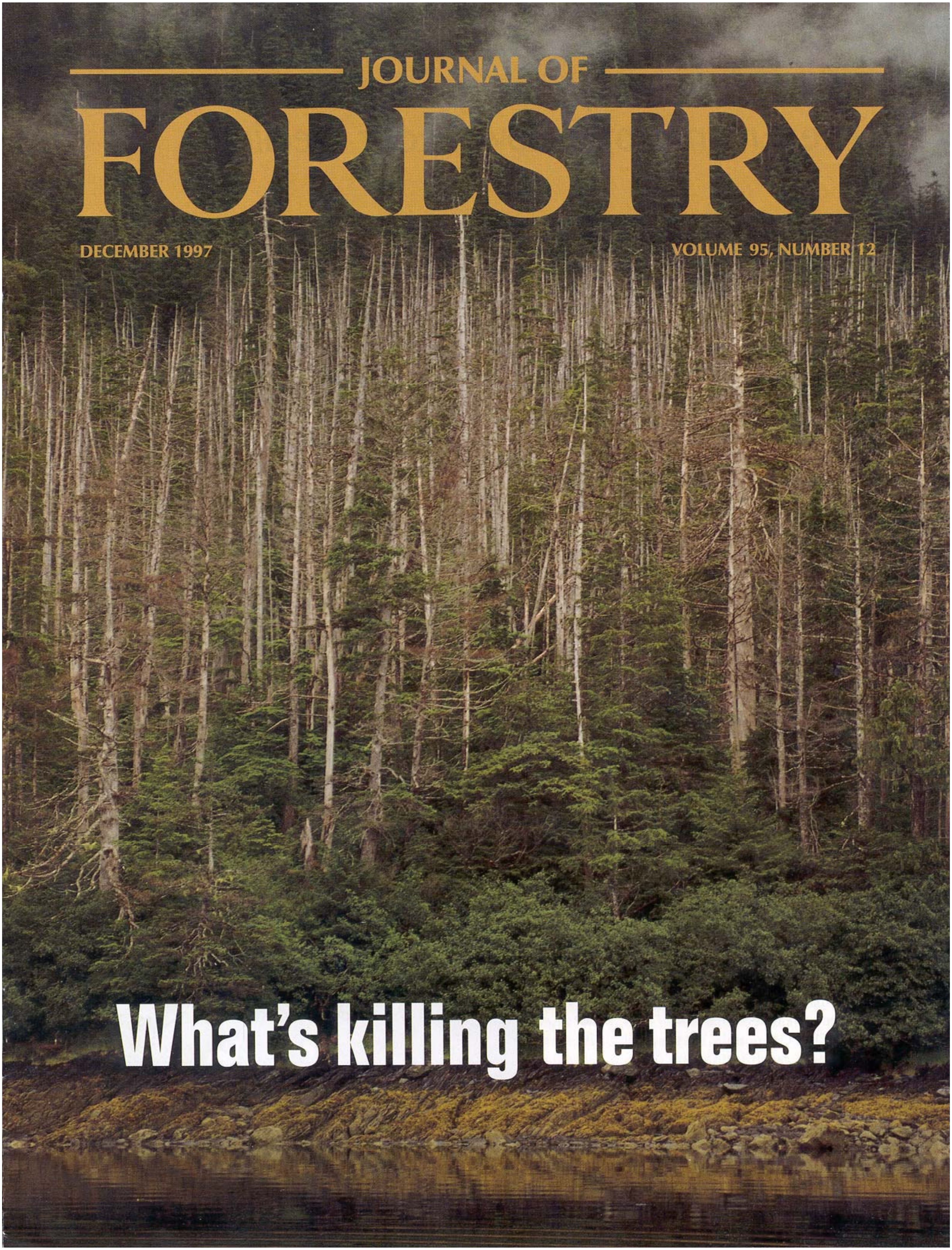
JOURNAL OF

FORESTRY

DECEMBER 1997

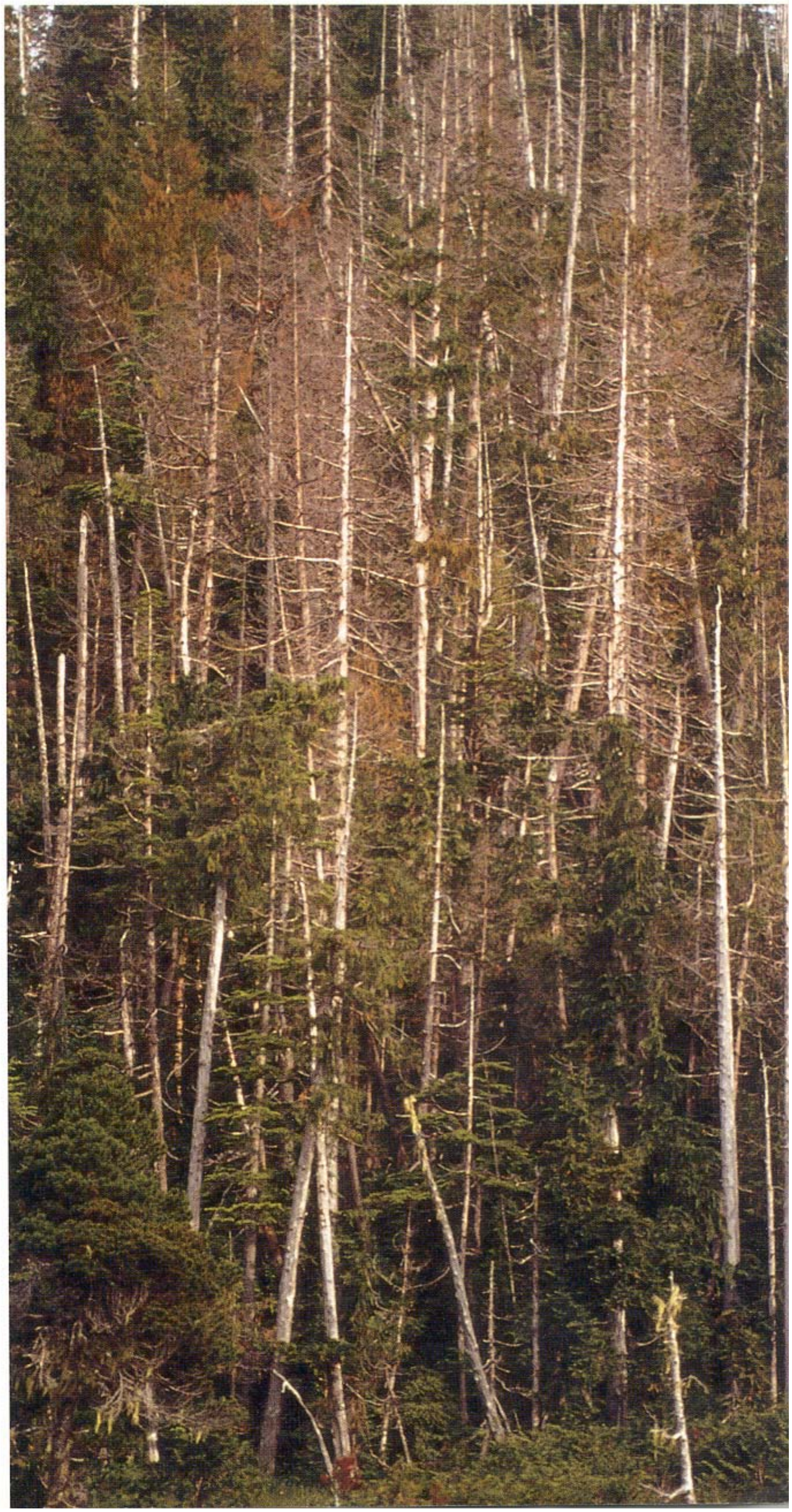
VOLUME 95, NUMBER 12



What's killing the trees?

The Enigma of Yellow-Cedar Decline

What Is KILLING These Long-Lived, Defensive Trees?



By Paul E. Hennon and Charles G. Shaw III

Yellow-cedar, also known as Alaska-*cedar (Chamaecyparis nootkatensis),* is ecologically important and economically valuable in coastal Alaska and British Columbia. It is a beautiful and fascinating tree whose common name is derived from its bright yellow heart- wood. Native Alaskans used the tree's wood and bark extensively, and the Russians built ships from its strong and durable wood when they occupied Alaska in the 1800s. The wood is currently exported to Asian markets; it is especially sought in Japan (Frear 1982).

Yellow-cedar's ecological strategy seems to be one of defense: tolerate harsh sites where competition is at a minimum, put relatively few resources into growth and reproduction, and outlive competitors. The color and distinct aroma of its heartwood come from powerful natural biocides, such as nootkatin (Barton 1976). The foliage contains volatile leaf oils (Cheng and von Rudloff 1970) that probably re- strict insect feeding. Yellow-cedar has few serious insect and disease pests and can live a millennium or longer.

Despite those defenses, something has been killing yellow-cedar since the 1880s across numerous islands on more than 500,000 acres of forest in southeast Alaska, generating the most severe forest decline in western North America. Large concentrations of snags accumulate as the wood's natural durability allows dead trees to persist standing for decades.

