Electrical Properties and Rate of Decay in Spruce and Fir Wood

Walter C. Shortle and Kevin T. Smith

Research plant pathologist, U.S. Department of Agriculture, Forest Service, P.O. Box 640, Durham, NH 03824; and postdoctoral research fellow, Department of Botany and Plant Pathology, University of New Hampshire, Durham.
Current address of second author: U.S. Department of Agriculture, Forest Service, P.O. Box 640, Durham, NH 03824.
This research was supported in part by the Canada–United States Spruce Budworms Program.
Trade, firm, or corporation names are included for information purposes only, and do not imply endorsement or approval by the U.S. Department of Agriculture, Forest Service.
Accepted for publication 21 October 1986.

ABSTRACT

Shortle, W. C., and Smith, K. T. 1987. Electrical properties and rate of decay in spruce and fir wood. Phytopathology 77:811-814.

Electrical resistance measurements were related to both the occurrence of discolored and decayed wood in red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*) sites and the rates of decay in balsam fir in vitro. Internal electrical resistance (R_i) of spruce and fir was measured for three sites per species and one mixed spruce-fir site in Maine and New Hampshire. Spruce with $R_i > 250$ kΩ (low ionization) had no discolored or decayed wood in stem cross sections at 140 cm above groundline. Within fir sites, as the percentage of trees with $R_i < 100$ kΩ (high ionization) increased, the mean cross-sectional area of discolored and decayed wood also increased. Electrical properties of aqueous extracts from various types of balsam fir wood were associated with different rates of decay caused by *Haematostereum sanguinolentum* and other fungi in vitro. Wood located interior to sapwood, nondiscolored, and of relatively low ionization decayed at the slowest rate. Visibly identical wood with relatively high ionization decayed at a faster rate, equal to the rate of decay by *H. sanguinolentum* of discolored wood. As wood became more altered as a result of the decay process in living trees, rates of decay by tree decay pathogens increased in vitro.

Additional key words: decay tests, white rot.

Detection and measurement of wood decay in forest stands and individual trees have long concerned forest pathologists (8,23). Estimates of the extent and categories of decay were developed on the basis of the visual appearance of decayed wood (11). However, Boyce (2) and Hubert (11) recognized that the decay process extends beyond the limits of visual detection. Detection of these early stages of decay in forest trees before the development of visible evidence of discoloration and decay would allow more time for remedial action to reduce disease losses in forest stands. The structural integrity of wood is lost early in the decay process and is difficult to detect using traditional methods (24).

Electrical methods have been developed to estimate the relative growth potential of spruce-fir stands as an index of vulnerability during severe outbreaks of defoliators (4). Measurements of cambial electrical resistance taken during the growing season have been related to cambial growth (1,22) and response to active stress (19,20). Preliminary studies of changing electrical, chemical, and biological properties within the stemwood of spruce and fir trees indicated that a single measurement of internal electrical resistance at a fixed depth may provide a useful index of susceptibility to tree decay in spruce-fir stands (21).

The purpose of this study was to determine the relationship of electrical properties of wood and wood extracts to the development of the progressive stages of decay in trees of mature spruce-fir stands.

MATERIALS AND METHODS

Internal electrical resistance, R_i, measurements were made in 10 canopy trees (dominants or codominants) in seven spruce-fir stands in Maine or New Hampshire during June or July. Three stands were predominantly red spruce, *Picea rubens* Sarg.; three predominantly balsam fir, *Abies balsamea* (L.) Mill.; and one equally mixed spruce and fir. Two sample trees were selected on each of five 400-m^2 plots per stand, the first plot chosen at random and the other four at cardinal points 80 m from center to center (except in the mixed spruce-fir stand, in which two spruce and two fir trees were selected in each plot). Trees were 50–80 yr old and 16–25 cm in diameter at 140 cm above ground.

To measure R_i, a hole 2.5 mm in diameter × 6 cm deep was drilled parallel to the ground and toward the pith at 140 cm above the ground. R_i was measured in kiloohms (kΩ) at a depth of 4.5 cm using a digital Shigometer, Model OZ-67 (Osmose Wood Preserving Company, 980 Ellicott Street, Buffalo, NY 14209), fitted with a 20-cm twisted wire electrode. The depth of 4.5 cm, which was determined empirically in an earlier study (21), was

considered optimal for representing columns of infected wood large enough to constitute serious potential damage to the stand.

