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Dating Decline and Mortality of *Chamaecyparis nootkatensis* in Southeast Alaska

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ABSTRACT. Alaska yellow-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach) has been declining and dying for a long, but undetermined, span of time in remote and undisturbed forests of southeast Alaska. Aerial photographs indicate mortality was widespread by 1927. The dates of death for individual snags of Alaska yellow-cedar were determined by counting annual rings on 73 western and mountain hemlock trees growing beneath larger, dead Alaska yellow-cedars, and in live callus strips on 46 Alaska yellow-cedars with partial bole death. Average time since death was 4, 14, 26, 51, and 81 years for snags in class I (foliage retained), class II (twigs retained), class III (secondary branches retained), class IV (primary branches retained), and class V (bole intact but no primary branches retained), respectively. Class V snags, which are common on all sites currenty expressing decline, appear to represent the trees initially affected. Snags in a sixth class with deteriorating boles are uncommon and not associated with sites of decline; their death most likely predated the onset of extensive mortality. Because some class V snags died over 100 years ago, these data suggest that extensive mortality began about 1880, and became obvious about 1900–1910—dates supported by historical records. FOR. SCI. 36(3):502–515.

ADDITIONAL KEY WORDS. Yellow-cedar, Alaska-cedar, aerial photography, release.

DECLINE AND MORTALITY OF ALASKA YELLOW-CEDAR (*Chamaecyparis nootkatensis* (D. Don) Spach) (Figure 1) occurs on more than 150,000 ha of undisturbed forest throughout southeast Alaska (USDA Forest Service 1988). The primary cause of decline is unknown even though severe cedar mortality has been observed in the region since 1909 (Sheldon 1912). How long the problem has occurred before that time is unknown. Concentrated mortality of Alaska yellow-cedar has not been repoted elsewhere in the range of this species, which is naturally distributed from Prince William Sound in Alaska south to the Oregon-California border (Harris 1971).

Symptoms of dying Alaska yellow-cedars are typical of forest tree declines: death of fine roots, reduced radial growth, yellowing and thinning of foliage, and the frequent presence of secondary organisms such as *Armillaria* sp. and bark beetles (Hennon et al. 1984, 1990b). Decline on many affected areas has expanded, with dying and recently dead trees surrounding patches of long-dead trees (Hennon et al. 1987, 1990a). Other tree species can be found dead within sites of decline, but Alaska yellow-cedar is the principal victim (Hennon 1986, 1990a). The local spread of decline and single species affected suggest a patho-

FIGURE 1. Mortality of Alaska yellow-cedar in southeast Alaska (dead trees appear white).

genic agent may be responsible, but no pathogen nor insect is evident as the primary cause (Hennon 1986, Hennon et al. 1990b). An alternate hypothesis to the biotic cause is that an adverse weather event (Anderson 1959), or some other environmental change, initiated mortality.

The objective of this study is to determine when extensive mortality began and when snags of Alaska yellow-cedar, now in various stages of deterioration, died. Alaska yellow-cedar wood is very resistant to decay (Harris 1971), and dead trees persist standing, slowly deteriorating for an undetermined number of decades. This characteristic provides a unique opportunity to date the death of individual trees and to use these data to reconstruct the patterns of mortality over a long span of time. Such information aids with interpretation of patterns of mortality spread, and provides valuable clues for possible causes of the problem. In addition, these results may also be used to study how time-since-death for cedar trees affects their potential salvage (Hennon and Shaw 1985).

MATERIALS AND METHODS

SITE DESCRIPTION

Studies were conducted in an area of severe cedar mortality in the vicinity of Peril Strait on Baranof and Chichagof Islands (latitude 57°) about 50 km northwest of Sitka in southeast Alaska (Figure 2). This roadless area is dominated by undisturbed old-growth forests of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Alaska yellow-cedar, and Sitka Spruce (*Picea sitchensis* (Bong.) Carr.) on well-drained soils, and by Alaska yellow-cedar, western hemlock, mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), and shore pine (*Pinus contorta* Dougl.) on poorly drained, deeply organic soils (Harris et al. 1974). On extremely boggy sites, shore pine and prostrate Alaska yellow-cedar are the only conifers. Understory plant taxa for this area are reported elsewhere (Hennon 1986).