Symptoms and Biotic Factors

Decline has been variously attrib- uted to bark beetles, root disease, and winter injury, but these suggestions were based on brief observations (Shaw et al. 1985). The first detailed examination of this problem began in 1981, when we evaluated symptoms of dying trees, organisms associated with symptomatic tissues, and their ability to in- cite disease. Generally, the crowns of declining trees die as a unit, suggesting a root or soil problem (Hennon et al. 1990d). By monitoring several hundred dying cedars for 16 years (Hennon, un- published data), we have observed that above-ground symptoms can develop rapidly, with relatively full crowned trees dying in a few years. Nevertheless, some trees that had thin, off-color crowns 16 years ago are still alive today, albeit in an advanced stage of decline.

Root excavations revealed that death of the fine root system is the initial symptom (Hennon et al. 1990d), followed by demise of small-diameter coarse roots. Dying roots often occur in dark, water-saturated, highly organic, mucky soil. As crown foliage begins to turn off-color, small-diameter roots die, and larger roots develop necrotic cambial lesions that spread up the bole. Radial growth slows, sometimes for decades, before tree death. Root systems of dying trees are very shallow, primarily in the top 6 inches of soil-perhaps indicating low levels of oxygen.

Bark beetles *(Phloeosinus* sp.) are common on dead and dying yellow- cedars; however, they attack trees only in late stages of decline (Shaw et al. 1985). None of the 50 fungi we obtained from symptomatic fine roots or necrotic lesions, or elsewhere on yellow-cedars, were consistently associated with dying or dead trees (Hennon 1990). Furthermore, none demonstrated the ability to kill unstressed seedlings (Hennon et al. 1990d). Be- cause lesions on dying yellow-cedars appeared similar to the serious root disease of Port-Orford cedar *(Chamae- cyparis lawsoniana)* in southwest Oregon, which is caused by *Phytophthora lateralis* (Roth et al. 1972), we specifically searched for *Phytophthora* in declining forests. One *Phytophtbora* species was recovered from soils and streams (where the pear baits we placed in streams to sample for these fungi were not eaten by brown bears); how- ever, the fungus occurred just as fre-quently away from mortality sites as in them, and no species of *Pbytophthora* were isolated directly from yellow- cedars (Hansen et al. 1988).

We also sampled for root-feeding nematodes (Hennon et al. 1986) and are now conducting a grafting experiment to evaluate viruses and mycoplasms, but none of these groups of organisms appear to be the primary cause of tree death. Basal scars are common on cedar trees in declining stands; for example, 49 percent of the yellow-cedars sampled on Chichagof and Baranof Islands had callusing scars (Hennon et al. 1990a). Fresh scars consistently had teeth or bite marks from feeding by Alaskan brown bears *(Ursus arctos).* Some scars are caused by Alaska Natives, who use bark stripped from cedar trees. Regardless of cause, basal scars were more common in healthy than declining stands and are not the primary cause of cedar decline.

Site Factors and Epidemiology

Lacking a primary biotic cause, we looked at various site and epidemiological factors of decline, finding strong associations with poor drainage. Mortality occurs on the edges of low- elevation (to 1,000 feet) open bogs, some of which extend, contiguously or in chains, for several miles along fairly flat or rolling terrain (Hennon et al. 1990b). Decline also is severe in scrub forests without open bogs where understory flora and tree stature indicate restricted drainage. When decline occurs on steep, very wet slopes, these sites suffer three times more landslides than unaffected forested areas of similar gradient Uohnson 1997). On aver- age, 65 percent of the standing basal area of yellow-cedar in declining stands is dead (Hennon et al. 1990b). Other tree species also die, but yellow-cedar is the principal victim, contributing 74 percent of the dead basal area. Even accounting for yellow-cedar's longer persistence as a snag, these stands have a disproportionate level of cedar mortality (Hennon et al. 1990b).

Most yellow-cedar trees in declining stands range from just under 100 years old to more than 700 years (Hennon and Shaw 1994). The ages for the oldest yellow-cedar trees cannot be determined because of heart rot, but some probably exceed 1,000 years old. After 100 years of age there is no clear relationship between tree age and mortality. Centuries-old yellow-cedar trees are in the prime of their lives; since the species has great potential longevity, these trees are not dying of senescence.

We used several methods to clarify how long decline of yellow-cedar had been occurring in southeast Alaska and to date the death of individual snags (Hennon et al. 1990c). Aerial photographs taken in 1926 and 1927 (Sargent and Moffit 1929) indicate that mortality of yellow-cedar was already widespread. Historical observations also note an abundance of dead yellow-cedars by 1909.