Two additional balsam fir trees were cut at the Bartlett Experimental Forest, Bartlett, NH. These trees had well-defined columns of discolored and decayed wood associated with infections of *Armillaria mellea* (Vahl ex Fr.) Kummer in the butt section, 20–150 cm above ground. Serial 5-cm disks were cut from where the column had visibly white-rotted wood to well beyond the associated visibly discolored wood. These disks were air-dried and used in bioassays of relative decay resistance for comparison with disks taken at random at 140 cm above the ground and representing the seven spruce-fir stands.

Determination of electrical and chemical properties of water extracts. R_i values for spruce trees were not highly variable (Table 1); therefore, five sample disks were selected at random for analysis of water extracts and bioassays. Because R_i values of fir were highly variable, 22 disks were selected to represent the varying degrees of tissue alteration occurring in fir stands. Tissue samples were obtained from freshly sanded, debarked, air-dried disks along four radii drawn on the upper transverse face before debarking. Three sample positions per radius were used: 1.2 cm inward from the outer bark (sapwood), 4.5 cm inward (corewood), and one-half the remaining distance to the pith (corewood) (Fig. 1A). Samples were removed using flat-headed drill bits held in an electric drill press. A 1.8-cm bit was used to clean the disk surface to a depth of ca. 0.5 cm and a 1.0-cm bit was used to remove sample shavings from the next 3 cm of wood. Samples were drilled from discolored and decayed wood (white rot or brown rot) where it was available. The collected wood shavings were combined for all four holes at each of the three positions for each disk. The combined tissue samples were ground in a Wiley mill to pass through a 425-μm sieve. Drilled disks were used in bioassays of relative decay resistance.

TABLE 1. Percentage of tree stems within internal electrical resistance (R_i) categories in balsam fir and red spruce related to percentage of discolored and decayed wood (wood types C + D)

Species	Site	Occurrence (%)[a] at R_i of >250 kΩ	Occurrence (%)[a] at R_i of <100 kΩ	Mean area (%)[b]
Red spruce	23	100	0	0
Red spruce	15	100	0	0
Red spruce	9	100	0	0
Red spruce	28	100	0	0
Balsam fir	1	50	30	3
Balsam fir	23	40	50	10
Balsam fir	26	10	70	24
Balsam fir	14	0	90	30

[a] Occurrence is expressed as percentage of tree stems with $R_i > 250$ or < 100 kΩ at depth of 4.5 cm (140 cm above ground). Sum of less than 100% indicates that some stems were intermediate in R_i. Ten stems were measured per site.

[b] Mean cross-sectional area of discolored and decayed wood taken at 140 cm above ground expressed as percentage of total cross-sectional wood area.

Duplicate 0.3-g samples of oven-dried (103 C), ground tissue were extracted with 20 ml of distilled, deionized water in a 25-mm-diameter test tube in a heater block at 90 C for 1 hr with gentle vortexing at 15 and 30 min. Extracts were gravity filtered using Whatman No. 1 filter paper. Ten-milliliter samples of each extract were cooled to ca. 25 C and added to a 50-ml beaker. Inserted in the sample beaker was a No. 2E Delmhorst moisture-detection electrode with a pair of 54-mm stainless steel pins, separated by 17 mm and connected to a Shigometer (Fig. 1B). Measurements of extract electrical resistance (R_e) in kiloohms were recorded at 15 sec, the extract pumped from the beaker, and the beaker rinsed well by washing and pumping out three 40-ml volumes of deionized, distilled water. The pH of 2 ml of the extract was determined using a small combination pH electrode. The total phenol content of the extract was determined on 0.25-ml samples by the Folin-Ciocalteau method using one-half the standard amount of each reagent (10).

Bioassay of relative decay resistance. Weight loss because of decay was determined using an agar-block method previously used for red pine and Douglas fir (12), except that the block shape was changed from 10 × 20 × 20 mm (20 × 20 mm end grain) to 50 × 10 × 5 mm (10 × 5 mm end grain), which is similar to the size recommended for rapid evaluation of wood-preserving fungicides (3,5). The sample blocks were split from air-dried disks between drill holes in the same growth rings sampled by drilling (Fig. 1A). Sample blocks were oven-dried for 24 hr at 103 C, cooled in a desiccator, weighed to determine initial oven-dried weight, placed in sterile petri dishes, heated at 103 C for another 24 hr, cooled, and placed aseptically on the mycelium of decay fungi growing on 25-ml malt-yeast agar (malt extract at 10 g/L, yeast extract at 2 g/L, and agar at 20 g/L) in 8-oz French square bottles in the horizontal position. The decay fungi were *Coriolus versicolor* (L. ex Fr.) Quel., incubated 1 wk at 23 C before blocks were added; *Haematostereum sanguinolentum* (Alb. & Schw. ex Fr.) Pouz.,