Southeast Alaska has a cool, wet climate with an annual precipitation of about 150–500 cm (Harris et al. 1974). Winters have relatively moderate temperatures,

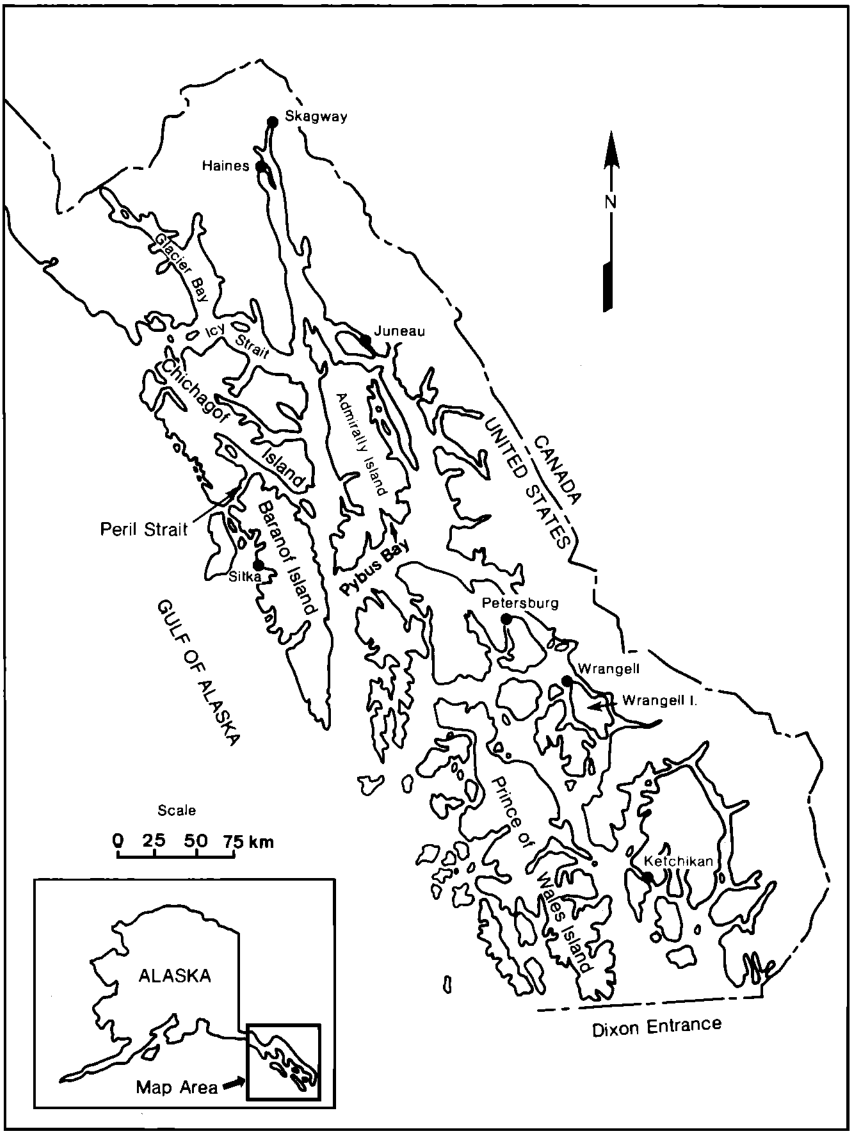

FIGURE 2. Location of study area along Peril Strait on Baranof and Chichagof Islands, Alaska.

and summers are cool and wet, without prolonged dry periods; thus, fire is not an important factor in forest succession. Mean temperatures at Sitka since 1922 has been 12.3°C in summer and 0.6°C in winter. Windthrow and landslides are common disturbances affecting stand characteristics in this region (Harris and Farr 1974). Patterns of plant succession on poorly drained sites are not understood.

