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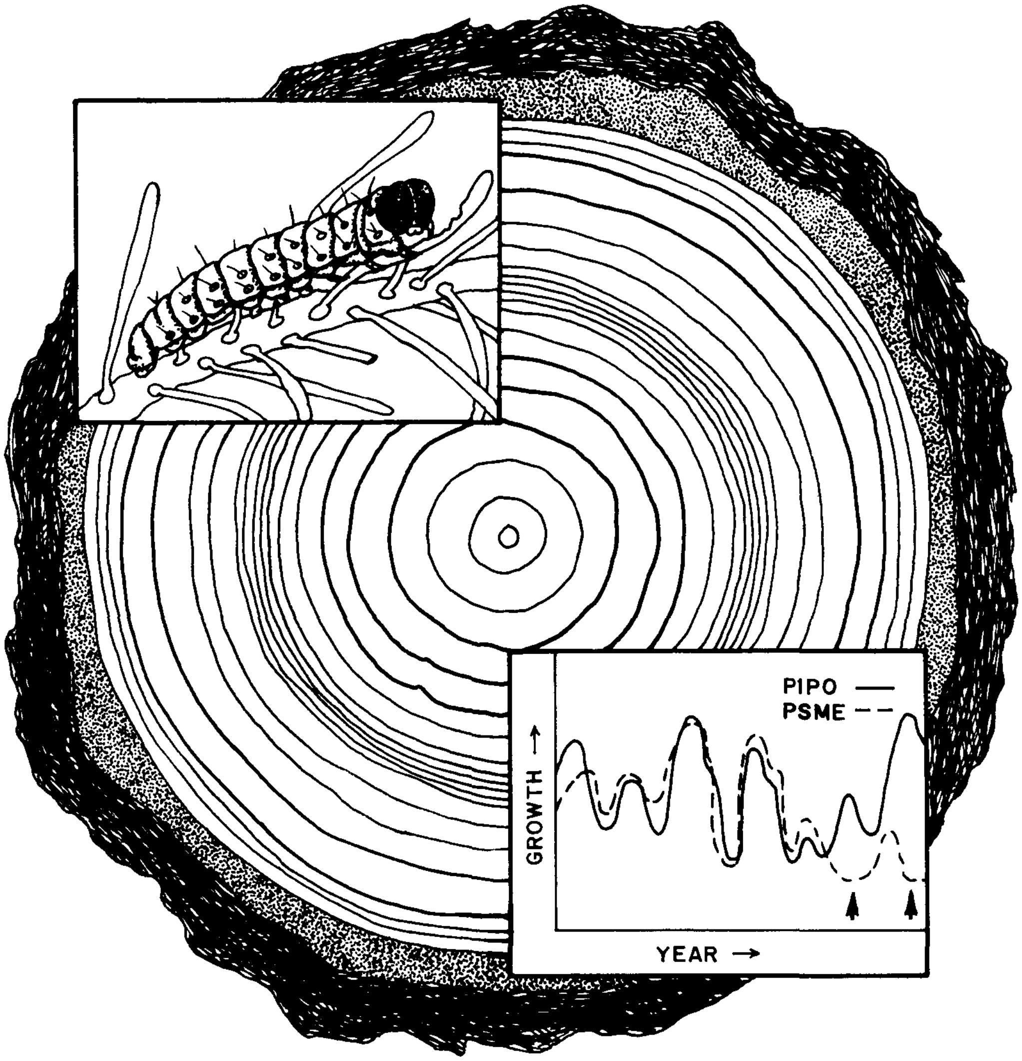
Agriculture
Handbook
No. 639

Spruce Budworms Handbook

Using Dendrochronology To Measure Radial Growth of Defoliated Trees



In 1977, the United States Department of Agriculture and the Canadian Department of the Environment agreed to cooperate in an expanded and accelerated research and development effort, the Canada/United States Spruce Budworms Program (CANUSA), aimed at the spruce budworm in the East and the western spruce budworm in the West. The objective of CANUSA was to design and evaluate strategies for controlling the spruce budworms and managing budworm-susceptible forests, to help forest managers attain their objectives in an economically and environmentally acceptable manner. The work reported in this publication was funded by the Program.

canusa

Canada
United States
Spruce Budworms
Program

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Contents

Using Dendrochronology To Measure Radial Growth of Defoliated Trees

by Thomas W. Swetnam, Marna Ares Thompson, and Elaine Kennedy Sutherland[1]

Introduction

Budworms (*Choristoneura* spp.) have repeatedly defoliated millions of hectares of conifers throughout North America. The seriousness of the problem is underscored by research findings in eastern Canada and the northern U.S. Rocky Mountains that the extent, severity, and frequency of budworm outbreaks have increased in the 20th century, primarily as a result of human-induced changes in forest structure and composition (Blais 1983, Carlson and others 1983, Fellin and others 1983).

Measurements of growth reduction and mortality may be the most important information in assessing damage caused by the budworm. Forest-pest managers can use this information to decide on appropriate responses and the timing of management actions. The extent of infestation, tree mortality, and height-growth reduction can usually be determined from aerial surveys and onsite observations, but measuring radial-growth reduction requires detailed analysis of tree-ring widths.

This paper describes dendrochronological techniques that can be applied to tree-ring samples to measure radial growth during past and present budworm outbreaks. The techniques will be illustrated with examples from a radial-growth study of trees infested by western spruce budworm (*C. occidentalis* Freeman) in northern New Mexico.[2] Most techniques described here have been standard for many years in dendroclimatic and dendroecologic studies (Anon. 1977, Fritts 1971) and have many advantages over other types of tree-ring analyses for evaluating effects of insects on radial growth. In particular, the rigorous use of cross-dating and standardizing can provide more precise measurements and improved understanding of the effects of insects, climate, and other environmental factors on tree growth.

Descriptions of dendrochronological techniques included here are not exhaustive because they are fully described elsewhere. Procedures are summarized in the context of the budworm problem so that they may be more accessible and useful to the interested researcher. The computer programs are described in general terms only. The programs (in FORTRAN 5), operating instructions, and limited technical advice are available from the Laboratory of Tree-Ring Research, Data Processing Section, University of Arizona, Tucson 85721. A small fee is charged for magnetic tape, handling, and shipping.

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[1] Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721.

[2] Swetnam, T. W.; Thompson, M. A. Dendrochronological assessment of western spruce budworm effects on tree growth in northern New Mexico. Manuscript in preparation.

Review of Methodologies

Researchers have used many different approaches to measure effects of budworm on radial growth of defoliated trees (for example, Alfaro and others 1982, 1985; Archambault 1983; Beveridge and Cahill 1984; Blais 1962, 1965, 1983; Brubaker and Greene 1979; Carlson and McCaughey 1982; Duff and Nolan 1953; Ferrell 1980; Ferrell and Scharpf 1982; Mott and others 1957; Thomson and Van Sickle 1980; Wickman and others 1980; and Williams 1967). MacLean (in press) summarized the results of these and many other studies on how budworm defoliation affects growth and yields.

Most of the studies cited have been successful in identifying past budworm outbreaks and had varying success in measuring growth reduction on surviving trees. All techniques, however, including those described in this paper, have one or more of the following disadvantages:

- Tree-ring samples not cross-dated. Without cross-dating, the chance of error increases because growth anomalies, such as missing and false rings, may not be detected. The likelihood of missing rings is highest in trees stressed by drought or defoliated by insects (Evenden 1940, Keen 1937, O'Neil 1963).
- Tree-ring series not standardized (systematic, biological growth trends removed). The effects of budworm may be obscured by growth trends related to increasing tree age and circumference.
- Inadequate control for climatic or other environmental effects through use of host trees only. Observed growth declines may be partly or entirely caused by drought or other factors not related to budworm damage.
- Using undefoliated (in a current outbreak) host trees to estimate expected growth in defoliated host trees. Some of the control trees may have been infested during past outbreaks or infested at undetected low densities during a current outbreak.
- Nonhost growth used to identify the timing of budworm effects in host trees, but not to correct estimates of growth reduction for climatic or other environmental effects. Timing of past infestations may be correctly identified, but estimates of growth reduction may be inaccurate because of environmental effects.
- Nonhost growth used to identify effects of budworm on host trees and to correct for climatic effects. Growth-reduction estimates may be biased: nonhost trees growing in the same stand as host trees may benefit from defoliation of host trees, and their growth may accelerate during infestations (Beveridge and Cahill 1984, Carlson and McCaughey 1982, Thomson and Van Sickle 1980). Also, other pests and diseases may have affected nonhost or host growth.
- Use of whole-tree dissection techniques. Because these techniques are extremely time consuming and destroy sample trees, only a few trees can be analyzed practically.
- Increment cores or cross sections taken only from the lower bole of host trees. Growth reduction may be underestimated because the effect of budworm on radial growth is usually more severe and immediate in the crown (Duff and Nolan 1953, Williams 1967).