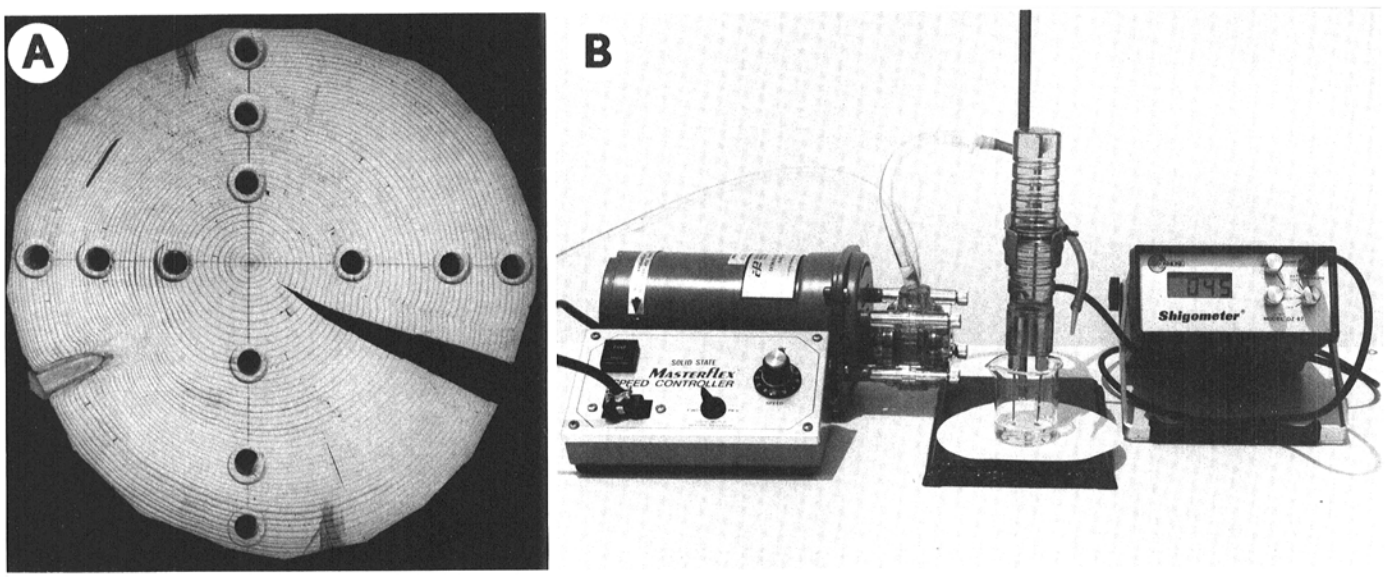

Fig. 1. Sampling position and equipment for measuring extract electrical resistance. **A,** Balsam fir disk drilled to remove samples. **B,** Electrode pins inserted into sample extract contained in beaker. Electrical resistance values (kiloohms) are displayed on Shigometer (right). Sample is removed using peristaltic pump (left).

incubated 2 wk at 23 C before blocks were added; and *Amylostereum chailletii* (Pers. ex Fr.) Boid., incubated as *H. sanguinolentum*.

Triplicate sample blocks of each of the four types of wood found in the core of fir trees (defined in Table 2) were harvested at 2-wk intervals for 12 wk (*C. versicolor*) or at 4-wk intervals for 16 wk (*H. sanguinolentum* and *A. chailletii*). Mycelium was carefully scraped from the surface of harvested blocks and the blocks were oven-dried for 24 hr at 103 C to determine the final oven-dried weight. Weight loss resulting from decay was calculated as percentage weight loss.

RESULTS

Characterization of spruce and fir sites. The R_i of all spruce trees was >250 kΩ at a radial depth of 4.5 cm, 140 cm above the ground; no discoloration or decay was observed in the butt section of these trees (Table 1). The R_i of fir trees was frequently <100 kΩ, accompanied by discolored and decayed wood generally located away from the point of R_i measurement. The mean transverse area of discolored and decayed wood at 140 cm above the ground in fir trees was positively correlated with the proportion of fir trees with R_i <100 kΩ, $r^2 = 0.975$.