Extensive glaciation has modified the landscape, but few glaciers are now located on islands where our studies were conducted. Most soils are spodosols, but histisols and several other series are also common (Martin 1989). Poorly drained soils, which are highly organic and shallow or deep, generally occur on sites without steep slope and overlay unfractured bedrock or compact glacial till (Martin 1989).

AERIAL PHOTOGRAPHY

We examined the earliest available aerial photographs of southeast Alaska, taken in 1926 and 1927, to confirm the existence of cedar decline at that time and to determine its local extent. These aerial photographs represent one of the earliest efforts anywhere to photograph large areas of forest (Sargent and Moffit 1929). One vertical and two oblique photographs were taken at each interval along flight lines. Thirteen sites (Figure 3) were examined for the occurrence and distribution of dead cedar snags in forest stands currently expressing decline and mortality.

SNAG CLASSES

Dead Alaska yellow-cedar trees used for dating time since death were grouped into one of six snag (dead tree) classes based on degrees of dead foliage, twig, and branch retention (compared to the condition of those tissues in the crown of a live, green cedar) and bole deterioration. Cedar snags had heights of 13–42 m, dbh of 27–90 cm, and all were older than 200 years. Snag classes (Figure 4) were as follows:

I—Foliage retained (at least 10% of total)
II—Twigs retained (at least 10% of total), most foliage missing
III—Secondary branches retained (at least 10% of total), most twigs missing
IV—Primary branches retained (at least 10% of total), most secondary branches missing
V—Most primary branches missing, bole intact to near the top
VI—Bole broken off and disintegrating.

Estimates of the time since death for snags in each class (except for class VI) were determined by counting annual rings of trees growing under these snags (released trees—Figure 5) and by counting annual rings in callus growth on partially killed stems of Alaska yellow-cedars (rope trees—Figure 6) that were interspersed among cedar snags.

RELEASED TREES

In the release tree method, 48 western hemlock, 25 mountain hemlock, and 44 Alaska yellow-cedar trees growing beneath previously dominant, but now dead, Alaska yellow-cedar snags (Figure 5) were located on sites of decline near Peril Strait. Only hemlocks or cedars primarily influenced by the death of a single Alaska yellow-cedar overstory tree were selected because growth release is more confidently interpreted from trees released by the death of one tree than from trees beneath several overstory trees that died at different times (Lorimer 1985). An additional 17 hemlocks growing beneath live and full-crowned Alaska yellow-cedars were selected as controls. All trees were 9–31 cm dbh, 5–15 m tall, and greater than 100 years old. Increment cores were taken from these trees at breast height (1.4 m), shaved with a razor blade, sprayed with water, and viewed at 60× using a dissecting microscope to determine patterns of annual ring growth.

On these cores, a release event was defined as any 5-year sequence of annual growth rings that was approximately twice as wide as that of the previous 5-year interval. When release was evident, the number of annual rings formed since

