally necrotic lesions spread from dead roots vertically from the root collar up the side of the bole. Crown symptoms occur after the early root symptoms. Crowns typically died as a unit with proximal foliage dying first, and then as trees finally died, distal foliage died. Note that this sequence of foliar symptoms differs from acute freezing injury to seedling and sapling foliage where newer, distal foliage is killed first. Generally, the study of symptoms suggested a below-ground problem as the cause of tree death. A number of types of organisms were evaluated as potential pathogens, but each was ruled out by inoculation studies or by the lack of association with symptomatic tissue or dying areas of the forest: higher fungi (Hennon, 1990, Hennon et al. 1990d), Oomycetes (Hansen et al. 1988, Hamm et al. 1988), insects (Shaw et al. 1985), nematodes (Hennon et al. 1986), viruses and mycoplasmas (Hennon and McWilliams 1999), and bears (Hennon et al. 1990a). Thus, the mechanism leading to tree death appeared to be underground, but not directly related to any biological agent.

## INFLUENCE OF CLIMATE

### Historical climate and cedar occurrence

An examination of the past climate of southeast Alaska and the historic abundance of yellow-cedar should offer clues about the climate preferences of the species, and could perhaps even reveal past episodes of decline. The last glacial maximum in southeast Alaska extended until between 16,000 and 12,000 years BP, before which southeast Alaska was thought to have been covered by ice (Hamilton 1994). Recent discovery of human remains and bones of large predators in caves on Prince of Wales Island in Alaska (Dixon et al., 1998), as well the current distribution of several plants and animals, indicate the existence of sizable low elevation refugia in the southwestern portion of Alaska's panhandle (Fig. 2) (Carrarra et al. 2003) during that glacial maximum. Here, trees and other subalpine vegetation existed during the late Pleistocene and provided seed sources for subsequent re-colonization as glaciers receded.

Climate during the Holocene Epoch can be inferred by examining the composition of trees and other plants using pollen profiles taken from lake and peat sediments, including 17 sites investigated by Heusser (1952, 1960). Unfortunately, yellow-cedar was not included in the early pollen profile studies because, as Heusser (1960, Page 78) stated, the pollen of ***Chamaecyparis*** and some other species had, "fragility and non resistance to decay….it was decided they be omitted [from analysis]." Recent investigations that included cedar pollen indicate that ***Cupressaceae*** became abundant about 7,000 years ago (Banner et al. 1983, Hebda and Mathewes 1984). In southeast Alaska, cedars may have become prevalent about 5,000 years ago (Tom Ager, USGS, Pers. Comm.). Our restricted understanding of the current distribution of yellow-cedar suggests that it originated from refugia in the southwest portions of Alaska's panhandle (Fig. 2). Preliminary genetic analysis supports this contention (Ritland et al. 2001). Because of its limited reproductive capacity (Harris 1990, Pawuk 1993), the post-glacial spread of the tree has been very slow, but it is migrating to suitable habitat towards the northwest (Fig. 2) (Hennon et al. 2006) where colder winters appear to be more favorable.

The late Holocene (4500 years BP to 200 years BP) was moist and cool, which promoted rapid organic matter accumulation and provided favorable conditions for the expansion of yellow-cedar populations. A cooler shift within this period, known as the "Little Ice Age", occurred approximately 500 years ago. Although the influence of the Little Ice Age on climate in southeast Alaska is not clearly understood, advances and retreats of glaciers are consistent with a change in climate (Viens 2001). The end of the Little Ice Age in the mid to late 1800s was associated with warming temperatures and marked the onset of yellow-cedar decline (about 1880 to 1900, discussed below). Information on the ages of canopy-level yellow-cedar trees (i.e., nearly all > 100 years old, (Hennon and Shaw 1994)), suggests that the trees that died throughout the 1900s, and those that continue to die today, regenerated and grew into their dominant positions during the Little Ice Age. We speculate that yellow-cedar colonized low elevation sites during this period, flourishing with deeper winter snow packs and late spring snow melt.