Many of these problems—but not all—can be circumvented by using the dendrochronological techniques described here. This handbook describes basic procedures of cross-dating and standardizing that can provide reliable and comparable tree-ring chronologies for trees and sites, despite problems of missing or false rings, or different ages and sizes of trees. A technique for removing growth effects not caused by the budworm from host tree-ring chronologies is also described. These methods estimate radial-growth loss in individual host trees by comparing their growth to expected growth, which is determined from the average of a collection of nonhost trees. Appropriate sampling schemes should allow extrapolation of these estimates to forest stands. Growth loss is expressed in percentages of expected growth only, but these measures could be readily translated into volume estimates using existing inventory systems and prognosis models. In addition to obtaining estimates of radial-growth reduction caused by the budworm, cross-dated and standardized tree-ring chronologies provide a data base with a wide variety of other research applications (Sutherland 1983).

Concepts and Requirements of Cross-Dating

Cross-dating is the comparison of ring-width patterns in different trees and the selection of the exact place of correspondence between them (Douglass 1941). Cross-dating between trees is possible because the same or similar environmental conditions limit tree growth throughout a region, and the year-to-year fluctuations in growth-limiting factors produce synchronous variations in ring width (Fritts 1978). Trees that respond to yearly fluctuations in limiting factors by producing larger or smaller rings are termed "sensitive." When growth is not limited by any factor that fluctuates annually, trees consistently produce rings of similar width; such trees are termed "complacent" (fig. 1).

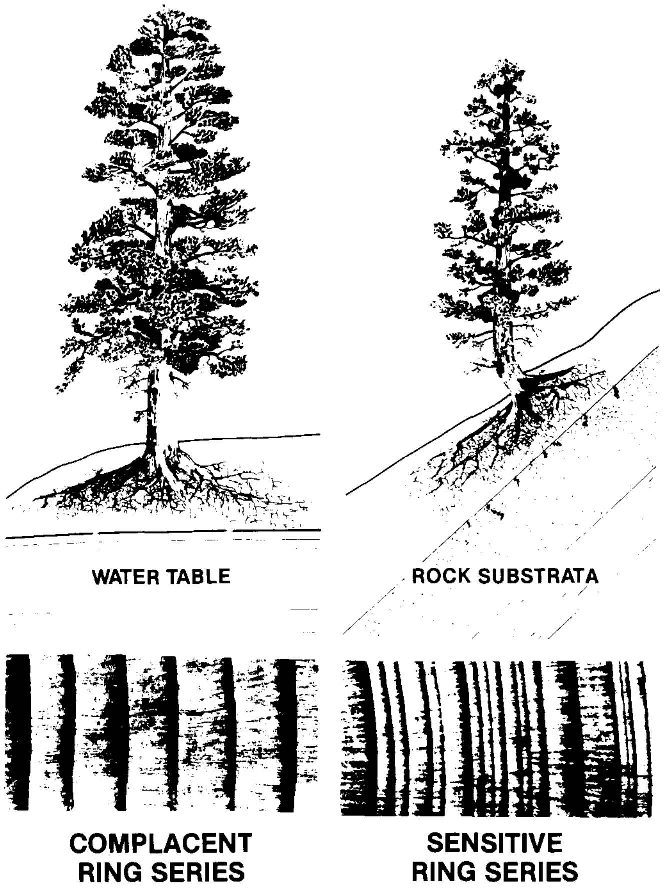


Figure 1—Ring series from a tree growing where water is in constant supply does not reflect precipitation patterns; a tree growing on a xeric site is more sensitive to precipitation.

Seasonal and yearly fluctuations in precipitation and temperature are the most common factors limiting growth in sensitive trees (Fritts 1974). To obtain climatic information from tree-ring series, dendroclimatologists select sites with trees that are most sensitive to climatic fluctuations in the region of interest. Usually, these trees grow on steep slopes, in well-drained soils, and at the upper or lower elevational limits for the species. Conversely, trees in poorly drained soils and near springs, rivers, or other water sources are usually climatically complacent. Figure 1 illustrates the classic effects of site and limiting factors on tree growth, but many recent dendroclimatic studies have shown that cross-datable and climatically sensitive trees can be found in less obviously limiting sites (LaMarche 1982).

Several structural characteristics of trees and tree rings are also necessary for cross-dating:

- The tree species must produce clearly defined, annual growth rings. Although the individual growth rings of many conifers and ring-porous angiosperms are distinct, the rings of diffuse-porous trees (for example, *Populus trichocarpa* Torr. & Gray) do not have distinct boundaries, and these trees cannot be dated accurately.
- One distinct growth ring is produced per year as the result of a single, distinct growing season in the study area.
- The widths of annual rings must be relatively uniform around the tree bole. The pattern of wide and narrow rings along one radius is repeated along any other radius in the tree.
- The tree-ring series must be long enough to be cross-dated. The minimum length is about 50 years. If the series is complacent or extremely sensitive with many absent rings, however, the length of the series and number of specimens should be increased.

Most budworm-infested forests include coniferous trees that have these ring-structure characteristics. Forests are usually composed of trees growing along environmental gradients, however, with ring-width series that range from complacent to sensitive (Fritts and others 1965). Mean sensitivity, a statistic that quantifies ring-width variability, is defined in a later section. Because most radial-growth studies are intended to assess growth of the whole stand, many such studies will have to include relatively complacent trees. Some extremely complacent trees may be impossible to cross-date, but most trees will have enough ring-width variability to be cross-dated.

Computer programs are useful for dating complacent tree-ring series and identifying statistically significant or nonsignificant matches (Baillie and Pilcher 1973, Holmes 1983).

Although the need for cross-datable tree-ring series may limit the application of our method to particular sites within budworm-infested areas, the success of dendrochronologists in cross-dating tree-ring series from relatively mesic sites in the Northwestern United States (Brubaker 1982) and portions of the Eastern United States (Conkey 1984, Cook and others 1982), as well as in many areas of Canada and Alaska (Cropper and Fritts 1981, Jacoby and others 1982), suggests that this method may be used in most areas of North America where budworms occur.

Field and Laboratory Procedures

The choice of areas for studying radial growth depends on several practical considerations, including management objectives, information needs, distributions of past and current infestations, and the representation of habitat types or other land-classification categories. The following sections describe field and laboratory procedures for studying reduction in radial growth within the framework of these considerations. The procedures and strategy are presented in eight steps.

1. Select study sites and collect increment cores or cross sections from the boles of host and nonhost trees, with due consideration to the concepts and principles of dendrochronology.
2. Mount and sand the samples.
3. Cross-date the tree-ring series using the skeleton-plot technique.
4. Measure the ring widths.
5. Develop standardized tree-ring chronologies by indexing and averaging the tree-ring series with the computer programs RWLIST, INDEX, and SUMAC.
6. Graphically compare filtered or unfiltered plots of standardized host and nonhost tree-ring chronologies to identify budworm effects on host-tree growth. Use available insect-infestation records to verify that periods of growth reduction were caused by budworm.
7. Use the nonhost tree-ring chronologies and the TRMCLM program to correct the host tree-ring chronologies for environmental effects.
8. Use the corrected host tree-ring chronologies to estimate growth reduction, growth decline, and recovery rates during identifiable periods of budworm outbreaks.

Site Selection

The ideal study area has host and nonhost trees growing in nearby but separate stands. Because nonhost trees are sampled to serve as a climatic and environmental control, the nonhost collection site should have the same weather patterns as the host-tree collection site, and the two sites should also be comparable in slope angle, aspect, and soils. Host and nonhost sites should be within the same major drainage.

