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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 its 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.

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.

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

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.

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[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 (½ 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).

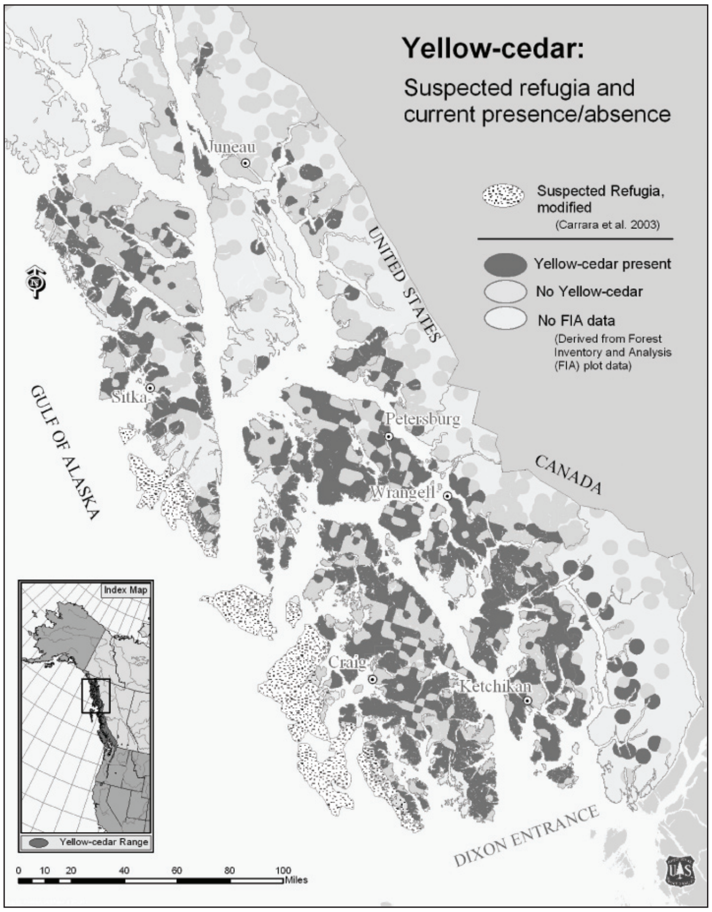

Figure 2—The occurrence of yellow-cedar (dark polygons) in southeast Alaska based on Forest Inventory and Analysis plot data. Areas where yellow-cedar was absent are depicted with lighter polygons; unsampled areas shown as very light grey. Also represented are areas of suspected refugia (stippled) (Carrarra 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 sub-alpine vegetation existed during the late Pleistocene and provided seed sources for subsequent recolonization 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 U.S. 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 percent (Barnett 2005) or 0.2 percent (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

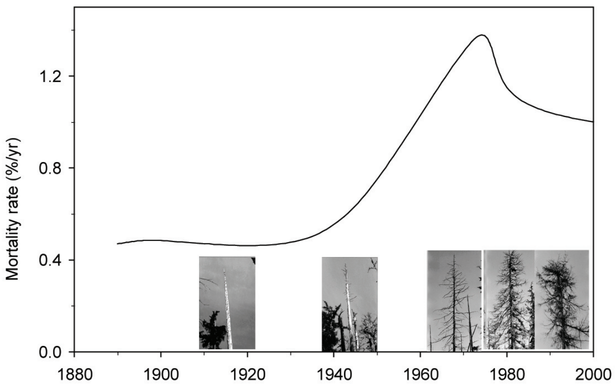

Figure 3—Estimated annual mortality rate of yellow-cedar in declining forests. This reconstruction combines time-since-death results of the five snag classes shown (Hennon et al. 1990c) with ground plot data (e.g., snag class frequencies) to create a splined-curve response for mortality rates through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

station data will be available soon from Beier and his colleagues at the University of Alaska, Fairbanks. A challenge in this 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 130 m elevation were more cold hardy than those growing below 130 m. 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

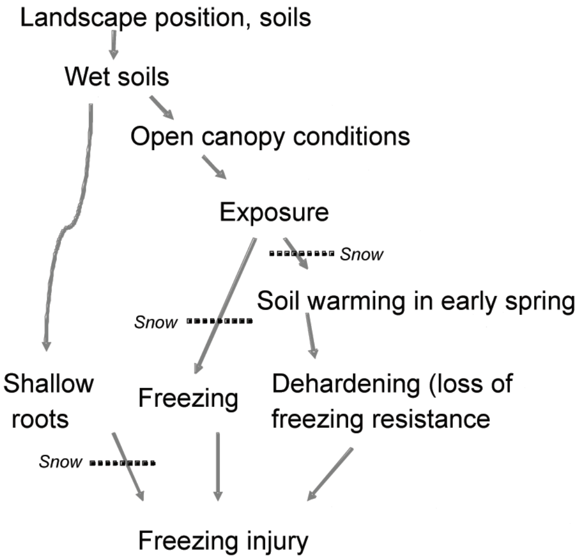

Figure 4— Conceptual diagram showing the cascading factors which form the leading hypothesis for the cause of yellow-cedar decline. The manner in which snow disrupts this process, thereby protecting yellow-cedar, is illustrated (dotted lines).