Estimates of the time since death for yellow-cedar trees in five of six snag classes *(table 1)* were determined by counting annual rings on previously suppressed western hemlock *(Tsuga heterophylia)* and mountain hemlock *(T mertensiana)* growing under large yellow-cedar snags and on callus growth of partially killed stems of yellow-cedars (we call these rope trees) that were interspersed among cedar snags (Hennon et al. 1990c).

Ground surveys suggest that class-5 snags represent the original extensive mortality (Hennon et al. 1990b,c). Older, class-6 snags are uncommon, not associated with decline sites, and likely represent a background level of mortality for yellow-cedar. Accounting for variation in dating class-5 snags, we estimate that the accelerated rate of mortality began about 1880. The survey also indicated that class-5 snags occured on all sites of decline-suggesting that the onset was a relatively simultaneous occurrence (although not necessarily a sudden event) throughout much of southeast Alaska and that there have been no sites that developed the problem since onset.

We also are studying spread patterns to evaluate the cause of yellow-cedar de- cline. Sequential aerial photographs (1926 to present) and ground surveys indicate that site-to-site spread has not occurred since the onset of decline; however, at some sites the perimeters of decline have expanded up to 300 feet in the last century (Hennon et al. 1990b). Interestingly, this expansion seems related to soil drainage: local spread has been along a preexisting gradient from bogs (now with old snags) to better-drained soils supporting more productive plant communities (with dying trees and recently killed snags).

The primary ecological effects of decline are an altered stand structure and species composition, with less yellow-