The ideal sampling situation may not occur in many budworm study areas. If no nonhost trees are growing in the area of interest, then nondefoliated host trees near a defoliated host stand might be used as controls. Then, estimations of budworm-induced growth reduction should be restricted to current outbreaks because the nondefoliated host trees might have been defoliated during past outbreaks.

Budworm study areas often include mixed stands of host and nonhost trees, which usually respond similarly to climatic factors. The nonhost trees may have benefited from defoliation of the host trees, however, and the released growth rate could cause overestimation of budworm impact.

Beveridge and Cahill (1984) found that, in stands where less than 10 percent of the basal area was composed of nonhost species, growth rates in ponderosa pine (*Pinus pondersosa* Dougl. ex Laws.) were usually higher at the time of defoliation than before defoliation. In stands where the nonhost component exceeded 20 percent, however, ponderosa pine usually grew at nearly or slightly below predefoliation rates. Although the sample size was small, these data suggest that increased growth of nonhost species because of host defoliation may not be significant in stands where the nonhost component exceeds 20 percent.

The size of collection sites may vary, but collections should generally be restricted to a relatively homogeneous area. Physical features—such as slope angle, aspect, soils, and species composition—should be similar to minimize microsite effects so that individual tree growth and measurements of growth reduction can be compared. Homogeneity within collection sites will also help to assure that averaged measurements from all trees (the site chronology) will be fairly representative of the site.

Records of past and present insect activity for a site should be examined to locate potential collection sites. Records of the timing and extent of past infestations and specific locations of damaged stands can provide independent data to verify that observed periods of growth reduction in the host-tree chronologies were actually caused by the budworm. Corrected host-tree growth may be biased if nonhost or host species have been attacked by other pests or diseases. Review of insect-survey records and preliminary field reconnaissance may help identify such sites.

Collections

After being cross-dated and measured, tree-ring samples are standardized and averaged for each tree and site. Separate chronologies are developed for host and nonhost trees. Fritts (1976) found that 2 cores from each of 10 trees that cross-date well are usually adequate for measuring the average growth response. In complacent sites or where correlation of tree-ring series between trees is low, 25 to 40 samples may be necessary to assess climatic growth response of a stand (Dewitt and Ames 1978).

Sampling strategies have not yet been developed to define the number and types of sample trees or number of samples per tree that are necessary to assess growth response to budworm outbreaks efficiently and reliably. A single, general strategy probably cannot be developed because budworm effects vary within and between trees, stands, and geographic regions, and because the needs of researchers and managers also vary.

Practically, however, considering the time required to collect, prepare, cross-date, and measure tree-ring samples, a reasonable collection size is 2 cores from each of 20 to 30 trees from each host and nonhost collection site.

Researchers may wish to sample individual trees more intensively by obtaining samples from many radii along the entire bole of host trees. Radial-growth measurements from the crown portion of the stem may reflect more immediate and severe effects from defoliation and thus provide more refined estimates of growth loss and timing. Several whole-tree dissection methods (stem analysis) have been developed for estimating effects of budworm on tree growth and have the advantage of directly assessing different effects along the entire bole of the tree (for example, Alfaro and others 1985). Such intensive sampling requires felling the sample trees and additional time for analyses, which reduces the number of trees that can be analyzed.

In their studies of Douglas-fir in British Columbia, Alfaro and others (1984) also found that computations of growth loss for the entire outbreak period, including the years of recovery, did not differ much from the treetop to the base because faster recovery within the crown partially compensated for the greater growth decline during the defoliation period. Because of the compensating effect of faster recovery and the small proportion of volume in the upper stem, measurements from only the lower bole may still provide reliable estimates of total radial-growth loss in the stem (Nichols 1984).

When only two cores are to be taken from the lower bole of sample trees, at least twice as many trees should be sampled as needed for the final chronologies because rot, branch scars, breakage, loss of cores, or other unforeseen problems will inevitably reduce the number of usable samples.

The two increment cores from each tree (more cores may be collected if desired) should be taken 90 to 180 degrees from each other and, if possible, parallel to the topographic contour (fig. 2). The cores can be stored in paper straws or corrugated cardboard and labeled with ballpoint pen or waterproof marker. If plastic straws or other airtight containers are used to store the cores, air must be allowed inside to prevent molding, which can occur within a day.

Field notes should include extensive information on the site and on each tree sampled. Examples of the site and specimen cards used at the Laboratory of Tree-Ring Research are shown in figure 2. Field notes should include information on all categories listed on these cards. In addition, observations on defoliation of each tree and defects such as broken tops, dieback, top-kill, fire scars, or other damage should also be recorded (Dean 1978).

Sample Preparation

Cores should be air dried for a few days and then placed in grooved wooden mounts with the tracheids aligned vertically to give a cross-sectional surface (Stokes and Smiley 1968). Aligning cores in the core mounts is important, so that individual cells and ring boundaries can be seen when the cores are surfaced. Dirt or resin inside the borer or a dull cutting tip sometimes twist or break the extracted core. The core must be straightened before it is mounted, or it may resemble the core illustrated in figure 3. The ring boundaries are not clear on the surface of the core before the break, and the core had to be surfaced differentially to bring out the boundaries clearly. Such a surface may also cause problems when the ring widths are to be measured.

As the core is being taken, the increment borer scores lines on the core perpendicular to the vertical alignment of the tracheids (fig. 4). These lines can be traced with a pencil to determine whether the core is twisted, and the pencil lines can be used as guides for straightening the core. Each end of the core can be held between thumb and forefinger over a jet of steam (fig. 5) and slight but constant torque applied with the fingers to straighten the core so that the penciled score lines become parallel. The straightened core should be glued into the mount so that the score lines run along the edges of the core mount. The core may then be secured with string (fig. 6). After the glue is dry, the string can be removed and the cores surfaced.

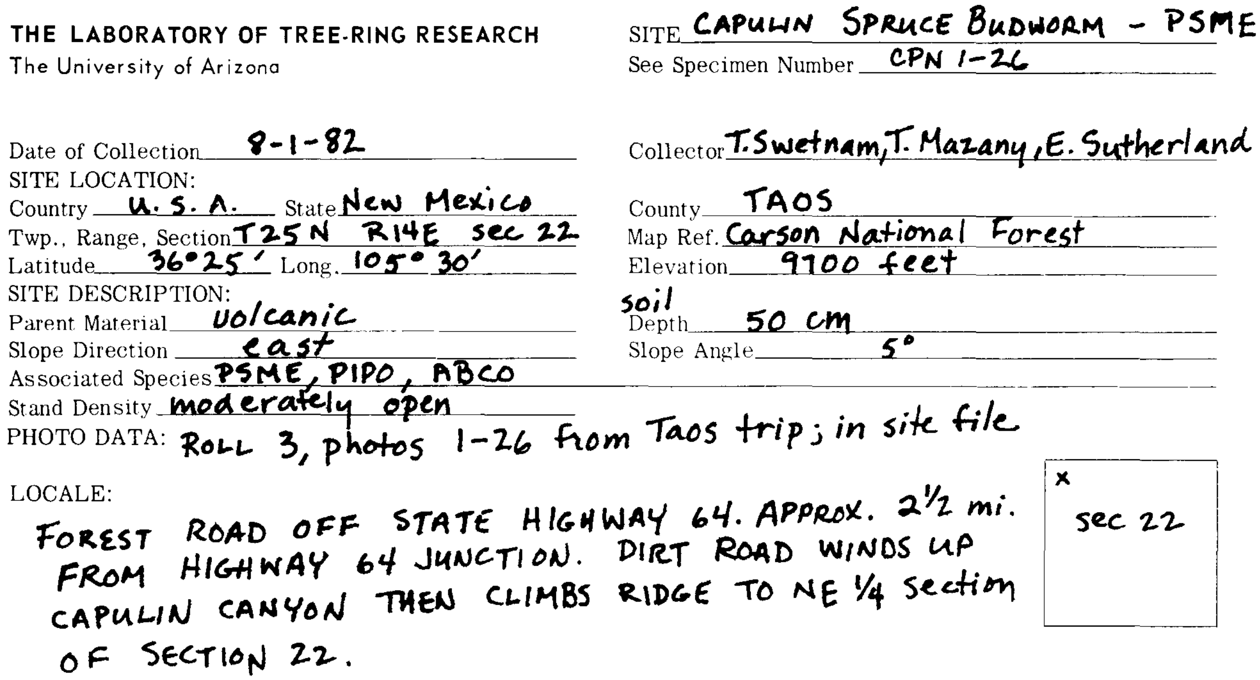
A finely sanded surface is crucial to the cross-dating of ring series. Ring boundaries, microrings, and diagnostic characteristics (such as frost damage, false rings, and injuries) are often discernible only when the surface is smooth. Increment cores should be sanded by hand with a series of sandpaper grits, such as 100, 220, 320, 360, and 400. Black sandpaper, which leaves fine grit embedded in the tracheid cells and obscures the ring structure, is not recommended.