Electrical and chemical properties of wood extracts. All spruce corewood sampled for electrical and chemical properties was categorized as type A—R_e and pH equal to sapwood, water-soluble phenol concentration at least twice that of sapwood, and accompanied by no visible discoloration or decay. In air-dried, sanded disks, this corewood was identical in color to sapwood, although in freshly cut disks the corewood appeared lighter in color.

Balsam fir yielded type A corewood in 42% (16/38) of samples free of discoloration and decay. However, 58% (22/38) of the samples that appeared similar to type A were designated type B because of significantly lower R_e (Table 2). Type B corewood had R_e similar to discolored wood that was designated type C (Table 2). The pH and concentration of water-soluble phenols were similar among wood types A, B, and C. Wood type C was most frequently located between visibly decayed wood and type B wood. Most frequently, the decayed wood was the result of white rot and was termed type D. Brown rot was also encountered, apparently as a result of root infections, and was termed wood type D′. Wood type D′ had a lower pH and higher phenol concentration than type D. Wood types B, C, D, and D′ had similar R_e.

Bioassays of decay resistance. Results from samples taken from randomly selected disks were equivalent to those from samples taken serially from well-defined decay columns associated with *A. mellea* in which wood types A–D were contiguous (Table 3). Greatest amounts of decay as indicated by weight loss occurred with wood type D for all combinations of incubation time and decay fungus (Table 3). The least amounts of decay occurred with wood type A in all cases. After 8 wk of incubation, type C was more decayed by *C. versicolor* and *H. sanguinolentum* than type B. After 12 and 16 wk of incubation with *H. sanguinolentum*, similar amounts of decay occurred in type B and C corewood with significantly less decay in type A. After 16 wk of incubation with *A. chailletii*, wood types A, B, and C were only slightly decayed, yet the extent of decay of type D fell within the ranges for the same wood type incubated with the other fungi. All test blocks at time of harvest had moisture contents of 100–150%.

DISCUSSION

R_i permits characterization of spruce and fir sites for frequency of discoloration and decay (Table 1). It is currently used to detect

TABLE 3. Comparative decay rates of three decay fungi on four different types of nonsapwoods taken from balsam fir

Inoculum	Incubation time (wk)	Weight loss from decay (%)[a] A[b]	B	C	D
Coriolus versicolor					
Among trees[c]	2	0	0	0	6
	4	0	0	1	12
	6	0	1	1	24
	8	1	1	3	30
	10	1	3	8	33
	12	1	6	16	40
Haematostereum sanguinolentum					
Among trees	4	0	0	0	7
	8	2	3	7	12
	12	3	14	16	27
	16	6	22	25	32
Within trees	4	0	0	0	5
	8	3	4	8	12
	12	5	10	14	24
	16	6	19	23	30
Amylostereum chailletii					
Among trees	4	0	0	0	4
	8	1	1	1	20
	12	1	1	1	31
	16	2	3	3	38
Within trees	4	0	0	0	5
	8	1	1	2	15
	12	1	2	3	26
	16	2	3	5	38

[a] Means of three observations joined by common underline do not differ significantly according to ANOVA, $P \leq 0.05$.
[b] Type A = wood free of discoloration and decay and electrical resistance of extracts (R_e) ≥ sapwood extracts; type B = wood free of discoloration and decay and R_e < sapwood extracts; type C = wood discolored and R_e < sapwood extracts; type D = wood decayed, white pocket rot, and R_e < sapwood extracts.
[c] Among trees = randomly selected disks of balsam fir containing A, B, C, or D type nonsapwoods. Within trees = disks taken from columns in which A, B, C, and D tissues were contiguous.

TABLE 2. Chemical and electrical properties of extracts of balsam fir and red spruce wood

Species	Tissue	*n*	R_e (kΩ)[a] Range	$\bar{x} \pm$ CL[b]	Phenol (mg/g) Range	$\bar{x} \pm$ CL	pH
Red spruce	Sapwood	5	29–41	34 ± 5	0.5–1.2	0.8 ± 0.3	5.5–5.8
Red spruce	Nonsapwood[c]	10	29–43	36 ± 4	2.1–4.7	3.6 ± 0.6	5.3–5.7
Balsam fir	Sapwood	22	25–40	33 ± 2	0.8–1.7	1.3 ± 0.1	5.4–5.9
Balsam fir	Nonsapwood[d]	61	6–52	19 ± 2	2.4–12.0	4.9 ± 0.5	3.4–6.2
Balsam fir	A	16	24–52	31 ± 4	3.6–5.8	4.3 ± 0.4	5.5–6.2
Balsam fir	B	22	10–20	16 ± 2	2.8–7.1	5.0 ± 0.5	5.0–6.2
Balsam fir	C	14	11–20	16 ± 2	3.4–5.2	4.4 ± 0.4	4.9–5.9
Balsam fir	D	6	6–15	12 ± 4	2.4–4.9	3.4 ± 1.1	4.1–5.4
Balsam fir	D′	3	6–16	11	12	12	3.4–4.1