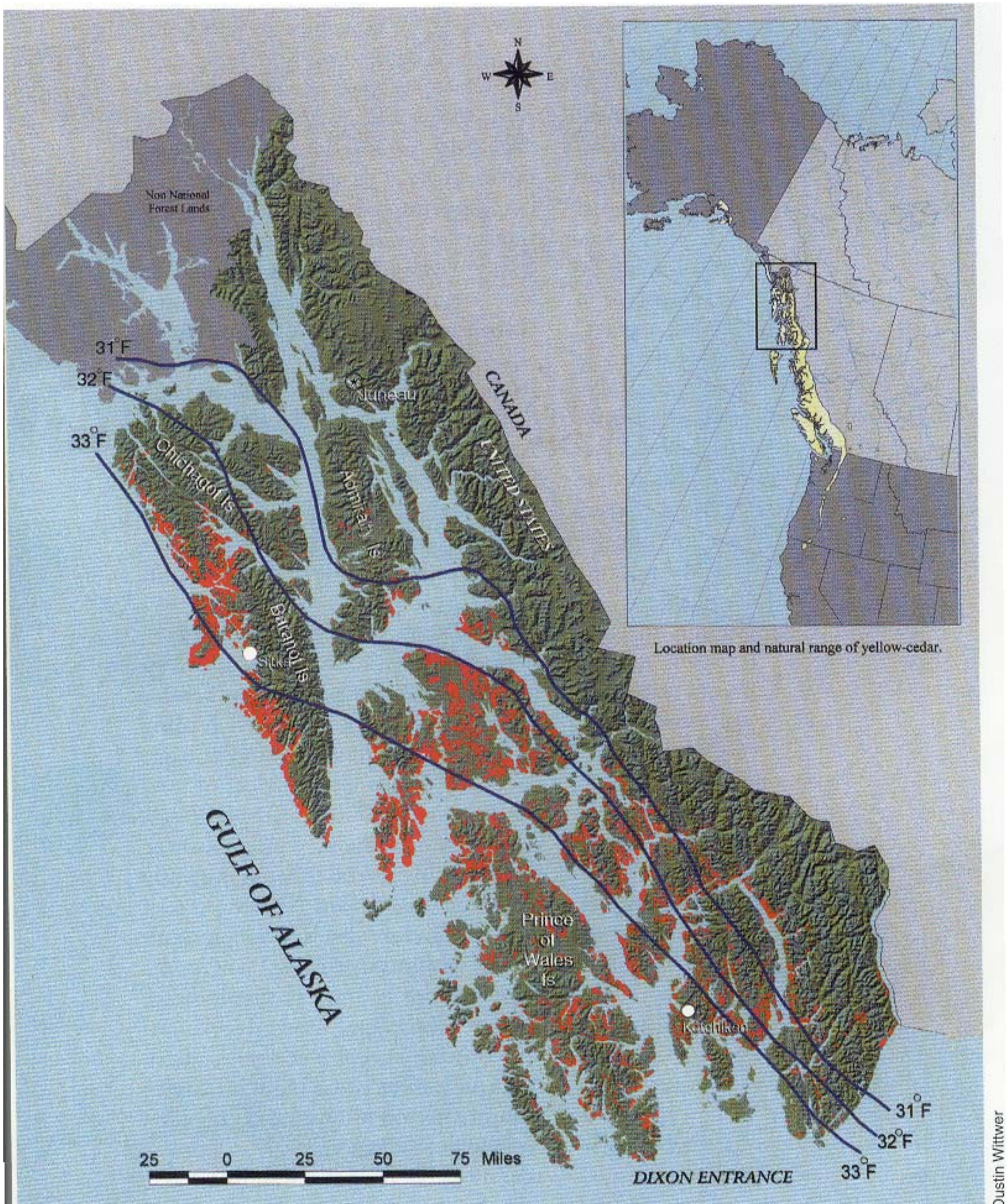


Figure 1. **Distribution of severe decline and mortality of yellow-cedar *(red)* in southeast Alaska. Three isotherms for the mean winter temperature (collective average of December, January, and February) are redrawn from Anderson (1955). Note the smaller amount of decline on the colder sides of the isotherms. The natural range of yellow-cedar *(yellow)* is depicted in the inset map.**

Table 1. Characteristics **of** yellow-cedar snags.

Snag class	Years since death	Foliage and branches	Bark	Bole	Sapwood	Heartwood
	4	Dead foliage; twigs retained				
2	14	Twigs retained	Sloughing	Intact	Decaying	Unaltered
3	26	Secondary branches retained	Mainly gone	Intact	Decayed, some sloughing	Unaltered
4	51	Primary branches retained	Gone	Intact	Mainly gone	Checking 1.2 inches deep
5	81	No primary branches retained	Gone	Intact	Gone	Checking 1.5 inches deep
6	Not dated	None	Gone	Broken	Gone	Decayed

Source: Hennon et al. 1990c.

cedar. The species is not threatened because it remains healthy in more productive communities on better-drained sites. Whether logging of dead cedars occurs or not, yellow-cedar populations are declining in bog and scrub communities of southeast Alaska (Hennon et at. 1990b). Mountain hemlock, western hemlock, and within its distribution, western redcedar *(Thuja plicata)* are the primary beneficiaries in this presumed natural process of succession.

Distribution of Decline

Yellow-cedar has a natural distribution from near Port Wells in Prince William Sound, Alaska, south through southeast Alaska and British Columbia, and at high elevations in the Cascades to near the Oregon-California border (Harris 1971). Severe decline is restricted to a broad band through most but not all of southeast Alaska (fig. *I).* Decline is either absent or not apparent farther south in British Columbia to California, around the Gulf of Alaska to Prince William Sound at the northwest limits of its range, and in the colder re7gions of southeast Alaska. Within the distribution of severe decline, nearly all stands have numerous dead and dying yellow-cedar trees if they occur below 1,000-foot elevation, have poorly drained soils, and have a substantial component of yellow-cedar.

Here, then, are clues to this mystery::

- Yellow-cedar forests began experi-

Opportunities for Management

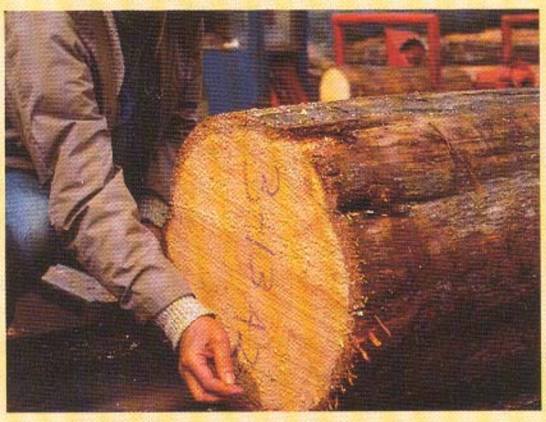
Yellow-cedar timber consistently commands the highest price of any tree in Alaska. The high value of the wood, its durability, and the extent of the decline have raised questions about the feasibility and economics of salvage. Researchers in the USDA Forest Service—State and Private Forestry, the Wrangell Ranger District of the Tongass National Forest, and the Forest Products Laboratory—recently initiated collaborative studies to evaluate strength properties, durability, recovery rates, and deterioration patterns of wood from dead yellow-cedars. A useful spinoff from basic research, the five-class snag system developed in epidemiological studies is the basis for all of this sampling. Preliminary results are very encouraging:

• *Strength properties.* There is no apparent reduction in wood strength and hardness as trees die and persist as snags, even 80 years after death (McDonald et al. 1997).