**Onset and epidemiology of yellow-cedar decline**

The earliest report of yellow-cedar decline was by the hunter Charles Sheldon (1912) who in 1909 noted, "vast areas of rolling swamp, with yellow cedars, mostly dead." Also, yellow-cedar decline can be observed on aerial photographs taken by the US Navy in the late 1920s (Sargent and Moffit 1929). A snag (standing dead tree) classification (Fig. 3) system was developed, with associated time-since-death estimates (Hennon et al. 1990c), and used to reconstruct coarse changes in cedar populations through the 1900s as expressed by annual mortality rates. The remarkable decay resistant heartwood of dead yellow-cedar trees (Kelsey et al. 2005) allows them to remain standing for 80 to 100 years after death, making this reconstruction possible. Results suggest that onset of yellow-cedar decline occurred in about 1880 to 1900 on most sites where trees are still dying (Hennon et al. 1990b). The higher proportion of class 3 snags (primary and secondary branches retained, but twigs missing--see Fig. 3) indicates yellow-cedar mortality accelerated to even higher rates in the later half of the 1900s (Fig. 3). Thus, mortality is progressive in declining forests, which now contain long-dead trees, more recently-killed trees, dying trees, and some survivors which are mainly other tree species (Hennon and Shaw 1997). The older mortality is typically on the wettest soils and recently-killed and dying trees are frequently found on better-drained soils and on the perimeters of the dying forests. This slow spreading pattern of tree death occurs along a hydrologic gradient (Hennon et al. 1990b, D'Amore and Hennon 2006). An annual mortality rate slower than 0.4 or 0.5 percent, which occurred in the first half of the 1900s, would be expected in a slow growing, long-lived tree species such as yellow-cedar. Such a sustainable mortality, more or less in balance with regeneration and growth to canopy status, has not been determined for mature yellow-cedar, but presumably would be very low (Parish and Antos 2006). Another tree species with similar very slow forest dynamics, ***Sequoia sempervirens***, has annual morality rates of approximately 0.1% (Barnett 2005) or 0.2% (Busing and Fujimori 2002).

A current study on the dendrochronology (i.e., tree ring research) of live yellow-cedar trees in southeast Alaska reveals that they were growing well during the Little Ice Age, but showed a synchronous reduction of radial growth rate in the later portion of the 1880s and into the 1900s (Beier 2007). More results on long-term cedar dendrochronology and correlations of cedar growth with weather station data will be available soon from Beier and his colleagues at the University of Alaska, Fairbanks. A challenge in this

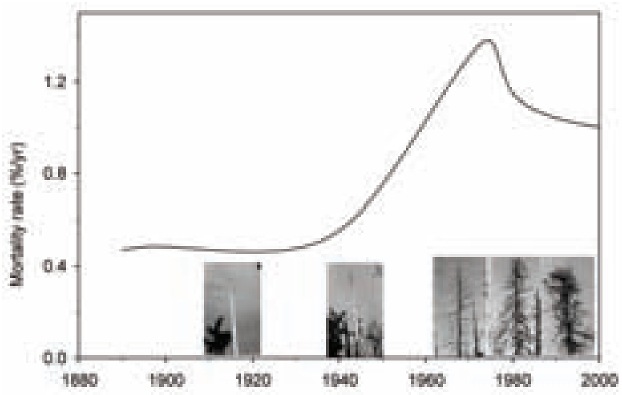


*Figure 3— Estimated annual mortality rate of yellow-cedar in declining forests. This reconstruction combines time-since-death results of the five snag classes shown (Hennon et al. 1990c) with ground plot data (e.g., snag class frequencies) to create a splined-curve response for mortality rates through the 1900s.*

research is to detect weather-induced episodes of tree injury, presumably before the growing season, in the context of weather patterns that influence annual radial growth during the growing season.

## THE LEADING HYPOTHESIS FOR THE CAUSE OF YELLOW-CEDAR DECLINE

The culmination of research on yellow-cedar decline led to a working hypothesis to explain tree death (Fig. 4). This scenario is too complex to be evaluated by a single study; thus, it has become the framework for an ongoing research program. Each of these interactions is evaluated with one or more studies on hydrology, canopy cover, air and soil temperature, snow, yellow-cedar phenology, and freezing injury to seedlings and mature trees. These topics are discussed in more detail elsewhere (Schaberg et al. 2005, D'Amore and Hennon 2006, Hennon et al. 2006).

The association of yellow-cedar decline with wet soils now has a reasonable explanation. Yellow-cedar trees growing on poorly drained soils have shallow roots. Exposure on these wet sites is created from open canopy conditions that allow for solar radiation to warm soil and shallow roots. Canopy exposure also promotes rapid temperature fluctuation and more extreme cold temperatures. These factors appear to work together resulting in root freezing as the primary injury mechanism to explain the cause of yellow-cedar decline.

