THE VITAL ROLE OF SNOW IN PROTECTING YELLOW-CEDAR FROM AN EXTENSIVE FOREST DECLINE IN ALASKA

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ABSTRACT

Yellow-cedar (*Chamaecyparis nootkatensis*) is a culturally and economically important tree that has been suffering from a severe mortality problem, "yellow-cedar decline," for about 100 years in pristine areas of southeast Alaska. Recent research indicates that a number of site factors predispose yellow-cedar to freezing injury in spring. Various remote sensing methods were used to investigate the distribution of healthy and dying cedar forests at three spatial scales. Aerial surveys identified nearly the entire broad distribution of decline, which covers about ½ million acres of forestland. This broad distribution of dead and dying forests aligns closely with the lowest snow accumulation zone in a regional snow model. At the mid-spatial scale, analysis of color infrared photographs revealed that cedar decline is limited to lower elevations, but extends somewhat higher on southerly aspects where snowmelt likely occurs earlier in spring. Measurements of forest trees, snow depth (by remote digital cameras), and hourly soil temperature at the finest spatial scale (small watershed) indicated that cedars remain healthy where snow persists through April. Snow apparently protects yellow-cedar in spring by either the delay of dehardening (loss of cold tolerance) by postponing the onset of soil warming, or by providing insulation from soil temperatures lethal to cedar roots (-5˚C). Climate forecasts and landscape models will be used to project future snow patterns to determine which portions of southeast Alaska are suitable for the planting and active management of this valuable, long-lived tree species. Yellow-cedar decline serves as an early example of the damaging ecological consequences of climate warming and, particularly, the detrimental effects of reduced snow pack.

INTRODUCTION

Yellow-cedar decline represents one of the classic forest declines of the world. These tree mortality problems are defined as being regional rather than localized, protracted over a number of years instead of acute in time, and have causes involving a number of interrelated factors (Manion and Lachance, 1992). Although there are dozens of forest tree problems that qualify as declines throughout the world, few have their causes adequately explained. Progress in the last few years indicates the importance of changing snow patterns in yellow-cedar decline. This paper reports our current understanding of yellow-cedar decline with an emphasis of how snow is involved in the problem, and how the presence of early spring snow can be used toused to make management decisions to sustain this valuable tree species.

Yellow-cedar Biology

Yellow-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach), is a commercially, ecologically, and culturally important tree species in Alaska and British Columbia. The species has an extensive natural range 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 the northern portions, especially 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 that are affected by the extensive mortality problem (Figure 1) known as yellow-cedar decline. 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 a paradox and a research challenge: what is the unique vulnerability, or "Achilles' heel," of this otherwise invincible tree species?

Ecosystems and Climate of Southeast Alaska

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

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of southeast Alaska is hyper-maritime, with abundant year-round precipitation and no prolonged dry periods. The temperature regime is cryic, with high summer temperatures mediated by abundant cloud cover, and frequent low-intensity precipitation events. 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 could dramatically influence snow 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 dead 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 peat soils (Neiland, 1971). Yellow-cedar has been competitive on these wet soils, typically reaching its greatest abundance here relative to other trees.

Occurrence of Yellow-cedar Decline

Yellow-cedar decline has been mapped 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 is the principle victim in these forests as its mortality rate far exceeds that of other trees. Approximately 70 percent of yellow-cedar mature trees are dead in these forests but some areas (e.g., Figure 1) have even more intensive tree death (Hennon et al., 1990; D'Amore and Hennon, 2005). Most of the forest decline is on wet soils (Johnson and Wilcock, 2002) where yellow-cedar was previously well adapted and competitive.