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 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 (~7 × 106 km^2, regional—southeast Alaska), meso-scale (~800 km^2, medium-sized island), and fine scale (~1 km^2; 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 150 m, lesser amounts between 150 and 300 m, and very little above 300 m. 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.

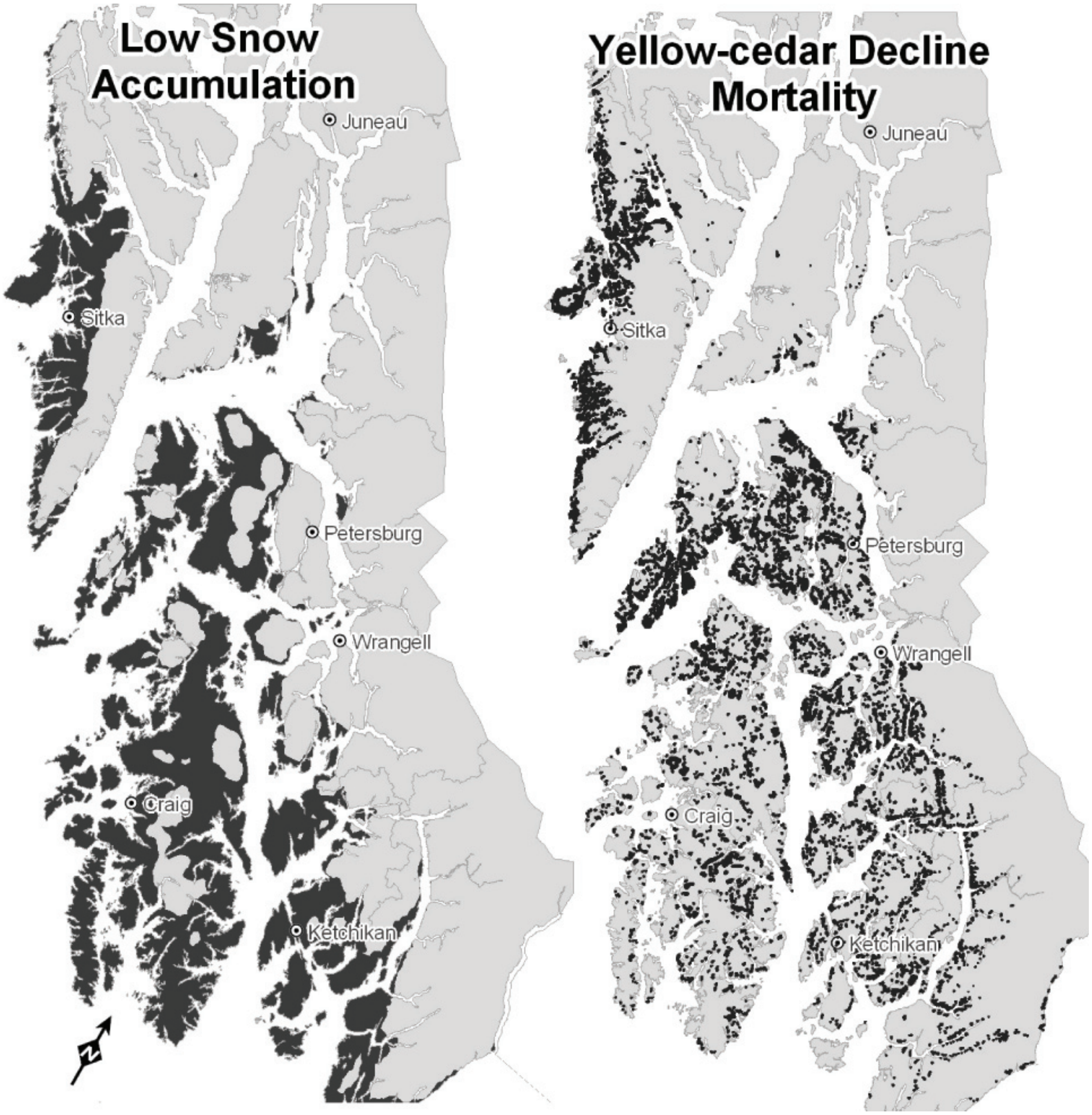

Figure 5—Association of yellow-cedar decline (right) with low snow accumulation (left). Yellow-cedar decline map was derived from aerial reconnaissance surveys. Map of lowest of four snow accumulation levels is from a regional snow model based on PRISM data estimates. The close association of yellow-cedar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

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 100 m grids at two small watersheds, Goose Cove on Baranof Island and Poison 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