An evaluation of seasonal cold tolerance of foliage on mature yellow-cedars and co-existing western hemlocks in open- and closed-canopy forests at several elevations (Schaberg et al. 2005) revealed strong seasonal tendencies for both species. In fall, yellow-cedars in open canopy settings were more cold tolerant than in closed-canopy settings, whereas western hemlocks appeared unresponsive to canopy conditions. In winter, yellow-cedar had cold tolerance to about -40°C, more cold tolerant than hemlock, and tolerant below any recorded temperature for the region. Susceptibility of yellow-cedar to cold temperatures develops in late winter and spring. Yellow-cedar foliage dehardened almost 13°C more than western hemlock between winter and spring, so that yellow-cedar trees were more vulnerable to freezing injury in spring than western hemlock (Schaberg et al., 2005). Also, trees above 130m elevation were more cold hardy than those growing below 130m. These results indicated that if freezing injury is an important factor in yellow-cedar decline, then damage to trees most likely occurs in late winter or spring.

The susceptibility of yellow-cedar to spring freezing injury has been the subject of study in British Columbia, with a focus on seedlings and rooted cuttings (Hawkins et al. 1994, 2001; Davradou and Hawkins 1998; Puttonen and Arnott 1994). Severe freezing injury to yellow-cedar seedlings growing in Juneau has been observed in recent

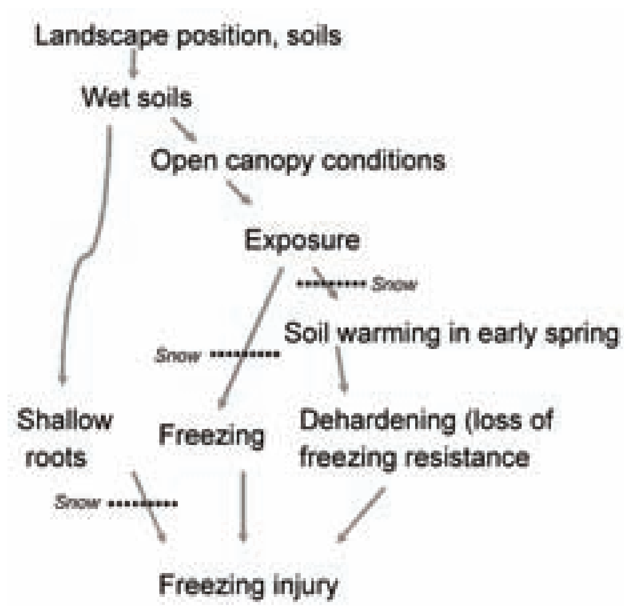


*Figure 4— Conceptual diagram showing the cascading factors which form the leading hypothesis for the cause of yellow-cedar decline. The manner in which snow disrupts this process, thereby protecting yellow-cedar, is illustrated (dotted lines).*

years, each time injury symptoms developed at the end of March or early April. The next step in this research was to study seedlings and evaluate late winter and early spring dehardening and cold tolerance of root and foliage tissue. Results (Schaberg et al., in press) demonstrate that initial injury is to roots, which were fully dehardened to a tolerance of about -5°C in February and March, earlier than expected. Foliar symptoms were delayed for about two months after root injury and only appeared when warm weather put transpiration demands on the seedlings. Seedlings whose roots were covered with perlite, used to mimic insulating snow cover, had complete protection and roots were not injured. All seedlings without this protection had severe root injury and died. Thus, this experiment on seedlings replicated the phenomenon of yellow-cedar decline, including root mortality leading to leading to whole-plant mortality, as well as protection from snow.

## SPATIAL EVALUATION OF YELLOW-CEDAR DECLINE

An evaluation of yellow-cedar decline at each of three spatial scales offers unique clues about the cause of yellow-cedar decline. Each scale shows close association of the absence of snow with decline, providing ideas for proactively managing the species. The three spatial scales include broad scale (~7x106 km2, regional--southeast Alaska), meso-scale (~800 km2, medium-sized island), and fine scale (~1km2; small watershed).