A belt sander can be used to surface cross sections. The best surfaces are obtained by sanding at 90 degrees to the previous direction, changing direction with each grade of sandpaper. Sanding belts may require frequent cleaning if specimens are resinous. Gum cleaning bars are effective in cleaning the sanding belts (fig. 7).

Cross-Dating With Skeleton Plots

Cross-dating requires becoming familiar not only with the patterns of ring width typical of the trees in the area, but also with diagnostic characters of the wood, such as frost damage, sometimes called "frost rings" (LaMarche 1970), or unusually wide latewood bands within a ring.

Skeleton plots, which are a graphical means of representing tree-ring widths, are useful in cross-dating; this conceptually simple technique requires only a pencil, graph paper, and experience. The inherent variability of wood characteristics also requires a technique that is flexible and immediate and permits recognition of patterns and problems in a ring series. Computer programs for cross-dating ring-



THE LABORATORY OF TREE-RING RESEARCH The University of Arizona	SITE CAPULIN SPRUCE BUDWORM - PSME See Specimen Number CPN 1-26
Date of Collection 8-1-82	Collector T. Swetnam, T. Mazany, E. Sutherland
SITE LOCATION:	
Country U. S. A. State New Mexico	County TAOS
Twp., Range, Section T25N R14E sec 22	Map Ref. Carson National Forest
Latitude 36°25′ Long. 105° 30′	Elevation 9100 feet
SITE DESCRIPTION:	
Parent Material volcanic	soil Depth 50 cm
Slope Direction east	Slope Angle 5°

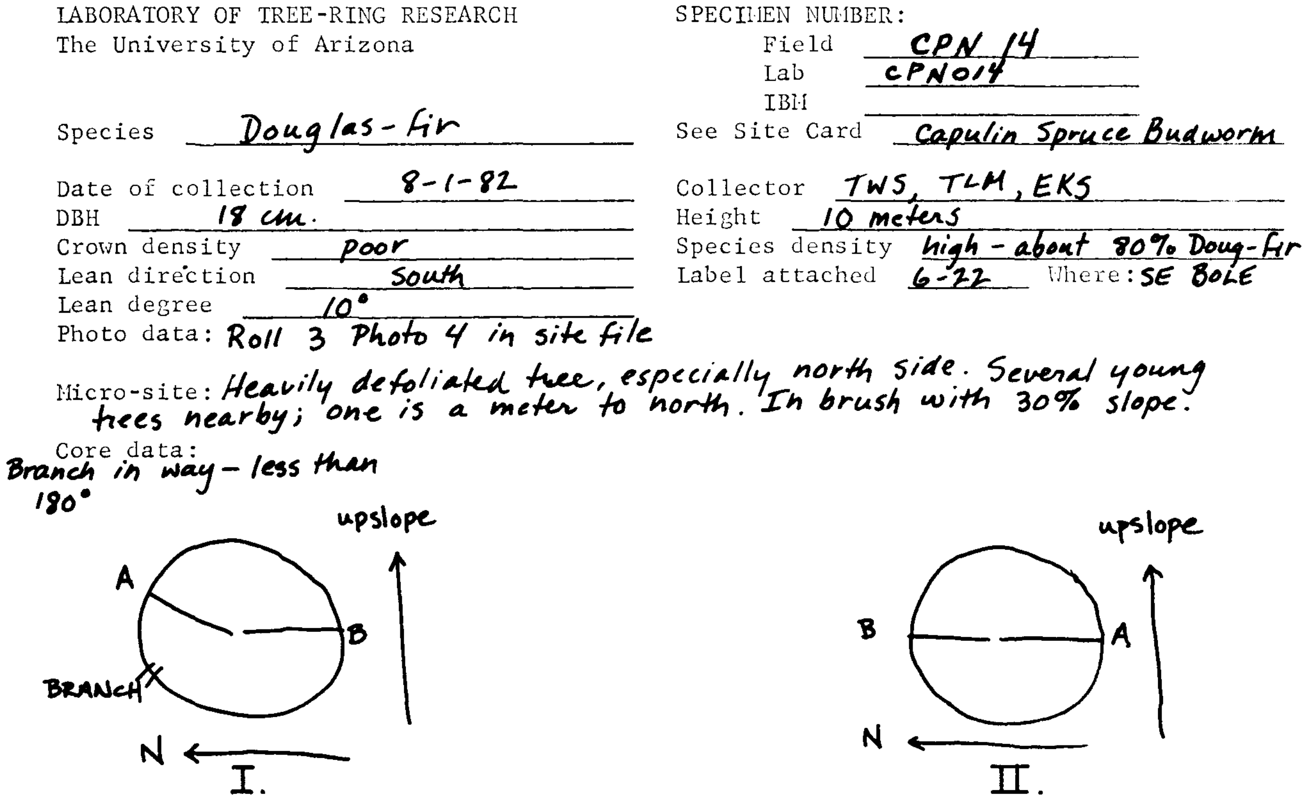
Associated Species PSME, PIPO, ABCO

Stand Density moderately open

PHOTO DATA: Roll 3, photos 1-26 from Taos trip; in site file

LOCALE:

FOREST ROAD OFF STATE HIGHWAY 64. APPROX. 2½ mi. FROM HIGHWAY 64 JUNCTION. DIRT ROAD WINDS UP CAPULIN CANYON THEN CLIMBS RIDGE TO NE ¼ section OF SECTION 22.



LABORATORY OF TREE-RING RESEARCH The University of Arizona	SPECIMEN NUMBER: Field CPN 14 Lab CPN014 IBM
Species Douglas-fir	See Site Card Capulin Spruce Budworm
Date of collection 8-1-82	Collector TWS, TLM, EKS
DBH 18 cm.	Height 10 meters
Crown density poor	Species density high - about 80% Doug-fir
Lean direction South	Label attached 6-22 Where: SE BOLE
Lean degree 10°	

Photo data: Roll 3 Photo 4 in site file

Micro-site: Heavily defoliated tree, especially north side. Several young trees nearby; one is a meter to north. In brush with 30% slope.

Core data:
Branch in way - less than 180°

Figure 2—The specimen card shows how cores are taken approximately perpendicular to the slope, avoiding possible distortion of ring-width pattern by branching (I), and how cores are taken perpendicular to the slope when no obstacles are present (II).

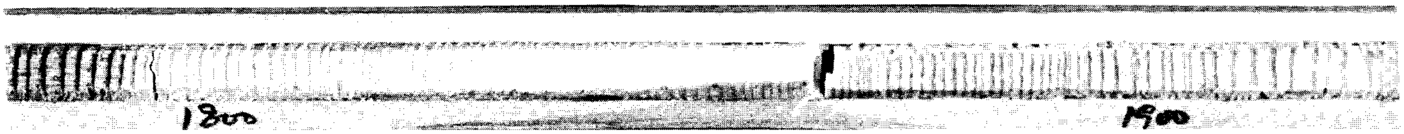


Figure 3—Mounted, twisted core showing poor alignment of tracheid cells.

Figure 4—Increment core showing score lines.