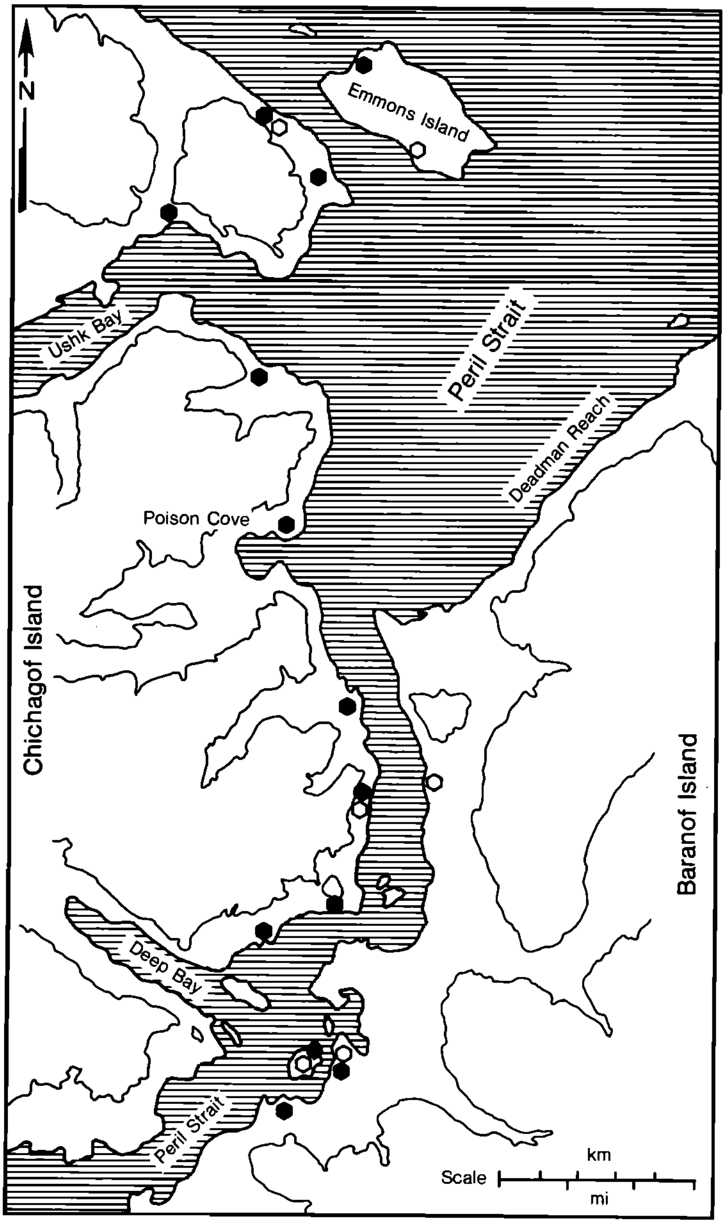

FIGURE 3. Map of 13 locations for which mortality was viewed on 1927 aerial photographs (closed hexagons) and six sampling locations for rope trees (partially killed Alaska yellow-cedars) used to determine the dates of snag death (open hexagons).

release was counted for each released tree, and was associated with the class of Alaska yellow-cedar snag under which the tree was growing. Differences in time since death among the released trees beneath dead cedars in each snag class were evaluated by a one-way analysis of variance (ANOVA) and the Bonferroni test ($P = 0.05$) (SAS Institute 1987).

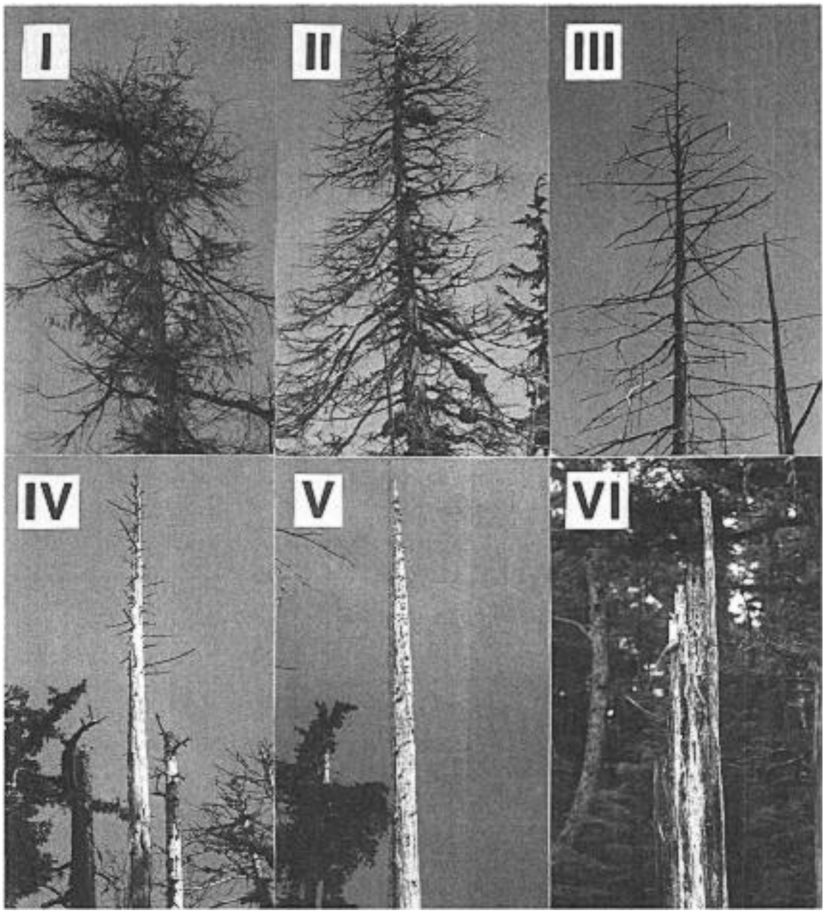

FIGURE 4. Six snag classes (I–VI) for dead Alaska yellow-cedars. Classes are differentiated by degrees of dead foliage, twig, and branch retention, and bole deterioration.