**Regional (broad) scale**

A complete distribution map of yellow-cedar decline for southeast Alaska was developed. It depicts more than 2,500 locations totaling over 200,000 hectares of dead and dying yellow-cedar forests (Wittwer, 2004) (Fig 5). This map was derived from sketch mapping from small aircraft, an approach that yields inexact locations and polygon boundaries. However, it is instructive to examine broad areas where decline is present or absent and relate any pattern to regional variation in climate. A previous use of the map illustrated that the forest decline aligns with warmer average winter temperature isotherms (Hennon and Shaw 1994), an early suggestion that climate was involved in the problem. Here, distribution of yellow-cedar decline is contrasted with the first detailed model of snow accumulation zones in southeast Alaska (Fig. 5). The snow accumulation model, developed by Dave Albert of The Nature Conservancy, is derived from PRISM data estimates of monthly temperature and precipitation (i.e., precipitation during months when mean temperature <+2°C). There is a close association between the occurrence of yellow-cedar decline and the lowest snow accumulation zone (Fig. 5); the three other zones of higher snow accumulation could not be visibly depicted on this grey scale map but appear in color elsewhere (Hennon et al. 2006).

Our yellow-cedar decline distribution map documents the occurrence of mortality in Alaska, but not in adjacent British Columbia. Recently, intensive areas of yellow-cedar decline were detected about 150 km south into British Columbia where it frequently occurred in bands at approximately 300 to 400 m elevation (Hennon et al. 2005). The British Columbia Forest Service continues to map the southern extent of the mortality. Generally, yellow-cedar decline in Alaska and British Columbia reaches higher elevations with decreasing latitude.

**Island (meso) scale**

Higher resolution meso scale maps of Peril Strait (adjacent areas of Baranof and Chichagof Islands) and southern Kruzof Island delineate polygons of yellow-cedar decline on color infrared photographs. These maps are useful in associating yellow-cedar decline with landscape position features including slope, aspect, and elevation. Mapped polygons of decline are concentrated at lower elevations: greater amounts below 150m, lesser amounts between 150 and 300m, and very little above 300m. Yellow-cedar decline occurs on all aspects within these zones, but more decline was evident on warm (south and southwest) aspects. The Mount Edgecumbe study area on Kruzof Island near Sitka is a dormant volcano with radial symmetry and fairly even slope gradients. The open canopy forests with abundant yellow-cedar extend from sea level to close to timberline. These features help control confounding factors and allow us to detect the influence of elevation and aspect on the decline problem. The elevational limits of yellow-cedar decline and interaction of aspect (i.e., decline occurs higher on the warmer aspects) support the contention that the lack of spring snow is an important factor for yellow-cedar decline.

**Watershed (fine) scale**

Research at the small watershed scale is directed at understanding how forest conditions vary over local areas of a landscape. Vegetation plots on 100m grids at two small watersheds, Goose Cove on Baranof Island and Poison