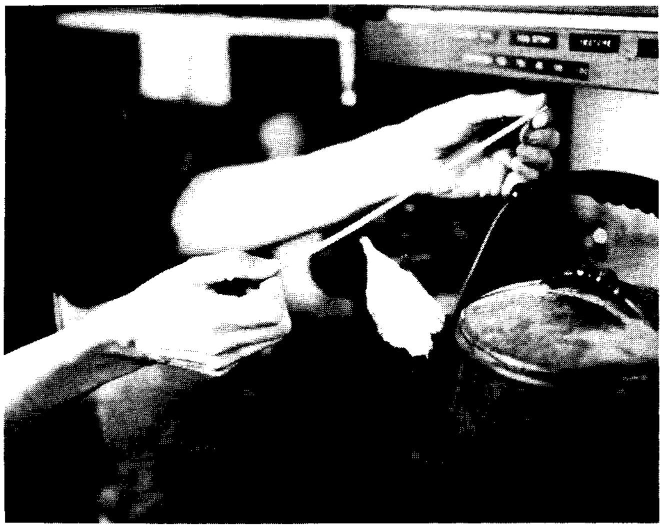


Figure 5—Straightening a twisted core over a jet of steam.

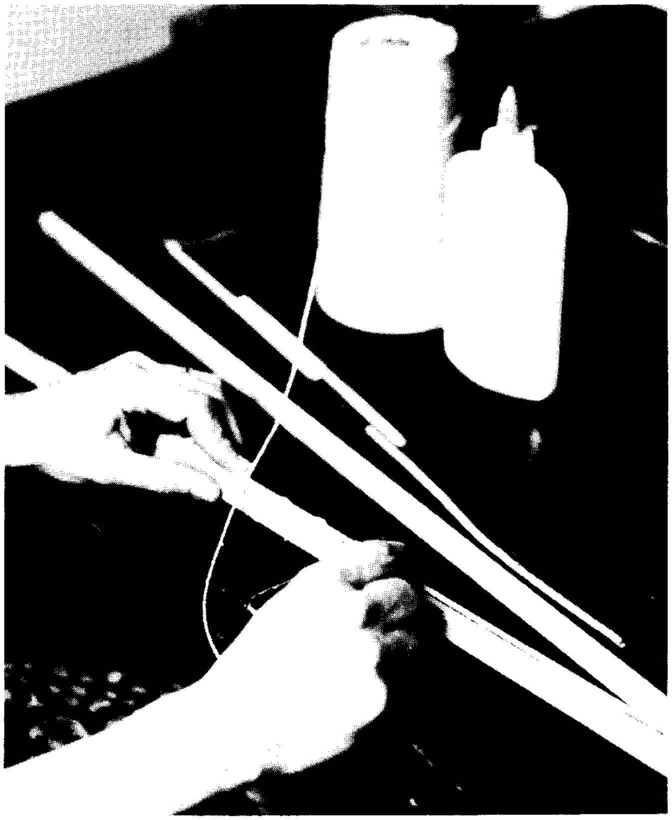


Figure 6—Mounting an increment core in a grooved wooden mount; the string holds the core in place until the glue is dry.

Figure 7—Belt sander and gum-cleaning bar for preparing surface of cross sections.

width measurements can provide a statistical and objective basis for assigning dates to tree-ring series. These programs are most useful for complacent tree-ring series, specimens that have few missing rings, or for checking previous dating from skeleton plotting. Computer programs for cross-dating are described by Baillie and Pilcher (1973), Cropper (1979), Holmes (1983), and Parker (1967).

The skeleton-plot technique we use is essentially the one described by Stokes and Smiley (1968). A detailed description of skeleton plotting is presented here because their book is out of print; we describe the technique so it will be accessible to interested researchers, who can use it to gain practical experience.

How skeleton plots are constructed from actual tree-ring series and how missing and false rings are accounted for by cross-dating are illustrated in this section. Each example includes a photograph of tree-ring series and a description of how a skeleton plot is to be constructed for each tree-ring series. Blank strips of graph paper (fig. 8) can be photocopied to construct your skeleton plot for each tree-ring series, and the results compared with the skeleton plots presented. When you construct skeleton plots for your own samples, we recommend using 5 × 5-to-the-centimeter graph paper.

How a skeleton plot is developed for the ring sequence in a single core is shown in figure 9. Each vertical line of the graph paper represents one ring. The skeleton plot does not include a drawn line for every ring. The narrower a ring, the longer the drawn line used to represent that ring on the skeleton plot. The maximum value assigned a drawn line on a skeleton plot is 10 (10 squares on the graph paper), and usually a 10 represents an extremely small or microring. The value (or length of the drawn line) to be assigned to a particular ring is decided by judging its width relative to that of three to five neighboring rings. This means that the relative width of a ring, rather than its actual width, is the important feature in skeleton plotting a sequence of ring widths.

Skeleton plotting of a ring sequence is best started at the innermost ring, using an arbitrary numbering sequence—starting with "0," as in figure 9. (For purposes of illustration, however, we did not begin the skeleton plotting with the innermost ring on the core.) The decades are recorded by putting a single pencil dot on each 10th ring, two dots on each 50th ring, and three dots on each 100th ring (fig. 10). After you have constructed a skeleton plot using a photocopy of a strip of graph paper, compare it to the one printed in figure 9. The two skeleton plots should be comparable in that the signature rings (narrow rings represented by relatively long drawn lines on the plot) should appear in the same place on both plots. Your plot will probably not correspond exactly with the one in figure 9, but the two should be similar.

Cross-dating requires matching common patterns of wide and narrow rings among cores and trees. First the skeleton plots from cores from the same tree are cross-dated and then the plots from trees within one collection site.

Cores from three red spruce trees (*Picea rubens* Sarg.) on a site in Nancy Brook, NH, are shown in figure 11. Construct a skeleton plot for the tree-ring series from each core and see if you can match the patterns of wide and narrow rings on your skeleton plots. Use another strip of graph paper to construct a composite skeleton plot from your three plots by visually averaging the drawn lines in the plots. Compare your results with ours (fig. 12).

Cross-dating of the three skeleton plots with the master chronology for the Nancy Brook site is shown in figure 13. The master skeleton plot for this site was