• *Recovery rates.* There is only a modest reduction in volumes recovered (5 percent reduction for recent snags to 16 percent for the 80-year-old class-5 snags).

• *Grades.* A minor shift to lower grades occurs with increasing snag age.

• *Durabililty.* Tests are now in place; results are expected in a few years.



Paul E. Hennon

Yellow-cedar's sapwood begins to decay shortly after death. Even if decayed as in this class-3 log without bark, however, the intact sapwood protects the valuable heartwood from the drying and checking that occurs once it sloughs away in older class-4 and class-5 snags.

• *Deterioration pattern.* Sapwood is not strongly durable; it decays and sloughs away in the transition from snag class 3 to class 4. But as long as it persists, even as it decays, the sapwood protects the heartwood from its most serious defect, checking. Class-4 and class-5 snags have checks averaging 1.2 and 1.5 inches of radial penetration.

• *Site aesthetics.* The first experimental salvage effort near Wrangell revealed that the wood retained sufficient value to justify helicopter yarding, which leaves a residual forest without detectable treatment when viewed from a distance.

encing a high rate of mortality around 1880.

- Yellow-cedar is the principal victim.
- Yellow-cedar trees die at various ages.
- No biotic agent appears to be the primary cause.
- Root systems are shallow, and fine root mortality is the initial symptom.
- Mortality occurs on wet, poorly drained soils.
- Mortality is concentrated in open- canopy stands where trees and soils are exposed.
- A high rate of mortality does not occur at high elevations or on low elevation sites with good drainage even though yellow-cedar may be present.
- AU affected sites have cedar snags dating to the time of onset, presumably 1880.
- Local spread is limited to short distances and occurs along a drainage gradient.

Possible Abiotic Factors

Epidemiological evidence and the lack of aggressive biotic factors suggest that some abiotic factor, probably associated with poor drainage, incites decline. Clues from our studies provide insight into which abiotic factors may be the primary stress.

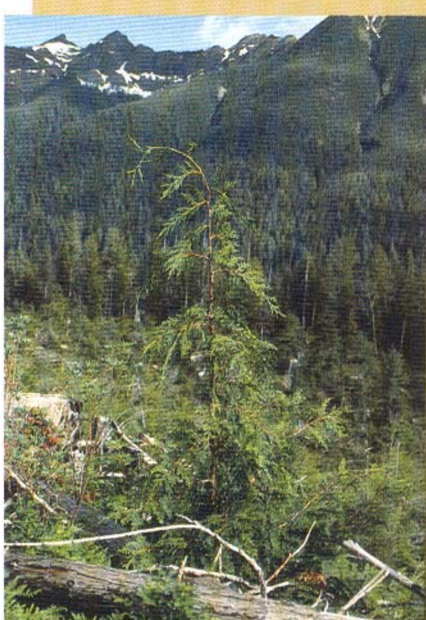
Bog expansion. One suggested abiotic cause of yellow-cedar decline is that bogs, for climatic or other reasons, are advancing onto the adjacent, semi-bog sites where so many trees are dying (Klinger 1988). Changing from forest to bog requires waterlogging of the forest floor, which could result from a proliferation of *Sphagnum* sp. moss or inhibited drainage through hardpan formation. These processes may lead to the death of forest trees as oxygen or nutrients become less available in wet soil. Whether there is a general succession from forest to bog or from bog to forest in southeast Alaska is unresolved. The relatively high rate of mortality for yellow-cedar (65 percent of its basal area), a species thought to be adapted to wet sites, compared with a lower incidence of mortality for other conifers (e.g., 29 percent for hemlock), seems to contradict the simple hypothesis that expanding bogs are the culprit (Hennon et al. 1990b).

Soil toxicity. Toxic substances in soils could kill fine roots, triggering the sequence of symptoms. Tree death may be rapid or slow, depending on the concentrations of such toxins or involvement of secondary organisms. Preliminary analyses from foliar and soil nutrients suggest that an inorganic toxin is probably not to blame because elements occurred in similar levels in healthy and dying trees and on sites with and without intense mortality. Organic toxins developing in saturated, organic soils would be more likely stressors in yellow-cedar decline. Decomposition in these soils is at least partially anaerobic, and by-products could kill vegetation. Perhaps yellow-cedar is more sensitive to such hypothetical organic compounds than other tree species.