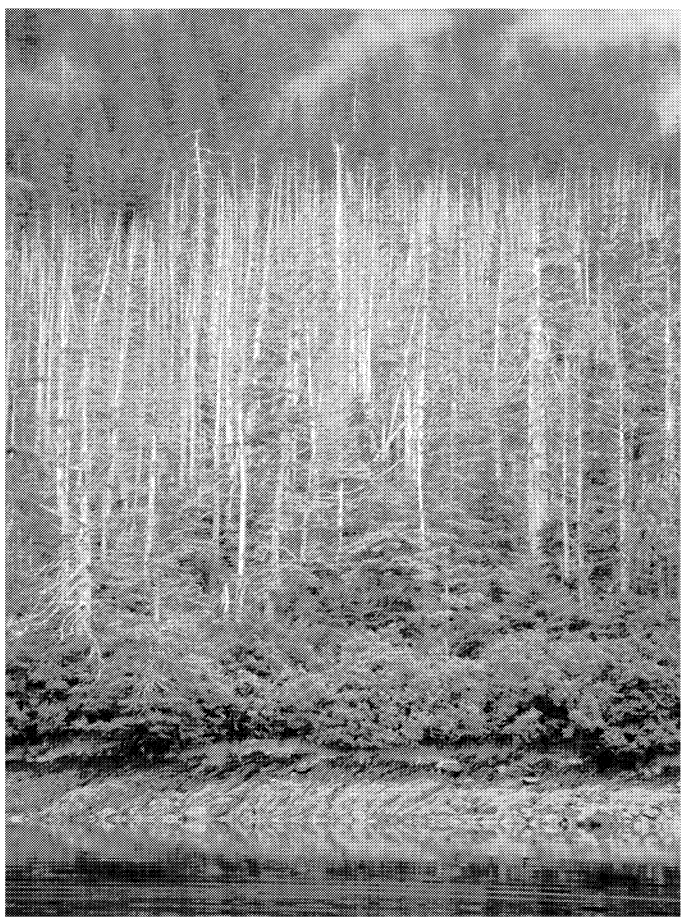

Figure 1. Intensive yellow-cedar decline near sea level in southeast Alaska

Symptoms of Dying Yellow-cedars, Absence of any Biotic Cause

Trees in varying stages of dying were examined for symptoms in their roots, bole, and crown to develop a sequence of symptoms (Hennon et al., 1990). Initially, fine roots die, then small diameter roots die, 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 these foliar symptoms differ from acute freezing injury to seedling and sapling foliage where newer, distal foliage is killed. Generally, the study of symptoms suggested a below-ground problem for affected trees. A number of types of organisms were evaluated as potential pathogens involved in the decline syndrome, 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., 1990), 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., 1990). Thus, the problem appears to be underground but not caused by any biological agent.

ONSET OF DECLINE AND LINK TO CLIMATE WARMING

Historical Climate and Conditions Favorable for Cedar Abundance

The last glacial maximum in southeast Alaska extended until between 16,000 and 12,000 years BP, before which time 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 (Carrarra et al., 2003). Here, trees and other subalpine vegetation existing during the late Pleistocene provided epicenters for subsequent recolonization as glaciers receded. Climate during the Holocene Epoch can be interpreted from the composition of trees and other plants from pollen profiles taken from lake and peat sediments, including 17 sites investigated by Heusser (1952, 1960). These pollen profiles provide direct evidence of the post-glacial abundance of conifers in the region. Unfortunately, yellow-cedar was not included in the early pollen 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]." More recent investigations have attempted to include cedar pollen. Cupressaceae pollen became abundant about 7,000 years ago (Banner et al., 1983; Hebda and Mathewes, 1984), indicating a cooling trend in climate. Recent pollen analysis in southeast Alaska is revealing that the cedars may have become prevalent only 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 these refugia in the southwest portions of Alaska's panhandle. Limited genetic analysis supports this contention (Ritland et al., 2000). Because of its limited reproductive capacity (Harris, 1990; Pawuk, 1993), the post-glacial spread of the tree has been very slow and it is still migrating to suitable habitat towards the northwest (Hennon et al., 2006). These are areas with colder winters that appear to be more favorable for the species in today's climate.