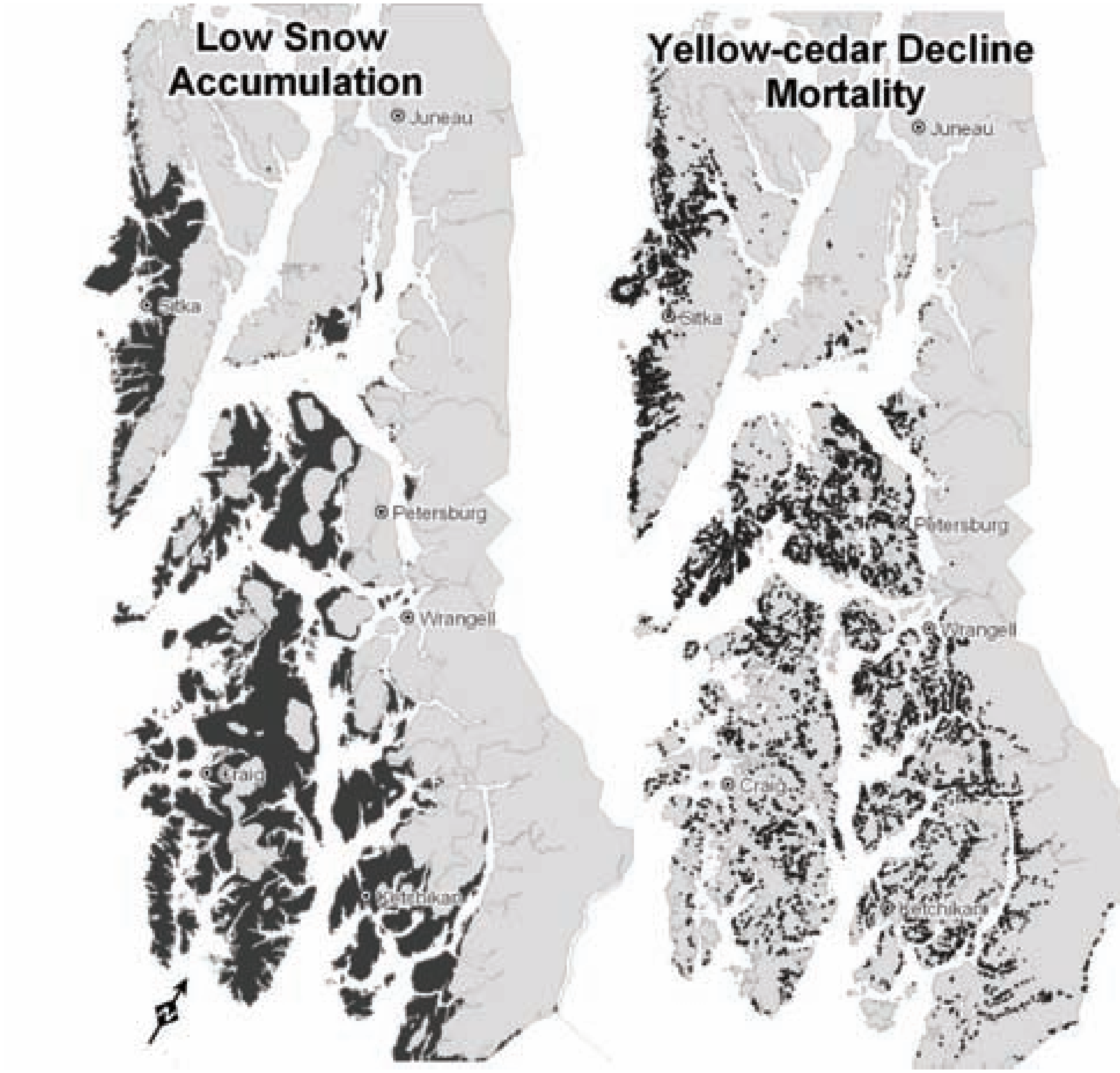


*Figure 5— Association of yellow-cedar decline (right) with low snow accumulation (left). Yellow-cedar decline map was derived from aerial reconnaissance surveys. Map of lowest of four snow accumulation levels is from a regional snow model based on PRISM data estimates. The close association of yellow-cedar decline with low snow accumulations suggests that yellow-cedar could be favored in areas where late winter and spring snow is more abundant.*

Cove on Chichagof Island, serve to measure live and dead trees and environmental variables, including hydrology, soil chemistry, canopy cover, air and soil temperature (D'Amore and Hennon 2006) and snow. Automated snow cameras were developed for daily snow measurements (Fig. 6). Digital cameras were housed in a plastic case with a Plexiglas window and contained a large battery pack and a circuit board with an intervalometer that directed the camera to turn on and record pictures daily. These snow cameras were mounted to the sides of trees and pointed toward scenes to photograph graduated meter boards so that daily snow depths could be recorded. Soil temperature loggers were located in some of the scenes to associate the presence of snow with patterns of soil temperature.

Snow appears to protect yellow-cedar from this presumed freezing injury. Measurements of snow pack at the Poison Cove study site indicate that yellow-cedar growing around an open-canopy bog at 240m, a setting without the

*Figure 6— Left, automated snow camera used to record daily snow depths. Right, healthy cedar forest surrounding a bog at 240m elevation with snow covering the ground in April. Snow typically occurs at this site until April or May, often several months after snow melt in the lower elevation dead yellow-cedar forests in the same watershed.*

decline problem, has snow covering the ground through April and through May during some years (Fig. 6). Snow appears to offer protection for yellow-cedar by: 1) delaying the dehardening process; and/or 2) protecting fine shallow roots from freezing. The depth of snow required to buffer soil temperature may be as little as several centimeters. Thus, the presence of snow from February through March or April allows yellow-cedar to pass a period of potential vulnerability (during spring freezing episodes) that kills trees growing without snow.