,Freezing. Another explanation for why yellow-cedars are dying around bogs is their limited protection from atmospheric events. Cedar trees on such sites are open grown and probably more vulnerable to extreme weather events (e.g., freezing, desiccation) than cedars growing within protective canopies. Perhaps the death of some trees along bog edges following such weather

Reproduction: Yet Another Problem for Yellow-Cedar

Forest decline is not the only threat to yellow-cedar. Inadequate reproduction compromises the species in some portions of its range. Natural regeneration occurs in some parts of southeast Alaska but not in others. Vegetative reproduction occurs in boggy areas (some of which have decline), where lower limbs root adventitiously, but such layering is not common in more productive, healthy forests, and it does not occur on harvested sites.



Paul E. Hennon

If reduced snowpack leaves yellow-cedar seedlings and saplings exposed, browsing deer may compound the problem of the species' naturally low regeneration.

Reasons for poor natural regeneration in some areas are not clear but may be partly attributable to the species' low seed production. But some seed is produced, and the abundance of young seedlings is highly correlated with the live basal area of yellow-cedar trees. The lack of older seedlings and saplings in many stands and harvested units may be due to intense browsing by deer. A warmer winter climate may trigger more than yellow-cedar decline: mild winters with reduced snowpack could favor higher deer populations—and leave regeneration more exposed to browse—than in colder previous centuries.

As long as light and drainage are not limiting, yellow-cedar seedlings planted in southeast Alaska have excellent survival and growth (Hennon 1992). Seed collection and planting of yellow-cedar seedlings are now operational on the Tongass National Forest. In British Columbia, difficulties in cone collection and slow, unpredictable seed germination have prompted nurseries to produce yellow-cedar planting stock from rooted cuttings, called stecklings.

events would cause adjacent trees to lose protection and likewise become vulnerable to damage during subsequent events. Such action might lead to a slow, local spreading of mortality from open stands in bogs and semibogs to more productive adjacent forests.

Any actual freezing damage may be to fine roots, whose necrosis is the initial symptom on declining trees. Fine roots of yellow-cedar are very shallow, especially in the saturated soils where decline is concentrated. Wet soils would be less insulating and lose heat more quickly than drier soils with better drainage. The hypothesis of "xylem injury by cavitation" was proposed by Auclair and others (I 992) to ex- plain several forest declines where chronic injury to xylem results from sudden shifts from mild weather to frigid temperatures. Such events can lead to cavitation: translocation streams in trees are disrupted by formation of gas bubbles when fluids and tissues freeze. This process is reversible if gases are dissolved but may be irreversible if trees endure extreme or repeated weather events.

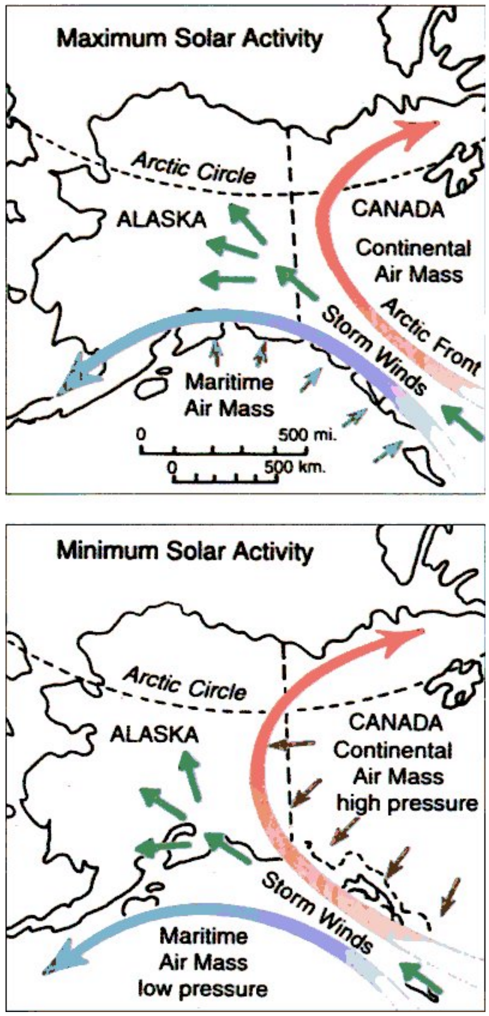


Figure 2. Typical influences of the maritime air mass (top) in southeast Alaska and its displacement offshore by the continental air mass *(bottom)* (from Miller 1985). These models may be used to understand general climatic patterns influenced by cycles of solar radiation or sudden shifts to frigid temperatures during winter in southeast Alaska.

interaction of Climate

The emergence of cedar decline late in the 1800s on numerous islands with intact yellow-cedar forests suggests that if an organic toxin is the primary cause of decline, then something triggered its widespread presence or increased concentrations. Higher precipitation or altered transpiration could lead to more anaerobic decomposition and trigger soil toxicity. Like- wise, a change in weather patterns might make either the bog expansion or the freezing hypotheses plausible. In either case, however, the lack of decline in cedar forests at higher elevations or outside the distribution of cedar decline must be reconciled.