The late Holocene (4500 years BP to 200 years BP) was moist and cool, favorable conditions for expansion of various yellow-cedar populations. A cooler shift, known as the "Little Ice Age", occurred approximately 500 years ago. Although the influence of the so-called Little Ice Age on the climate of southeast Alaska is not clearly understood, advances and retreats of glaciers are consistent with its occurrence (Viens, 2001). The end of the Little Ice Age in the mid to late 1800s was associated with a time or warming and subsequently, marked the onset of yellow-cedar decline in 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. It is conceivable that yellow-cedar colonized low elevation sites during this period, flourishing when winter and spring snow packs were more consistent.

Onset of Yellow-cedar Decline

The earliest report of someone observing 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, the occurrence of yellow-cedar decline has been documented (Hennon et al. 1990) on aerial photographs taken by the US Navy in the late 1920s (Sargent and Moffit, 1929). The presence of dead yellow-cedars in forests was used to reconstruct the onset of yellow-cedar decline before these observations. A snag (standing dead tree) classification (Figure 2) with associated time-since-death estimates (Hennon et al., 1990) was developed and used in ground surveys (Hennon et al., 1990) 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. The onset of yellow-cedar decline occurred in about 1880 to 1900 on most of the sites where trees are still dying. The proportion of each of the snag classes represented in these surveys suggest that yellow-cedar mortality accelerated to even higher rates in the later half of the 1900s (Figure 2). Thus the decline is progressive in declining forests, which now contain long-dead trees, more recently-killed trees, dying trees, and some survivors, usually other tree species (Hennon and Shaw, 1997). The mortality problem is typically associated with wet, poorly drained soils (Johnson and Wilcock, 2002) with long-dead cedars often on the wettest soils. Recently-killed and dying trees are frequently found on better-drained soils and on the perimeters of the dying forests, indicating a slow spreading pattern along a hydrologic gradient (Hennon et al., 1990; D'Amore and Hennon, 2005). An annual mortality rate slower than 0.4 or 0.5% would be expected in a slow growing, long-lived tree species such as yellow-cedar before the onset of yellow-cedar decline. Such a sustainable mortality, more or less in balance with regeneration and growth to canopy status, of mature yellow-cedar is not known but presumably would be very low (Parish and Antos, 2006). Another tree species with very slow forest dynamics, *Sequoia sempervirens*, has annual morality rates of approximately 0.1% (Barnett, 2005) or 0.2% (Busing and Fujimori, 2002).

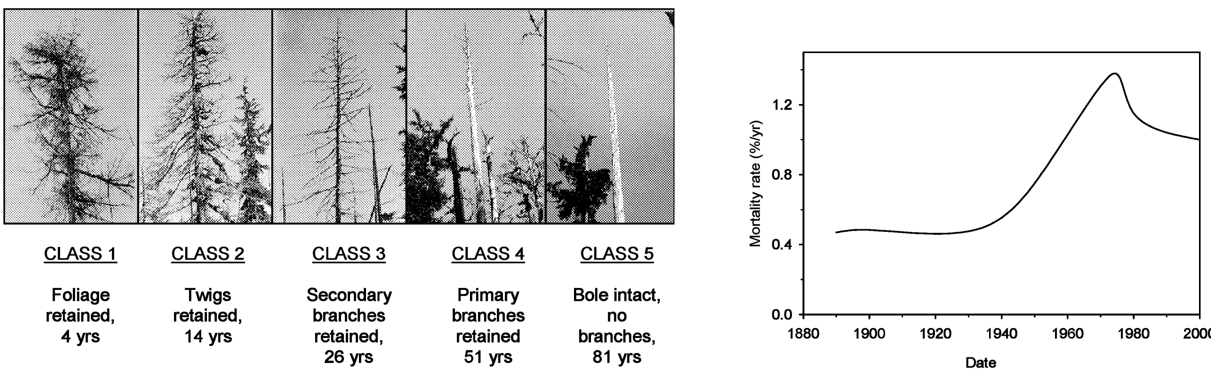

Figure 2. Left, snag classification system and time-since-death estimates (Hennon et al., 1990), and right, these estimates combined with ground plot data (e.g., snag class frequencies) to reconstruct the onset and epidemiology of yellow-cedar decline through the 1900s (Hennon and Shaw, 1997). The splined-curve response for mortality rates uses the mean time-since-death as five midpoints.