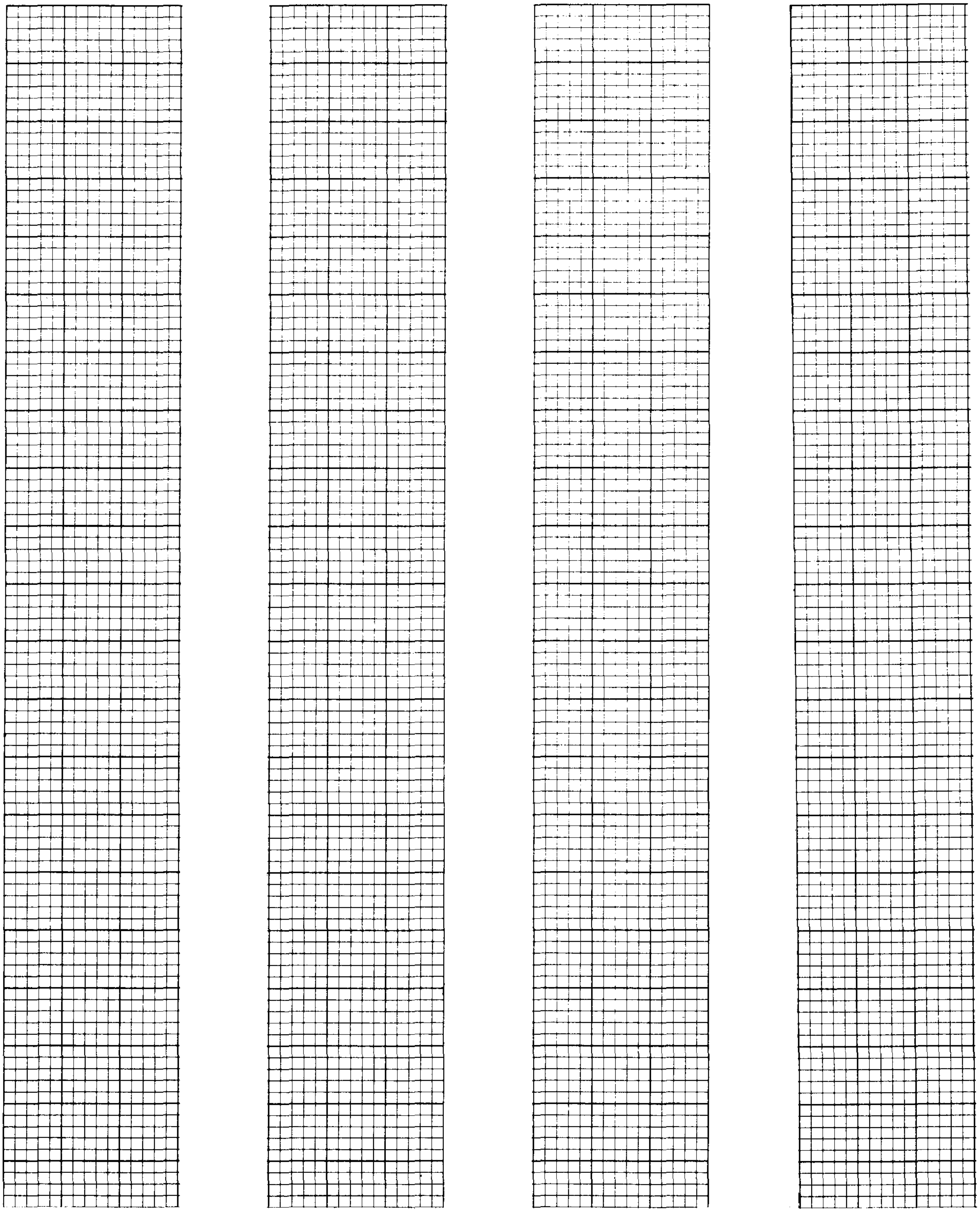


Figure 8—Strips of graph paper. This page may be photocopied and the strips cut out and used in the exercise described in the text.

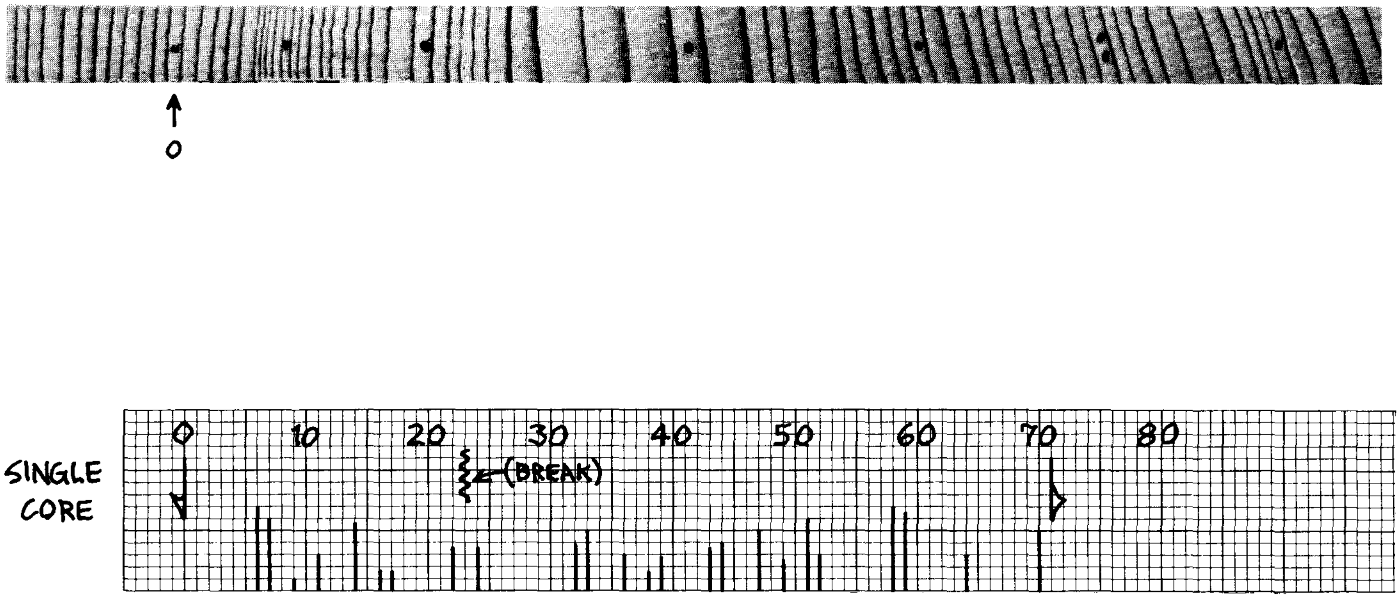


Figure 9—Single increment core and skeleton plot.

constructed by visually averaging the length of the drawn lines for each year from all core skeleton plots for the entire site collection, and thus represents the pattern of wide and narrow rings common to all cores from that site. Actual calendar dates can now be assigned to the ring sequences on your skeleton plots.

Once the calendar dates have been determined, the pencil marks can be removed from the core. The actual dates are recorded on the wood using pinpricks, again putting a single pinprick in each decade ring, two in each half-century ring, and three in each century ring (see fig. 10). After actual dates have been determined from cores of living trees, ring sequences from dead trees or downed logs can be cross-dated with the master skeleton plot for the site and placed properly into the dated sequence.

The procedure of cross-dating the Nancy Brook site is straightforward because no missing or false rings occur in any of the ring sequences. Because false and missing rings are common, however, cross-dating is crucial to determining actual calendar dates for every tree-ring series in a collection. When a tree is stressed during a growing season, cambial growth may not occur in all parts of the tree, causing the growth ring for a particular year to be missing from the ring-width series in the sampled portion of the tree bole. Occurrence of two locally absent rings in a section of bristlecone pine (*Pinus aristata* Engelm. var. *longaeva* (D. K. Bailey) Little) from the White Mountains of California is shown in figure 14.

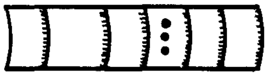
False rings occur when conditions change during a growing season, causing the tree to form latewood cells (small diameter and noticeably thick walls) before the end of the growing season. Then, when conditions improve, the tree resumes forming earlywood cells (larger diameter and thinner wall), leaving a band of latewood cells with an indistinct boundary within the annual ring. This band of latewood cells can be mistaken for the boundary of the annual ring. False rings in a core from a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the Santa Catalina Mountains of southern Arizona are shown in figure 15.

If skeleton plots are compared among many trees, the most likely date for a ring to be locally absent can be determined—that is, the year when most trees grew a markedly narrow ring. The plot for that particular tree can then be corrected, as illustrated in figures 16 to 19.

Cores from three Douglas-firs on a site in Silver Springs, NM, are shown in figure 16. Construct a skeleton plot for each tree-ring series shown (fig. 16) and try to match the patterns among the skeleton

One pinprick indicates the 10th year.

Two pinpricks in a vertical alignment indicate the 50th year.



Three pinpricks in a vertical alignment indicate the 100th year.

Two pinpricks, horizontally aligned, indicate the presence of a microring.

Two pinpricks aligned at an angle across a latewood band indicate that a ring is missing from the sequence.

A slash across two rings indicates a false ring.

A SCHEMATIC RING SEQUENCE

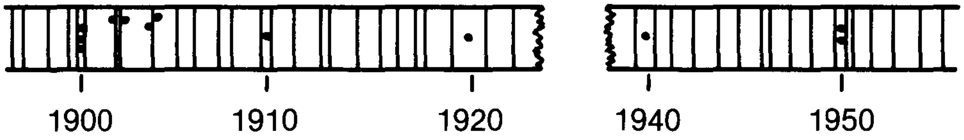


Figure 10—Method for noting 10-year, 50-year, 100-year rings, and micro-, missing, and false rings.