ROPE TREES

The other method for determining the time since death for snags in each deterioration class used partially dead Alaska yellow-cedar trees that grew in or near bogs expressing decline. These trees have a dead top (snag class I to V); but one narrow strip of live tissue, consisting of callusing bark and sapwood, connects roots to one live and bushy branch cluster (Figure 6). For lack of a better term, these cedars are called "rope trees." The cause of this condition is not known; however, we hypothesize that these trees were severely injured, but not completely killed, by whatever caused nearby cedars to die.

Stem discs were removed with a chain saw at approximately 20 cm above the ground from eight rope trees at each of six sites (Figure 3) for a total of 46 trees. The time since death of the cambium adjacent to the live callus was determined by counting annual rings in the callus tissue on the live part of the disc from the present cambium back to where the bole was dead. Each rope tree was placed into one of the snag classes based on the condition of the dead top above the live branch cluster. Differences among the snag classes in time since top and bole

TABLE 1.

Time since release of previously suppressed western and mountain hemlock trees growing beneath different classes of Alaska yellow-cedar snags. Snag classes are based on degrees of foliage, twig, and branch retention (see Figure 4).

Snag class	Hemlock examined (no.)	Years since release[z] Mean ± SD	Range
I foliage retained	10	3.6 ± 3.2[a]	0–10
II twigs retained	14	13.6 ± 6.9[b]	3–24
III secondary branches retained	21	26.2 ± 12.3[c]	12–52
IV primary branches retained	13	55.4 ± 25.2[d]	24–100

[z] Values followed by different letters differ significantly ($P = 0.05$). Values are reported in years, but ln (years) were used to reduce heterogeneity of variance and in Bonferroni test of significance.

death were evaluated by a one-way ANOVA and the Bonferroni test ($P = 0.05$). Width of annual rings before top and bole death was also examined to determine if these trees experienced a decline in growth prior to damage.

The six sampling sites for rope trees were located on different islands or, if on the same island, were separated by several kilometers (Figure 3). This separation allowed us to test by ANOVA ($P = 0.05$) whether trees in snag classes from different locations had been dead for similar lengths of time.

RESULTS

AERIAL PHOTOGRAPHY

The 1927 photographs are now of variable quality; but, on both vertical and oblique prints with good contrast, cedar mortality clearly appears as patches of white snags. Mortality of Alaska yellow-cedar was already widespread by 1927,

TABLE 2.

Time since callus tissue formation on 46 rope trees (partially living Alaska yellow-cedars). Classes are based on degrees of foliage, twig, and branch retention (see Figure 4).

Snag class (above live branch)	Rope trees examined (no.)	Age of callus growth[z] Mean ± SD	Range
II twigs retained	2	8.5 ± 0.7[a]	8–9
III secondary branches retained	3	39.0 ± 15.7[a,b]	25–56
IV primary branches retained	13	51.2 ± 18.1[b]	27–96
V no primary branches retained	28	81.4 ± 22.0[c]	49–128

[z] Values followed by different letters differ significantly ($P = 0.05$). Values are reported in years, but ln (years) were used to reduce heterogeneity of variance and in Bonferroni test of significance.

FIGURE 5. Mountain hemlock (arrow) growing directly beneath a previously dominant, but now dead, Alaska yellow-cedar. Growth ring patterns of such released hemlocks were used to determine when the Alaska yellow-cedar died.

and occurred at all 13 sites with current mortality that was visible on these photographs.