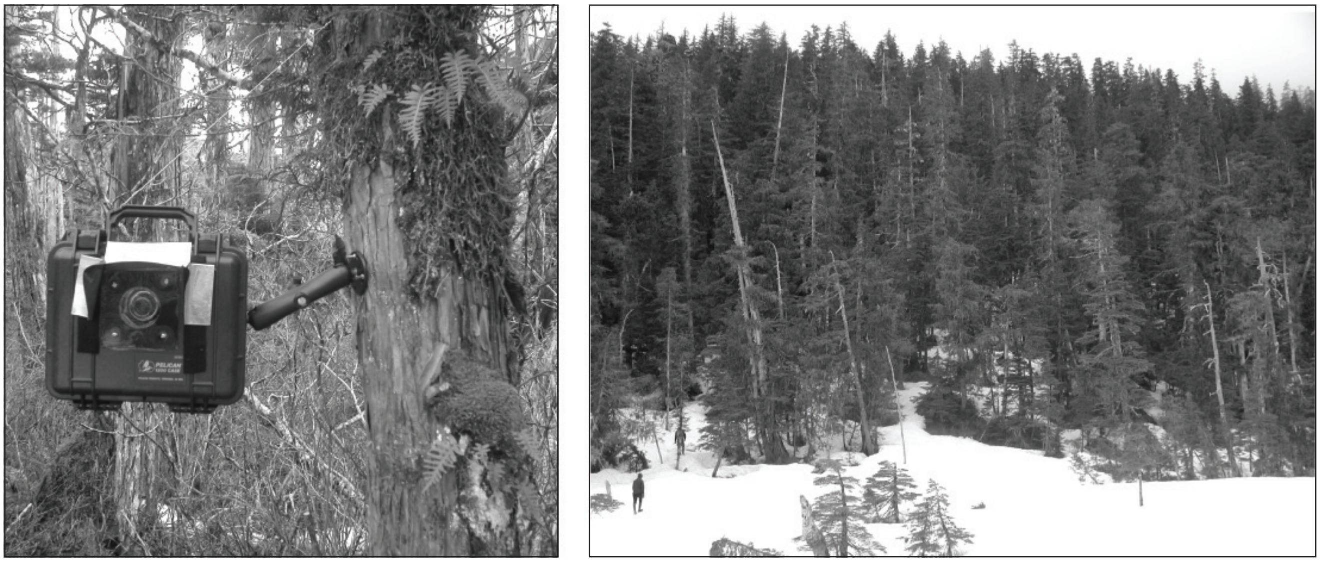

Figure 6—Left, automated snow camera used to record daily snow depths. Right, healthy cedar forest surrounding a bog at 240m elevation with snow covering the ground in April. Snow typically occurs at this site until April or May, often several months after snow melt in the lower elevation dead yellow-cedar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

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 240 m, a setting without the 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.

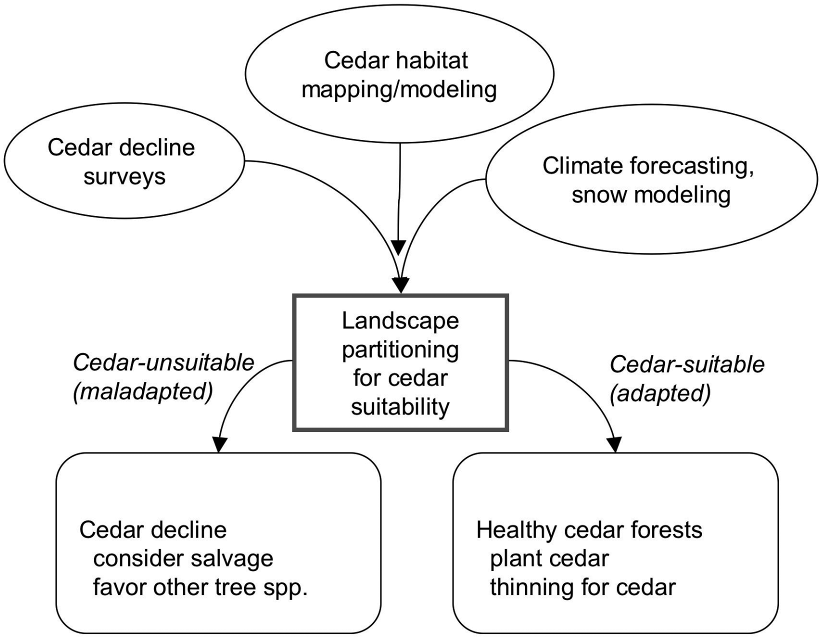

Figure 7— Management strategy for yellow-cedar and its decline problem involves (1) partitioning the landscape into areas that are favorable or unfavorable for yellow-cedar, (2) encouraging yellow-cedar in areas where it is currently healthy (i.e., typically with spring snow) or areas where yellow-cedar 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).

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.

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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