A current study on the dendrochronology (i.e., tree ring research) of yellow-cedar suggests that yellow-cedars were growing well during the Little Ice Age, but showed a synchronous reduction of growth 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.

HYPOTHETICAL MECHANISM OF TREE DEATH

The cumulative knowledge on yellow-cedar decline has led to the following scenario to explain tree death (Figure 3). This scenario is too complex to be evaluated by a single study; thus, it has become the framework for the current 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 injury to seedlings and mature trees. These topics are discussed elsewhere (Schaberg et al., 2005; D'Amore and Hennon, 2005; Hennon et al., 2006). The focus of this paper is to explore the association of the health of yellow-cedar forests relative to snow patterns, and to explain the likely protective mechanisms afforded by snow.

The association of yellow-cedar decline with wet soils now has a reasonable explanation as a contributing site factor. 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. Thus, these factors work together to result in root freezing injury as the cause of yellow-cedar decline. More detail about the nature of freezing injury and the protective role of snow are discussed below.

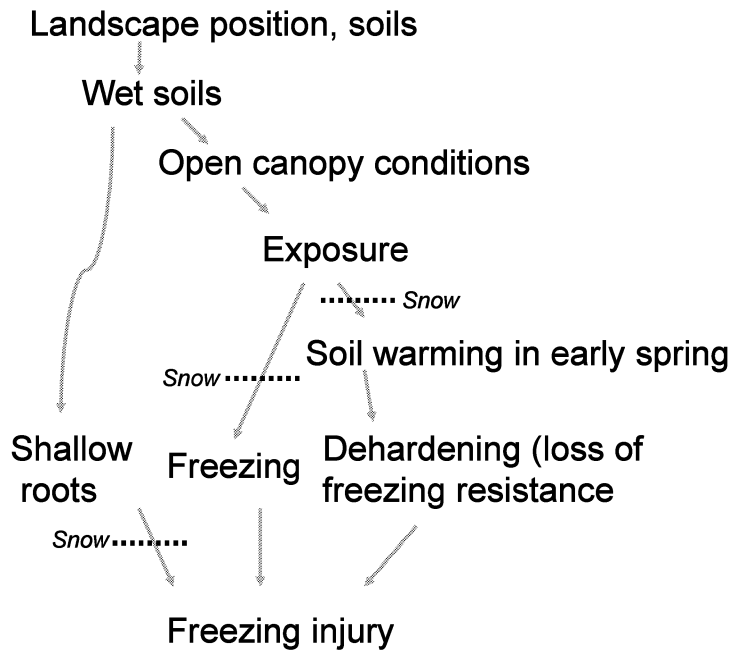

Figure 3. Conceptual diagram showing the cascading factors which form the leading hypothesis for the cause of yellow-cedar decline. The manner in which snow disrupts this process, thereby protecting yellow-cedar, is illustrated (dotted lines).

ASSOCIATION OF SNOW AND YELLOW-CEDAR DECLINE

Along with reconstructing mortality through the 1900s on the temporal scale discussed above, the yellow-cedar problem is being evaluated at three spatial scales: broad scale (~7x10^{6} km^{2}, southeast Alaska), meso scale (~800 km^{2}; e.g, medium-sized island), and fine scale (~1km^{2}; small watershed). Each of these approaches provides unique clues about the cause of yellow-cedar decline, shows the close association of snow, and highlights opportunities for proactively managing the species in the context of the decline problem.