RELEASED TREES

Of the 73 hemlocks examined growing beneath dead cedars, 58 (79%) released from their otherwise relatively constant rate of annual growth. The times of these growth releases differed significantly among snag classes (I–IV) under which the trees grew (Table 1) and ranged from an average of 4 years ago for class I snags to 55 years ago for class IV snags. Few hemlocks released under class V snags.

Fifteen hemlocks (21%) had no increase in radial growth, even though they were growing beneath large Alaska yellow-cedar snags. Western and mountain

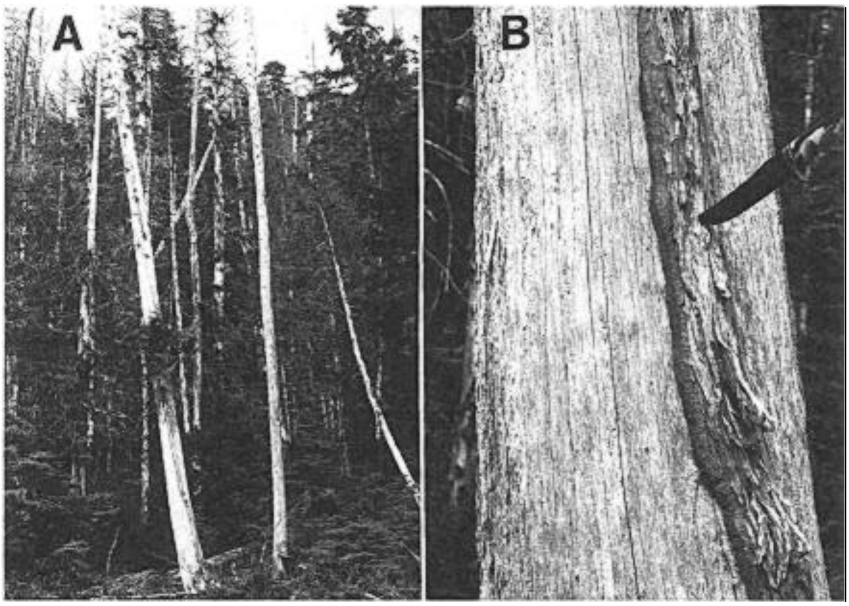

FIGURE 6. (A) Alaska yellow-cedar rope tree. These trees have a dead top and dead bole except for a narrow strip of live callusing tissue (B), that connects roots to one live, bushy branch cluster. Ring counts on strips of callus tissue were used to determine when the main boles died. These results were used to estimate when snags with tops in a similar stage of deterioration died.

hemlock had about the same tendency to release. Eleven (73%) of the nonreleased trees were growing under long-dead cedar snags (i.e., class IV and V), although 4 (27%) grew beneath snags from the more recently dead classes (I–III). Furthermore, 5 of the 17 (29%) hemlocks that were growing beneath live, full-crowned Alaska yellow-cedars (controls) had unexpected episodes of increased growth—one tree each at 5, 9, 13, 57, and 95 years ago. The remaining 12 hemlocks growing under live Alaska yellow-cedar did not release.

Many Alaska yellow-cedars growing under Alaska yellow-cedar snags also released, but their radial growth fluctuated so much throughout their life that possible times of release, perhaps associated with overstory death, were obscured; thus, Alaska yellow-cedar increments were not analyzed further.

ROPE TREES

Most rope trees had dead tops in snag class IV or class V; few rope trees had class I tops. Rope trees in classes II, IV, and V differed significantly from one another in number of callus growth rings and, presumably, in time since death of the top and most of the bole (Table 2). Time since top kill on class IV or V rope trees did not differ significantly by site for the 34 rope trees on six sites.

Stem discs cut from 23 rope trees in snag classes IV and V had clear, sound heartwood, and the growth rings prior to bole death were readily measured. The other 18 rope trees had stain or decay that prevented counting rings formed prior to bole death. All 23 rope trees with sound heartwood experienced a growth slowdown starting many years prior to bole death. Radial growth was as slow as

10 or more annual rings per millimeter. This growth slowdown began an average of 99 ± 26 years ago for class IV rope trees and 141 ± 30 years ago in class V rope trees. Thus, a reduction in radial growth preceded bole death by an average of 48 and 59 years for rope trees in classes IV and V, respectively. There were no significant differences among sites for the decline in growth for rope trees in class IV or V. Too few rope trees from classes I to III were sampled to determine if any growth differences were related to site.