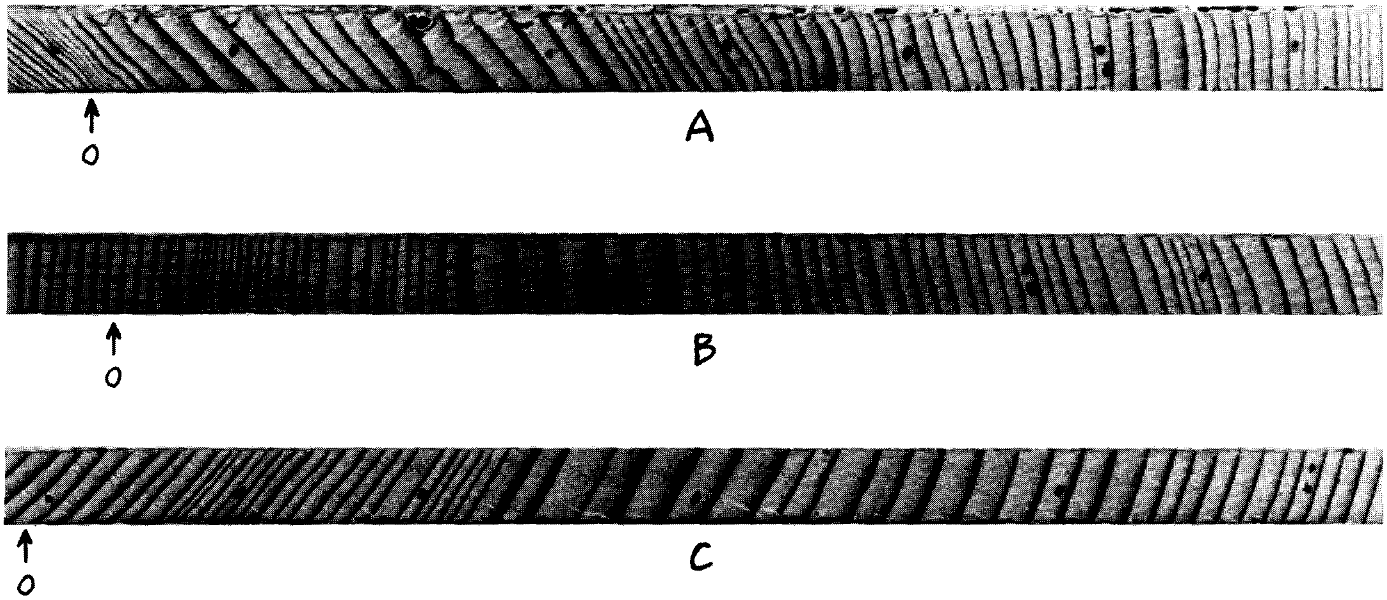


Figure 11—Increment cores from three red spruce trees, Nancy Brook, NH.

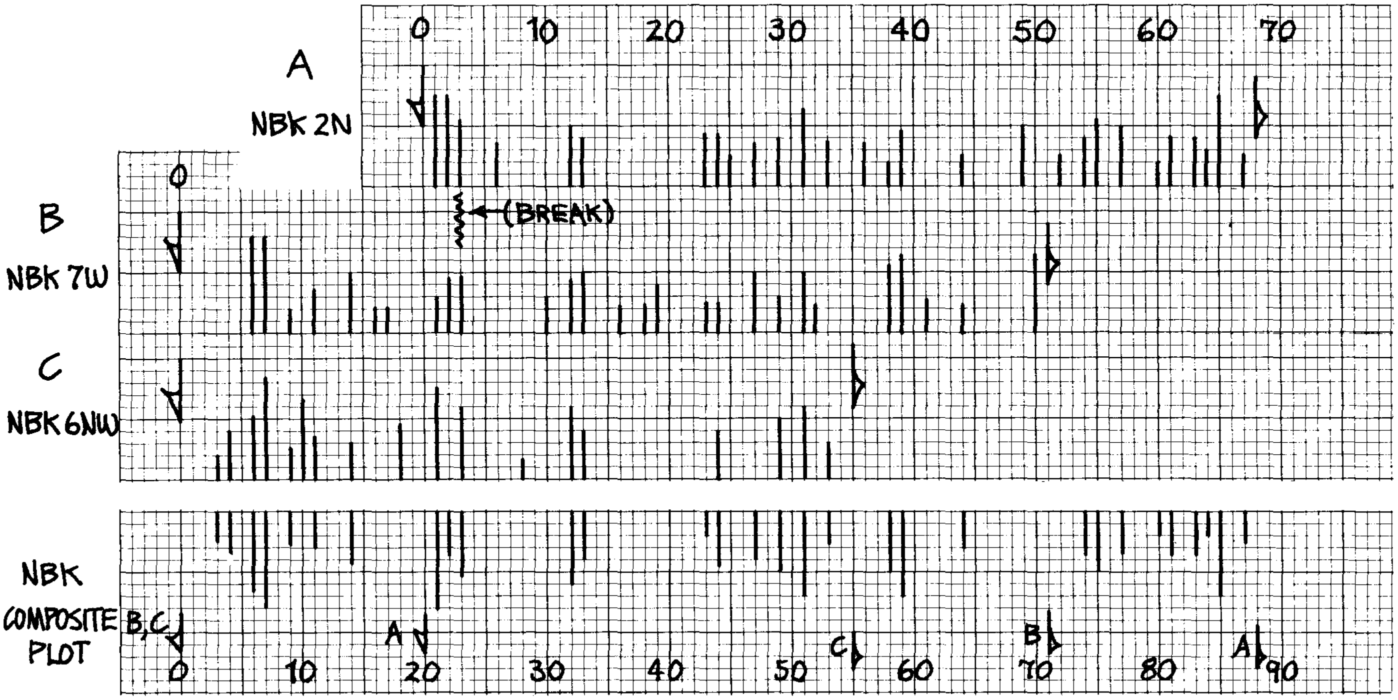


Figure 12—Skeleton plots for three Nancy Brook (NBK) cores and composite plot.

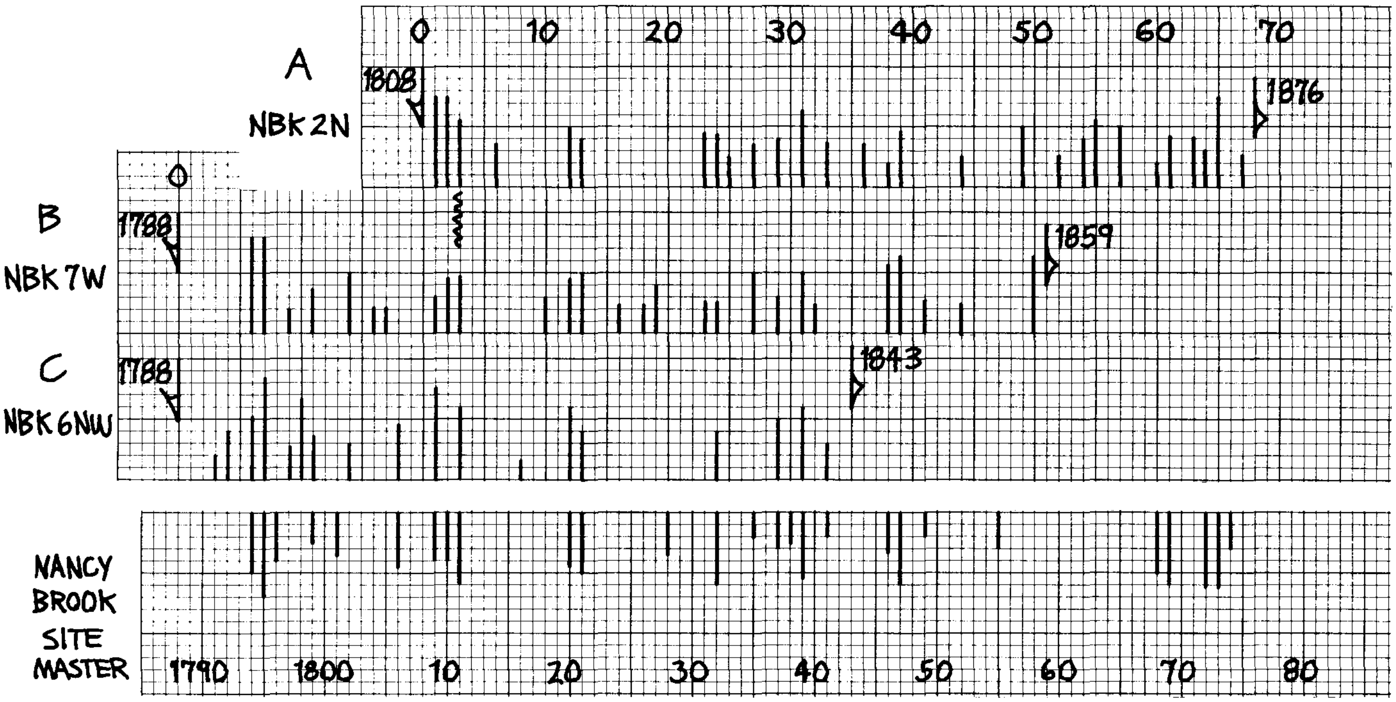


Figure 13—Cross-dating skeleton plots of three cores with the NBK site master.