Regional (Broad) Scale

For the broadest scale, a distribution map was developed that depicts more than 2,500 locations totaling over 200,000 hectares of dead and dying yellow-cedar forests (Wittwer, 2004) (Fig 4). 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. In a previous use of the map, the forest decline was found to align with warmer average winter temperature isotherms (Hennon and Shaw 1994), an early suggestion that climate was involved in the problem. Here, the distribution of yellow-cedar decline is compared to the first detailed model of snow accumulation zones in southeast Alaska (Figure 4). 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 <+2ºC). Note the close association between occurrence of yellow-cedar decline and the lowest snow accumulation zone (Figure 4); 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).

The distribution map captures occurrence of yellow-cedar 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). Surveys by the British Columbia Forest Service continue in an attempt to completely map the southern extent of the problem. Generally, yellow-cedar decline reaches higher elevations with decreasing latitude.

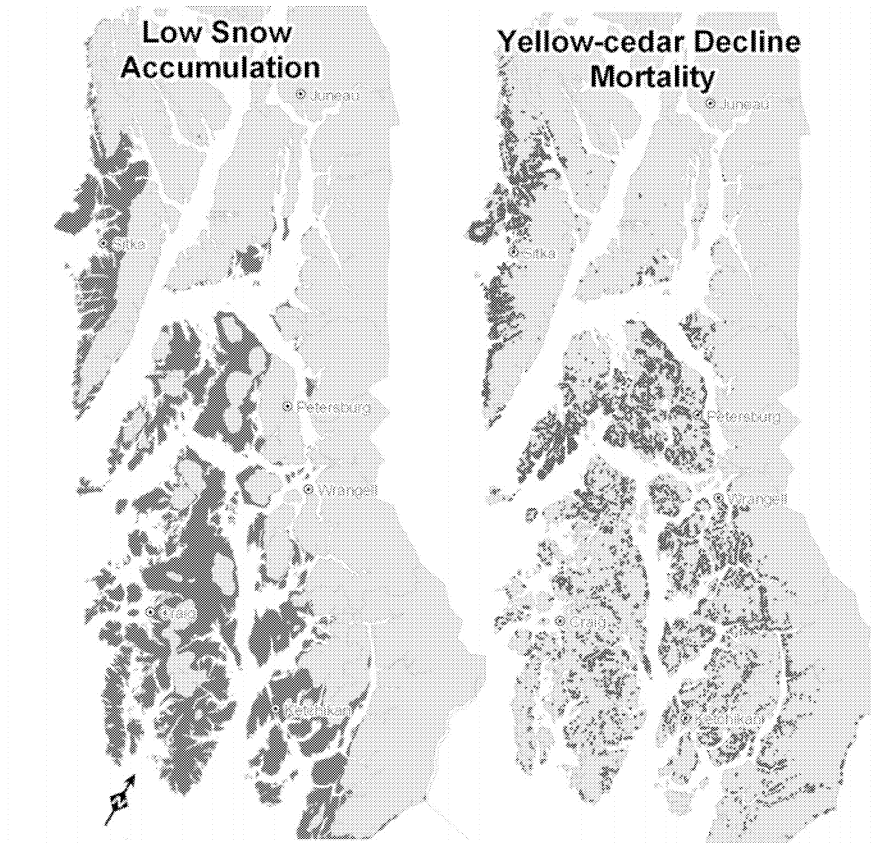

Figure 4. Association of yellow-cedar decline (right) with low snow accumulation (left). Yellow-cedar decline map was derived from aerial reconnaissance surveys. Map of lowest of four snow accumulation levels is from a regional snow model based on PRISM data estimates, courtesy of Dave Albert, The Nature Conservancy.