[a] Extract electrical resistance (R_e) expressed as thousands of ohms (kΩ).
[b] CL = Confidence limits. Mean of *n* sample extracts ± t ($P < 0.05$, $n - 1$ df) × standard error.
[c] All red spruce nonsapwood samples examined were designated type A: wood free of discoloration and decay and $R_e \geq$ sapwood extracts.
[d] Aggregate of all nonsapwood samples. Type A = wood free of discoloration and decay and $R_e \geq$ sapwood extracts; type B = wood free of discoloration and decay and $R_e <$ sapwood extracts; type C = wood discolored and $R_e <$ sapwood extracts; type D = wood decayed, white pocket rot, and $R_e <$ sapwood extracts; type D′ = wood decayed, brown rot, and $R_e <$ sapwood extracts.

discoloration and decay in individual trees (16,17). An early stage in the decay process involves increased relative ionization of wood resulting in decreased electrical resistance (18) measurable as R_i and R_e. Degree of penetration by decay fungi has been related to electrical resistance of wood (21).

Wood types A–D represent a continuum of corewood (wood located interior to sapwood found in living fir trees). Type A is the result of age alterations or maturation of sapwood and is commonly termed *heartwood* (14). Type B wood, although superficially similar to type A, differs in being more highly ionized and less resistant to decay in vitro (Table 3). Type B wood occupies an intermediate position in the decay process, eventually resulting in discolored type C wood and ultimately in type D decayed wood. R_i measurements distinguish between type A and types B, C, and D in living trees. The predominant stem decay fungus of balsam fir, *H. sanguinolentum*, discriminated between visually similar wood types A and B after 12 wk and made no distinction between wood type B and discolored wood type C after 12 or 16 wk of incubation. The ubiquitous *C. versicolor*, frequently isolated from living hardwoods and from hardwood and softwood in service (6,25) and often used in tests of decay resistance of conifer wood (5,12,18), distinguished between wood types A, B, and C after 10 wk of incubation. The decay fungus of damaged fir and slash *A. chailletii* (7) made no distinction between wood types A–C, and amounts of decay of all three types were slight; this may be the result of the high humidity maintained in the decay chamber atmosphere, which does not reflect the drier habitat of this fungus. However, *A. chailletii*, as well as the other two fungi, caused substantial weight loss of the type D wood that was partially decayed within the living trees. Factors limiting the rate of decay were thus inherent in the properties of the wood block, and not in the physical conditions of the chamber. This finding that wood decay rates in vitro are increased by the degree of previous decay alteration has been described for sugar maple (15). Differences in decay rates for the wood types were not the result of phenol concentration or pH, which were similar among corewood types A–D (Table 2).

The basic pattern of ionization of fir undergoing the decay process has been described (21) and has been more fully studied in red maple (13). Briefly, increases in ion concentration reflect shifts in metabolism as a result of the response of trees to wounding and interactions with microorganisms. Cations identified in this process are H^+ (especially in the case of brown rot; Table 2) and K^+ with organic anions identified in the maple system.

The modified agar-block decay test of decay resistance was designed to model decay column expansion in living trees. The tangential face of the wood sample is directly applied to the mycelium, as is consistent with the lateral spread of a decay fungus operating from an established food base. The small test samples (50 × 10 × 5 mm) permit the sampling of small zones or layers of different wood characteristics, allow adequate aeration, and aid in the rapid determination of decay resistance. The wood samples are dried in a low-temperature (103 C) oven to minimize alteration of the wood substance and destroy potential microbial contaminants before testing. Questions about the validity of the standard soil-block test (American Society for Testing and Materials D 2017) have arisen, especially concerning the white-rot fungi used in this investigation (9). The traditional test better reflects the durability of wood products such as fence posts in soil contact than the development of decay in living trees.

Electrical resistance measurements in the field have the potential to assist forest assessment for wood alterations arising from the decay process, which could influence harvest scheduling and application of treatments. Distinguishing between wood types that differ in relative ionization is important in determining potential for subsequent decay in trees and products.