## CONSERVATION AND MANAGEMENT

Yellow-cedar is closely associated with snow zones, suggesting that snow plays an important role in protecting yellow-cedar. At our meso-scale analysis, the lack of spring snow may explain why yellow-cedar decline is limited to lower elevations and why it reaches higher elevations on warm aspects compared to cold aspects. At the broad scale, the distribution of yellow-cedar decline aligns closely with the lowest snow zone (Fig. 5). Some modification in the environment must have initiated yellow-cedar decline. It appears likely that reduced late winter and spring snow pack, which occurred as the region emerged from the Little Ice Age, represents that environmental change.

A strategy to manage yellow-cedar in the presence of climate-induced change is proposed (Fig. 7). One stage in this endeavor is to partition the landscape into areas that have yellow-cedar decline and areas that have healthy yellow-cedar forests (Fig. 7). Dead and dying forests have already been mapped (i.e., Fig. 5). These represent areas where yellow-cedar was once well adapted and is now maladapted due to climate change. In the dead zones, there is an opportunity of capturing economic value from the dead trees through salvage harvesting; this could help meet the timber demand for yellow-cedar. The various wood properties are preserved by the unique heartwood chemistry for decades, only diminishing slightly in the oldest snag classes some 50 and 80 years after tree death (Green et al. 2002, Hennon et al. 2000, Hennon et al. 2007, Kelsey et al. 2005). Evaluating the habitat potential of dead standing yellow-cedar trees for birds and small mammals is still a research need. Information on tissue deterioration through time, and the persistence of hard wood in snags (Green et al. 2002, Hennon et al. 2002), suggest that cavity excavating animals would not frequently use dead yellow-cedar.
Insectivorous birds feeding on insects that colonize recently dead cedars would represent a more likely use. Knowledge on the successional trajectory in the declining yellow-cedar forests is also needed, to document the future composition of these forests. Other conifer species, already present as understory trees, appear to be favored where the yellow-cedar overstory has died. Observations suggest that the

successional trajectory will vary by soil drainage and overall vegetation productivity. Successional processes will occur whether or not declining forests are salvaged, especially if snags can be yarded selectively by helicopter.

To help compensate for losses due to yellow-cedar decline and commercial logging on other sites, an active yellow-cedar forest regeneration program could be expanded. Yellow-cedar does not regenerate as prolifically as other species in the region. The success of natural regeneration (e.g., seed tree harvests) should be evaluated. Yellow-cedar can be successfully regenerated by planting either seedlings (Hennon, 1992) or rooted cuttings (Russell, 1993), but the barriers to seedling performance (competing vegetation, deer browsing, and spring freezing) need to be considered. Favoring yellow-cedar during thinning operations will increase the yellow-cedar component in managed forests; however, planting may be necessary to establish a viable population to be manipulated. A schedule for timing thinning operations based on site productivity and the severity of competing vegetation is currently underway at several USFS ranger districts led by Chris Dowling and Sheila Spores. More knowledge on yellow-cedar silvics and experience with young-growth yellow-cedar management are needed in southeast Alaska.