Moderate climatic warming during winter months would dramatically affect patterns of snow deposition and duration in southeast Alaska. Because of maritime influences, winter temperatures currently average around freezing and precipitation is heavy throughout much of the region. Whether precipitation falls as rain or snow is controlled by minor temperature changes. Slightly warmer winter temperatures, particularly at low elevations, would mean rain, and the snowpack (and its duration) would be reduced or eliminated.

Nevertheless, southeast Alaska is sometimes frigid when cold arctic air from interior northwest Canada pushes a low-pressure warm system offshore *(@6g. 2)* and brings clear, sometimes windy weather with dramatic drops in temperature. Such events occur sporadically most every winter and have variable duration before more typical maritime conditions return. If soils are unprotected because of inadequate snowpack, the fine roots of trees growing in wet soils at low elevations, where decline is severe, would be susceptible to freezing because of their shallow rooting. Limited decline on wet sites at higher elevations and those sites to the northwest would be explained by the persistent winter snowpack in these areas, even in today's presumed warmer climate.

The distribution of yellow- cedar decline appears to be associated with known climatic patterns in southeast Alaska. The eastern perimeter of decline is somewhat restricted to the warm side of isotherms (Anderson 1955) de- rived from the three winter months (fig. 1). The perimeter is apparently associated with slightly warmer isoclines (31' to 33' F) as latitude increases.

A relationship between winter climate and the distribution of decline suggests that snowpack could be a factor in the etiology of decline. Heavy snowfall occurs at all elevations within the range of yellow-cedar north and northwest of the distribution of cedar decline; to the South, arctic continental air masses may not cause such an extreme or rapid drop in temperature. That concentrated mortality is restricted to low elevations is a further clue that climate, or more specifically snowpack, is a factor in yellow-cedar decline; however, analyses of snowpack depth and duration (Bowling and Slaughter 1983) are limited by the dearth of weather stations at middle and higher elevations.

Records from weather stations and analyses of climate are best documented for the 20th century in Alaska after the onset of yellow-cedar decline; there are few instrument records of temperature before 1900 (Juday

1984). Interpretations of previous climatic variation suggest a warming trend has occurred in most of Alaska since the late 1800s (Hamilton 1965). This conclusion is based on reconstructions of Alaskds climate made by comparing Alaska's 20th-century weather with locations having longer weather records. The Little Ice Age ended during the late 1800s, but Miller (1985) suggests that there has been much variation within this time of warming. Recent maximum glacial advance occurred in the 1600s through the early 1800s, according to Heusser (1952), but since about 1850, recession has been continuous in most areas of southeast Alaska. Recession was very rapid about 1900 and during the 1930s. Meteorological records indicate that the late 1880s were colder than today in many locations of western North America (Heusser 1952). Techniques involving the measurement of oxygen and hydrogen isotopes in the wood of old trees (Burk and Stuiver 1981) could be used to estimate average annual temperature and humidity in southeast Alaska before, during, and after the presumed onset of yellow-cedar decline.

Conclusions

Yellow-cedar decline appears to be an outstanding example of a naturally induced forest decline. Extensive mortality before 1900 on numerous remote, undisturbed sites without nearby sources of anthropogenic pollutants argues against atmospheric pollution as the cause of decline. Climatic warming, which apparently coincided with the onset of extensive yellow-cedar mortality, could be responsible for triggering some stress factor that has led to the demise of yellow-cedar forests on some 500,000 acres. Warmer temperatures could influence crucial environmental factors by, for example, changing winter precipitation from snow to rain. Changes in temperature or precipitation may affect decomposition processes, perhaps resulting in the formation of soil compounds toxic to yellow-cedar. Research on possible abiotic factors, such as freezing of fine roots and soil toxicity, and their link to climatic change, could solve the mystery.

If climate has been a trigger, then yellow-cedar decline in Alaska may be an excellent example of the devastating effects of a moderate climate shift on a forest ecosystem. Long-lived tree species that do not reproduce often, such as yellow-cedar, may be unable to adapt to a changing environment. That inability to adapt could explain the enigma of what is killing this de- fensive tree. mi

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PautE Hennon (e-mail.- PHennon@ fi.fed.us) is research pathologist, USDA Forest Service, State and Private Forestry, and Pacific Northwest Research Station, 2770 Sherwood Lane, Suite 2A, Juneau, AK99801; Charles G. Shaw III is Tongass issues coordinator, Pacific Northwest Research Station, Juneau, Alaska.