LITERATURE CITED

1. Blanchard, R. O., Shortle, W. C., and Davis, W. 1983. Mechanism relating cambial electrical resistance to periodic growth rate of balsam fir. Can. J. For. Res. 13:472-480.
2. Boyce, J. S. 1920. The dry rot of incense cedar. U.S. Dep. Agric. Bull. 871. 58 pp.
3. Bravery, A. F. 1979. A miniaturised wood-block test for the rapid evaluation of wood preservative fungicides. Pages 57-65 in: Screening Techniques for Potential Wood Preservative Chemicals. Swed. Wood Preserv. Inst. Rep. 136. 149 pp.
4. Davis, W., Shortle, W. C., and Shigo, A. 1980. Potential hazard rating system for fir stands infested with budworm using cambial electrical resistance. Can. J. For. Res. 10:541-544.
5. Duncan, C. G., and Deverall, F. J. 1964. Degradation of wood preservatives by fungi. Microbiology 12:57-62.
6. Duncan, C. G., and Lombard, F. F. 1965. Fungi associated with principal decays in wood products in the United States. U.S. For. Serv. Res. Pap. WO-4.
7. Etheridge, D. E., and Morin, L. A. 1963. Colonization of decay fungi of living and dead stems of balsam fir following artificial injury. Can. J. Bot. 43:181-183.
8. Hartig, R. 1874. Important diseases of forest trees. Translated by W. Merrill, D. Lambert, and W. Liese, 1975. Phytopathological Classics 12. American Phytopathological Society, St. Paul, MN. 120 pp.
9. Highley, T. L., and Scheffer, T. C. 1970. A need for modifying the soil block method for testing natural resistance to white rot. Mater. Org. 5:281-292.
10. Horowitz, W., ed. 1960. Official Methods of Analysis of the Association of Official Agricultural Chemists. 9th ed. Association of Official Agricultural Chemists, Washington, DC.
11. Hubert, E. E. 1924. The diagnosis of decay in wood. J. Agric. Res. 29:523-567.
12. Owens, C. W., Shortle, W. C., and Shigo, A. L. 1980. Preliminary evaluation of silicon tetrachloride as a wood preservative. Holzforschung 34:223-225.
13. Shevenell, B. J., and Shortle, W. C. 1986. An ion profile of wounded red maple. Phytopathology 76:132-135.
14. Shigo, A. L., and Hillis, W. E. 1973. Heartwood and discolored wood, and microorganisms in living trees. Annu. Rev. Phytopathol. 11:197-222.
15. Shigo, A. L., and Sharon, E. M. 1970. Mapping columns of discolored and decayed tissues in sugar maple, *Acer saccharum*. Phytopathology 60:232-237.
16. Shigo, A. L., and Shortle, W. C. 1985. Shigometry: A reference guide. U.S. For. Serv. Agric. Handb. 646.
17. Shortle, W. C. 1979. Detection of decay in trees. J. Arboric. 5:226-232.
18. Shortle, W. C. 1982. Decaying Douglas-fir wood: Ionization associated with resistance to a pulsed electric current. Wood Sci. 15:29-32.
19. Shortle, W. C. 1983. Effects of acute stress on fir and spruce trees vary as growth potential determined electrically. (Abstr.) Phytopathology 73:1347.
20. Shortle, W. C. 1984. Electrical methods for evaluating growth and decay potentials of fir/spruce sites. Pages 99–103 in: Spruce-Fir Management and Spruce Budworms. D. Schmitt, ed. U.S. For. Serv. Gen. Tech. Rep. NE-99. 217 pp.
21. Shortle, W. C., and Ostrofsky, A. 1983. Decay susceptibility of wood in defoliated fir trees related to changing physical, chemical, and biological properties. Eur. J. For. Pathol. 13:1-11.
22. Smith, K. T., Blanchard, R. O., and Shortle, W. C. 1984. Cambial electrical resistance related to the number of vascular cambial cells in balsam fir. Can. J. For. Res. 14:950-952.
23. Wagener, W. W., and Davidson, R. W. 1954. Heart rots in living trees. Bot. Rev. 20:61-134.
24. Wilcox, W. W. 1978. Review of literature on the effects of early stages of decay on wood strength. Wood Fiber Sci. 9:252-257.
25. Zabel, R. A., Lombard, F. F., Wang, C. J. K., and Terracina, F. 1985. Fungi associated with decay in treated southern pine utility poles in the eastern United States. Wood Fiber Sci. 17:75-91.