DISCUSSION

Aerial photographs verified that decline predates 1927, when numerous and extensively distributed dead trees were already evident. Both the hemlock release and rope tree methods were helpful in estimating the time of death for individual snags. Yet the estimated times since death for each snag class were not identical for the two methods (particularly for class III—26 years by release, 39 years by rope tree). The hemlock release method was more useful in determining time since death of more recently dead snags (i.e., those in classes I—4 years, II—14 years, and III—26 years) but was not useful in determining the time of death for long-dead snags because many hemlocks under such snags did not release. Rope trees were more reliable in estimating dates of death for long-dead snags because rope trees usually had tops in snag classes IV and V (51 and 81 years, respectively), and thus were the best tool for estimating when extensive mortality began.

Not all hemlocks growing beneath long-dead class IV and V snags increased their radial growth. Many snags in class IV and V were located on bog and semibog sites (Hennon et al. 1987, 1990a) where growing conditions may not improve after the overstory dies. Factors responsible for hemlock release were not studied, but changes caused by overstory death—such as increased light; nutrient release into the soil from the decomposition of Alaska yellow-cedar roots and foliage; or decreased nutrient competition—could contribute to faster radial growth of some hemlocks growing under dead cedars.

Estimating the date of death of overstory snags using release trees is hampered because the two events, overstory death and initiation of increased radial growth of the release tree, may not coincide in time. Some declining Alaska yellow-cedar trees die slowly with their crowns thinning over a period of years (Shaw et al. 1985), perhaps partially releasing some understory hemlocks one or several years prior to cedar death. However, a lag effect may delay faster radial growth when better conditions develop (e.g., optimal light and moisture) as trees adjust to new conditions (McCaughey and Schmidt 1982) and because the optimal conditions of one year influence foliage growth, and consequently radial growth, during the following year (Kramer and Kozlowski 1979). Reasons for periods of fast and slow radial growth in understory cedars are not known and should be investigated.

Rope trees were useful in estimating the time of death for completely dead snags of the same class. Moreover, they provided clues regarding the potential causes of decline. Rope trees shared several characteristics with dead Alaska yellow-cedar snags: (1) rope trees often occurred adjacent to snags with tops in similar stages of deterioration; (2) both experienced a decline in radial growth before death (Shaw et al. 1985), or partial bole death for rope trees; and (3) snag classes of both are similarly associated with particular forest communities (Hennon 1986, Hennon et al. 1990a). Thus, the cause of damage to rope trees should be considered when evaluating causes for Alaska yellow-cedar decline.

Rope trees were not injured during one sudden incident such as an extreme climatic event; those with the most deteriorated tops (class V) had boles that were killed in different years from about 50 to 125 years ago. Also, their slow decline in growth many years prior to bole death, initiated at different times, does not support a sudden event as the cause of tree injury.

Rope trees differ from dead snags in that there are fewer rope trees with recently killed tops. In an extensive survey of mortality sites (Hennon et al. 1990a), 8% of the Alaska yellow-cedars examined (live and dead) were rope trees. The longer dead tops predominated on these rope trees as 39% had class V tops and 31% had class IV tops; in contrast, 15% had class III tops, 8% had class II tops, and 7% had class I tops, even though these classes I–III were commonly represented as dead snags. The reason why class I, II, and III rope trees are uncommon, even though cedars continue to die, is not understood. Tree species other than cedar sometimes develop the unusual rope tree growth form. For example, old bristlecone pine (*Pinus aristata* Engelm.) experiences partial cambial dieback and unilateral growth that results in one or more strips of cambium supporting a reduced crown (Ferguson 1968).