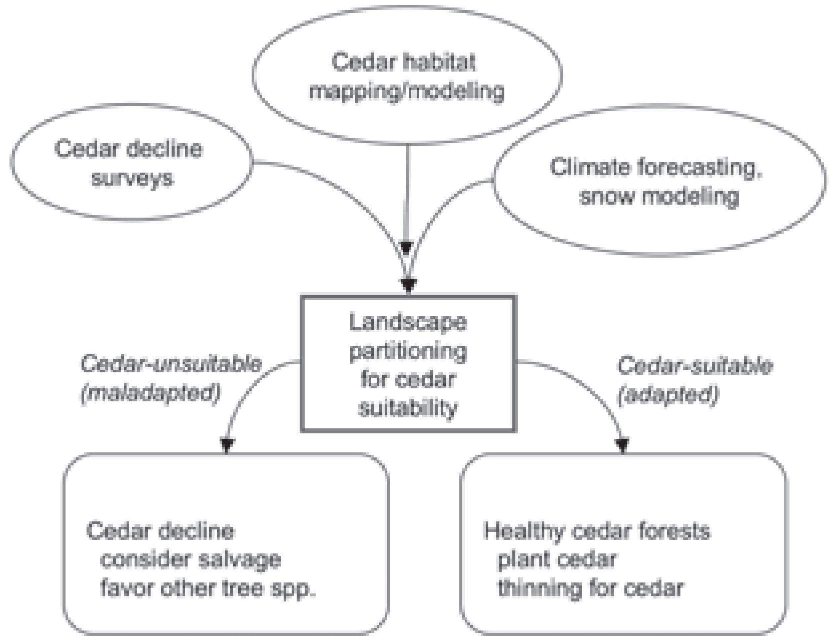


*Figure 7— Management strategy for yellow-cedar and its decline problem involves (1) partitioning the landscape into areas that are favorable or unfavorable for yellow-cedar, (2) encouraging yellow-cedar in areas where it is currently healthy (i.e., typically with spring snow) or areas where yellow-cedar has not been competitive but can be planted and managed (i.e., well drained soils) and (3) encouraging other tree species where yellow-cedar is no longer well adapted (i.e., declining forests where dead trees could be salvaged).*

Our present information suggests that yellow-cedar should be favored in:

1) northern and eastern regions of southeast Alaska that have cold winters,

2) higher elevations within the general distribution of yellow-cedar decline, and

3) better drained soils supporting greater forest productivity where roots penetrate more deeply and canopy shading cools soils during early spring.

Note that the first two of these three factors are highly related to late winter and spring snow pack.

It will not be sufficient to manage yellow-cedar where it is currently healthy because this approach would not account for climate warming. Managing this long-lived tree species requires predictive models that reveal where the decline problem is expected to occur in the next few centuries. Scenarios indicate that the climate may shift faster than vegetation is able to respond (Hamann and Wang 2006). Climatic models help focus management on areas where long-term persistence probability for yellow-cedar is high. Although we have a detailed map of dead cedar forests, our knowledge of the distribution of healthy yellow-cedar forests is surprisingly limited. Current USFS GIS layers, TIMTYPE and CLU (Common Land Unit), are based on interpretation of aerial photographs and are inadequate for managing Alaska's cedar species. Determining forest composition among plant communities that dominate wet soils is challenging because several tree species cannot reliably be distinguished on aerial photographs. We propose a different approach: use data from the many forest vegetation plots that have been collected over the last five decades in southeast Alaska.

A new project initiated with the Nature Conservancy uses a large number of permanent vegetation plots (approximately 50,000) to map and model the occurrence of healthy yellow-cedar in southeast Alaska. Assembling the various plot systems will reveal the distribution of western red cedar and yellow-cedar in southeast Alaska. The older plot systems are particularly valuable because they fill voids created by the lack of sampling in wilderness areas that were established in the 1980s. We intend to use all of these plots and "nearest ecological neighbor" methods (Ohmann and Gregory 2002) to model the distribution and habitat preferences of each cedar species. This approach should yield a high resolution map of cedar occurrence and also indicate specific habitat preferences for cedars.

Of course, yellow-cedar is no longer well adapted in all of these areas given the extensive forest decline. The yellow-cedar decline map as well as the low snow pack map (Fig. 5) can be used to determine where yellow-cedar is no longer suited and is maladapted. Another stage in partitioning the landscape for yellow-cedar suitability is to model expected snow accumulation zones into the future using several climate projections. This would appear to represent the best method for identifying areas that will be suitable for yellow-cedar over a long period of time. The final product will be a map that provides guidance to managers on areas that will and will not be suitable for favoring yellow-cedar over the next century or so.

## SUMMARY

A plausible explanation for yellow-cedar decline must account for some particular vulnerability of this defensive tree species and some change in the environment. Yellow-cedar appears to be susceptible to premature dehardening and spring freezing injury, a vulnerability probably acquired by living at high elevations in heavy spring snow. Minor climate warming at the end of the Little Ice Age may have reduced late winter and spring snow pack at lower elevations, eliminating the protective snow that insulated yellow cedar roots during freezing events. This could be the environmental change that initiated yellow-cedar decline. If our explanation for yellow-cedar decline is correct, then this phenomenon represents an excellent example of how a shifting climate can cause dramatic change in a tree species and its associated ecosystem. The elusiveness of determining the cause of tree death and the complexity of our hypothetical scenario illustrate the difficulty in predicting forest ecosystem effects of climate change. Perhaps, however, several effects of a warming climate are predictable, such as the phenology of plants no longer in tune with seasonal weather events. Also, as yellow-cedar decline demonstrates, some species may develop problems related to altered snow accumulation and melt in regions such as southeast Alaska with winter climate at the snow-rain threshold. A clear understanding of the mechanism of decline, future climate projections, and landscape modeling will be needed to solve the problem of where to favor this long-lived, valuable tree species in the future.

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