Island (Meso) Scale

Higher resolution meso scale maps of the Peril Strait (adjacent areas of Baranof and Chichagof Islands) and also most of southern Kruzof Island were produced by delineating polygons of yellow-cedar decline on color infrared photographs. These higher resolution maps help evaluate the association of yellow-cedar decline with landscape position features including slope, aspect, and elevation. Mapped polygons of decline in these study areas are concentrated at lower elevations: higher 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 mapped on warm (south and southwest) aspects. The Mount Edgecumbe study area on Kruzof Island near Sitka is particularly useful. It 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 to more directly test 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 an understanding of how forest conditions vary over local areas of a landscape. Vegetation plots on 100m grids were established at two small watersheds, Goose Cove on Baranof Island and Poison Cove on Chichagof Island, to measure live and dead trees and environmental variables, including hydrology, canopy cover, air and soil temperature (D'Amore and Hennon, 2006) and snow.

Automated snow cameras (Figure 5), housed in a plastic case with a Plexiglas window and consisting of a digital camera, large battery pack, and a circuit board with an intervalometer, recorded pictures daily. These snow cameras were mounted to the sides of trees and pointed towards scenes to photograph graduated meter boards so that daily snow depths could be noted after the cameras were recovered. Soil temperature loggers were located in some of the scenes to associate the presence of snow with patterns of soil temperature.

Figure 5. Left, automated snow camera used to record daily snow depths. Right, healthy cedar forest surrounding a bog at 200 m 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.

PROTECTIVE NATURE OF SNOW

The close association of snow and yellow-cedar decline, documented at several spatial scales, suggests that snow plays some role in protecting yellow-cedar, and also that diminishing snow accumulations probably triggered the decline problem.

Dehardening and Freezing

The seasonal cold tolerance of foliage on mature yellow-cedars and co-existing western hemlocks in open- and closed-canopy forests was evaluated at several elevations at one of our study sites (Schaberg et al. 2005). Strong seasonal tendencies were found for both species. In fall, yellow-cedar in open canopy settings were more cold tolerant than cedar in closed-canopy, whereas western hemlock 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. In our testing of tree foliage, yellow-cedar 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 tested growing 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 et al., 1994, 2001; Davradou and Hawkins, 1998; Puttonen and Arnott, 1994). I have observed severe freezing injury to yellow-cedar seedlings growing in Juneau across several years, each time severe foliar symptoms developed in late March or early April. Based on these observations and cold tolerance testing of cedar trees, a study on seedlings has been initiated to intensively evaluate the spring dehardening and cold tolerance of root and foliage tissue in late winter and early spring. Results indicate that 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 protected with a covering of perlite used to mimic snow, gave 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.

Soil Temperature Buffering and Root Protection

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 150m, a setting without the decline problem, has snow covering the ground through April and through May during some years (Figure 5). Temperature at the shallow rooting depth (i.e., 7.5 cm deep) reached below -10˚C during a cold event in the 2005-2006 winter in the dead forest at Poison Cove, well below the lethal temperature for yellow-cedar fine roots. Snow was absent on these plots at that time. During the same cold event, soil temperatures remained close to 0˚C (above the root injury threshold) at the higher elevation plots because of the presence of snow. Thus, snow appears to offer a form of protection for yellow-cedar by 1) delaying the dehardening process, and/or 2) protecting fine shallow roots from freezing. In either case, the presence of snow through March and April allows yellow-cedar to pass a period of potential vulnerability (during spring freezing episodes) that affects trees growing without snow.

At the mid-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 (Figure 4). Some change in the environment must have initiated yellow-cedar decline. It appears likely that reduced late winter and spring snow pack as the climate emerged from the Little Ice Age represents that environmental trigger.

SNOW AS A GUIDE FOR MANAGING YELLOW-CEDAR DECLINE

A strategy is proposed to manage yellow-cedar in the context of this climate-induced problem. The landscape needs to be partitioned into areas that have yellow-cedar decline and areas that have healthy cedar forests (Figure 6). Dead and dying forests have already been mapped (i.e., see Figure 4). In the dead zones, shifting more of the timber production to capture value from the dead trees is recommended. 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 (Hennon et al., 2000; Green et al., 2002; 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 (Hennon et al., 2002), suggest that minimal use of yellow-cedar snags would be expected, however. Knowledge on the successional trajectory in the declining yellow-cedar forests is also needed. Other conifer species, already present as understory trees, appear to be favored where the yellow-cedar overstory has died. This successional process differs somewhat by site productivity and will likely play out whether or not declining forests are salvaged.