We consider that class V snags (boles intact, but no primary limbs retained) represent the original extensive mortality. These trees died an average of 81 years ago, as estimated by the rope tree method, and were present and common at all mortality sites examined (Hennon et al. 1987, 1990a). Because numerous class V snags died before the average of 81 years ago, some Alaska yellow-cedars probably began to die before the turn of the century, an estimate being about 1880. The early aerial photographs support this date by showing the extensive and widespread occurrence of dead trees in 1927. The more deteriorated snags in class VI with broken off and deteriorated boles were only infrequently encountered and were not associated with distinct mortality sites (Hennon et al. 1990a). These latter trees probably died prior to the onset of extensive mortality and may represent the nonepidemic or background level of mortality. Also, downed cedar snags, which could hypothetically represent an earlier mortality, were represented by all snag classes in some local areas of blowdown but were generally infrequent on most mortality sites (Hennon 1986).

We recently determined that 66% of the basal area of Alaska yellow-cedar within the boundaries of 21 mortality sites was dead (Hennon 1990a). Results from our dating methods indicated that nearly all of these trees died within the last 100 years; thus, cedar has experienced an exceptional mortality rate in the last century. This excessive level of mortality, combined with the age required for cedars to grow to tree-size (nearly all trees larger than 10 cm diameter are >200 years old) and inadequate replacement by natural regeneration on decline sites (Hennon 1986, Shaw et al. 1985), suggest that the population of live cedars in these forests is diminishing and that the problem has not been an on-going phenomenon in recent centuries.

The appearance of numerous dead Alaska yellow-cedars around 1900 is also supported by historical observations. Mertens (1827), Rothrock (1867), Dall (1870, observations in 1865), Petrof (1884, observations in 1880), Nelson (1887, observations in 1877–1881), and the Harriman Expedition (Emerson et al. 1904, observations in 1899) all observed Alaska yellow-cedar near Sitka and elsewhere in southeast Alaska, but none mentioned Alaska yellow-cedar mortality. Sheldon (1912) was the first observer to report extensive mortality and noted dead Alaska yellow-cedar near Pybus Bay on Admiralty Island in 1909, stating that, "vast areas are rolling swamp, with yellow cedars, mostly dead." Mortality is still present in Pybus Bay. Five years later, Anderson (1916) described the size and growth form of Alaska yellow-cedar near Sitka, and his plate XXI shows an "open formation [bog] at 1800 feet." The caption accompanying this photograph reads, "A dying cedar appears on the extreme right. . . ." No further mention of dead or dying Alaska yellow-cedar was made. Subsequent references to dead or dying Alaska yellow-cedar occur from 1927 until the present (Laurent 1982), especially in the annual USDA Forest Service reports, "Forest Insect and Disease Conditions in Alaska." Thus, the first historical references of dead or dying Alaska yellow-cedar (1909) seem consistent with our estimates of when a large number of Alaska yellow-cedar snags would have first become obvious in southeast Alaska.

The slow deterioration of Alaska yellow-cedar snags likely results from the species' extreme resistance to decay (Duff et al. 1954, Harris 1972), as well as the cool and moist climate of southeast Alaska (Farr and Harris 1979). Sapwood of Alaska yellow-cedar is decayed by a flourishing fungal community following tree death (Hennon 1986, 1990); however heartwood, even when exposed, is resistant to decay.

Time since death has not previously been estimated for Alaska yellow-cedar snags. Lowery's (1982) review on dating tree death in the western United States did not mention Alaska yellow-cedar, but he did place cedars in the class with the most durable wood. Most studies on dating tree death have been conducted on pines and firs and describe characteristics of snags up to ten years after their death. Embry (1963) reported on the state of decomposition of western redcedar (*Thuja plicata* Donn ex D. Don) and western hemlock up to 9 years after girdling or poisoning in southeast Alaska. We recently examined those trees 38 years after their death (Hennon, unpublished data). Nearly all hemlocks had broken off and were decayed, but redcedars were generally standing and appeared similar to the class IV snags of Alaska yellow-cedar (dead an average of 51 years) reported in this study.

In conclusion, aerial photographs, the rope tree method of dating cedar death, and historical references all support the suggestion that the onset of extensive mortality of Alaska yellow-cedar began before the turn of the century (about 1880), perhaps too early for some forms of human involvement, particularly anthropogenic pollutants, to be considered directly causal.

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