To compensate for losses due yellow-cedar decline, and yellow-cedar removed by commercial logging on other sites, an active forest regeneration program could be expanded. 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 can 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 the Wrangell Ranger District of the USFS.

Which parts of the landscape are appropriate to favor yellow-cedar in the context of the devastating decline problem? The close association of yellow-cedar's health with snow can be used as a guide. A simple solution would be to favor yellow-cedar in areas outside of the current decline distribution or in areas of low snow. It will not be sufficient to manage yellow-cedar in areas where it is currently healthy because this approach would not account for climate warming. Managing this long-lived tree species will require predicting where the decline problem will occur in the next few centuries. Although a detailed map of the dead forests exists, knowledge of the distribution of currently healthy yellow-cedar forests is surprisingly limited. A project to use a large number of permanent vegetation plots to map and model the occurrence of healthy yellow-cedar has been initiated in southeast Alaska. Thus, 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 the species by management in the future. 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 distribution of yellow-cedar decline, and

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

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

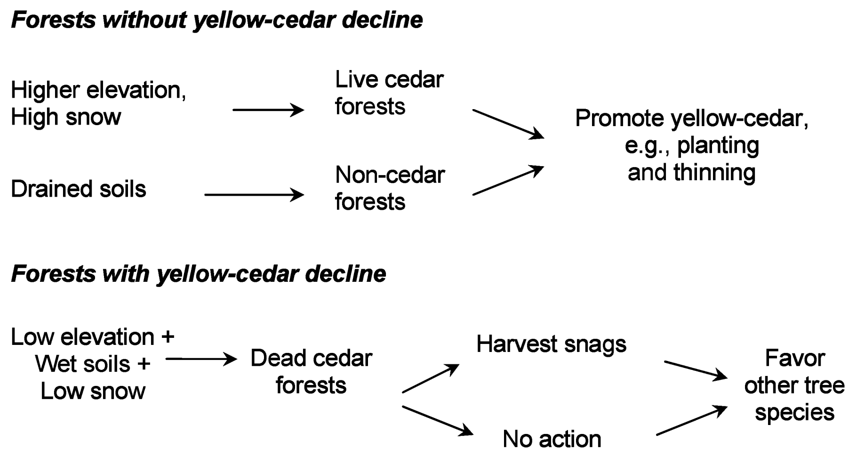

Figure 6. Management strategy for yellow-cedar and its decline problem involves 1) partitioning the landscape 2) favoring yellow-cedar in areas where it is currently healthy (i.e., typically with spring snow) or areas where yellow-cedar has not been competitive but can be planted and managed (i.e., well drained soils) and 3) favoring other tree species where yellow-cedar is no longer well adapted (i.e., declining forests where dead trees could be salvaged).

LESSONS FROM YELLOW-CEDAR DECLINE

A plausible explanation of the cause of yellow-cedar decline must account for some particular vulnerability of this defense tree species and some change in the environment. Yellow-cedar appears to be susceptible to premature dehardening and spring freezing injury, a vulnerability that may have adapted by living at high elevations where snow is heavy. Minor climate warming at the end of the Little Ice Age may have reduced late winter and spring snow pack where cedar grows at lower elevation, eliminating the protection during freezing events offered by snow to this species. If this explanation for yellow-cedar decline is correct, then this phenomenon represents an excellent example of how a shifting climate can cause dramatic changes 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. A thorough understanding of the cause of yellow-cedar decline and the contributing role of climate and its influence on snow patterns will be necessary to manage this valuable long-lived tree species in the context of the decline problem.

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