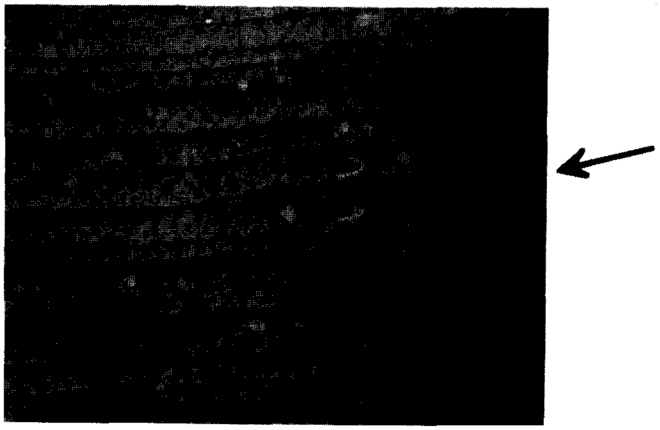


Figure 14—Two locally absent rings in bristlecone pine.

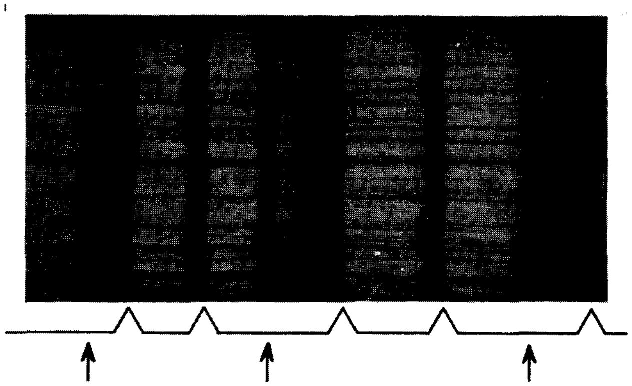


Figure 15—Arrows indicate intra-annual latewood bands (false rings) in a Douglas-fir core. In three of the rings, the actual ring boundary is clearly defined, but the boundary of the false ring is not. (Bark is to the right.)

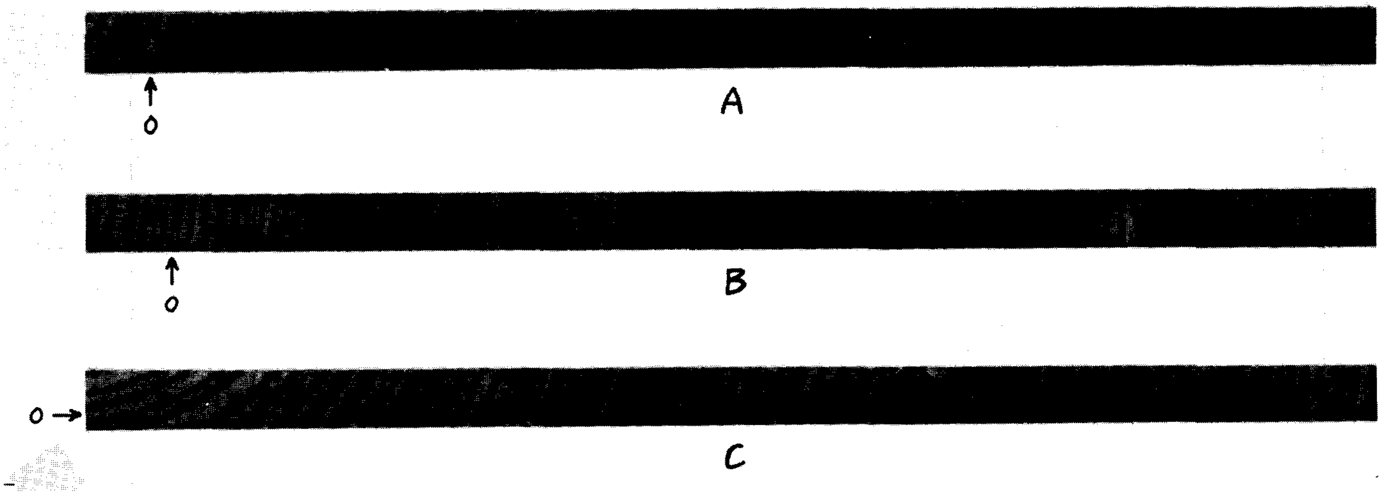


Figure 16—Increment cores from three Douglas-fir trees, Silver Springs, NM.

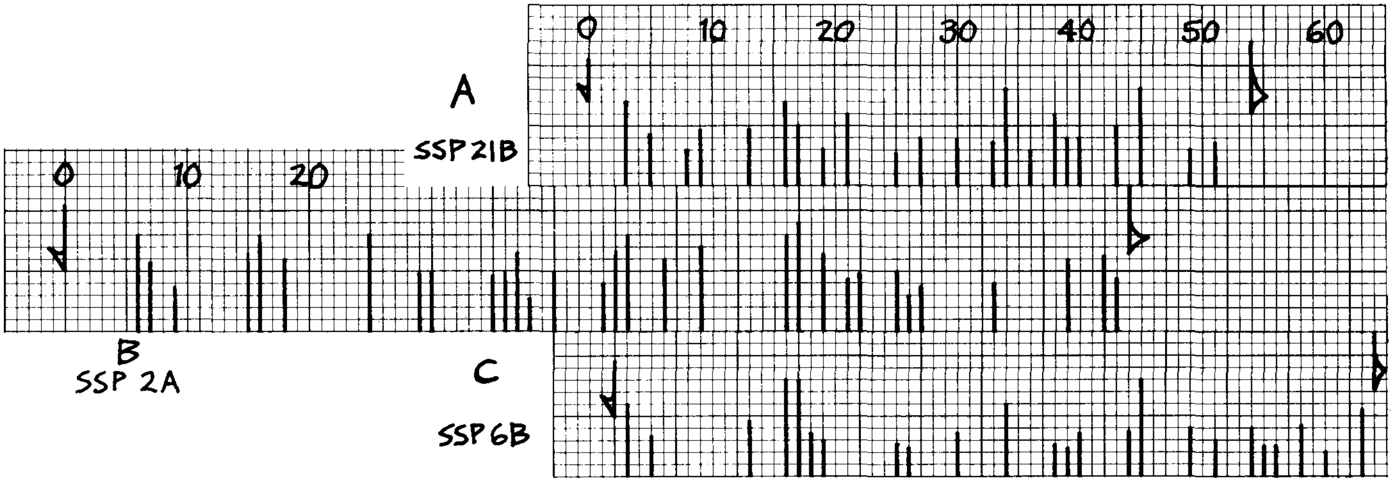


Figure 17—Skeleton plots for three Silver Springs (SSP) cores.

plots. Plot only the first 86 rings on core B. Not visible (fig. 16) is a microring along the latewood of ring 86 and another microring along the latewood of ring 106. Their presence explains why only eight instead of nine rings appear between the marks for these two decades. Compare your plots with those in figure 17. The plots agree from rings 0 to 33 on core A, rings 43 to 76 on core B, and rings 0 to 31 on core C. Ring 34 on core A and ring 32 on core C are narrow, but a corresponding narrow ring does not occur on core B; the skeleton plot for core B does not agree with the other two plots after this point. If a long, dotted line is inserted to represent the locally absent ring and the plot for core B is moved (fig. 18), the plotted ring sequence for core B matches—or cross-dates—with the plotted sequences for the other two cores. To confirm the cross-dating of the skeleton plots, construct a composite skeleton plot and compare it and the three core skeleton plots with the master skeleton plot for the Silver Springs site (fig. 19). You may then assign the appropriate calendar dates to your skeleton-plotted ring series. The presence of a locally absent or missing ring in a tree-ring series is pinpricked in the wood (fig. 10).

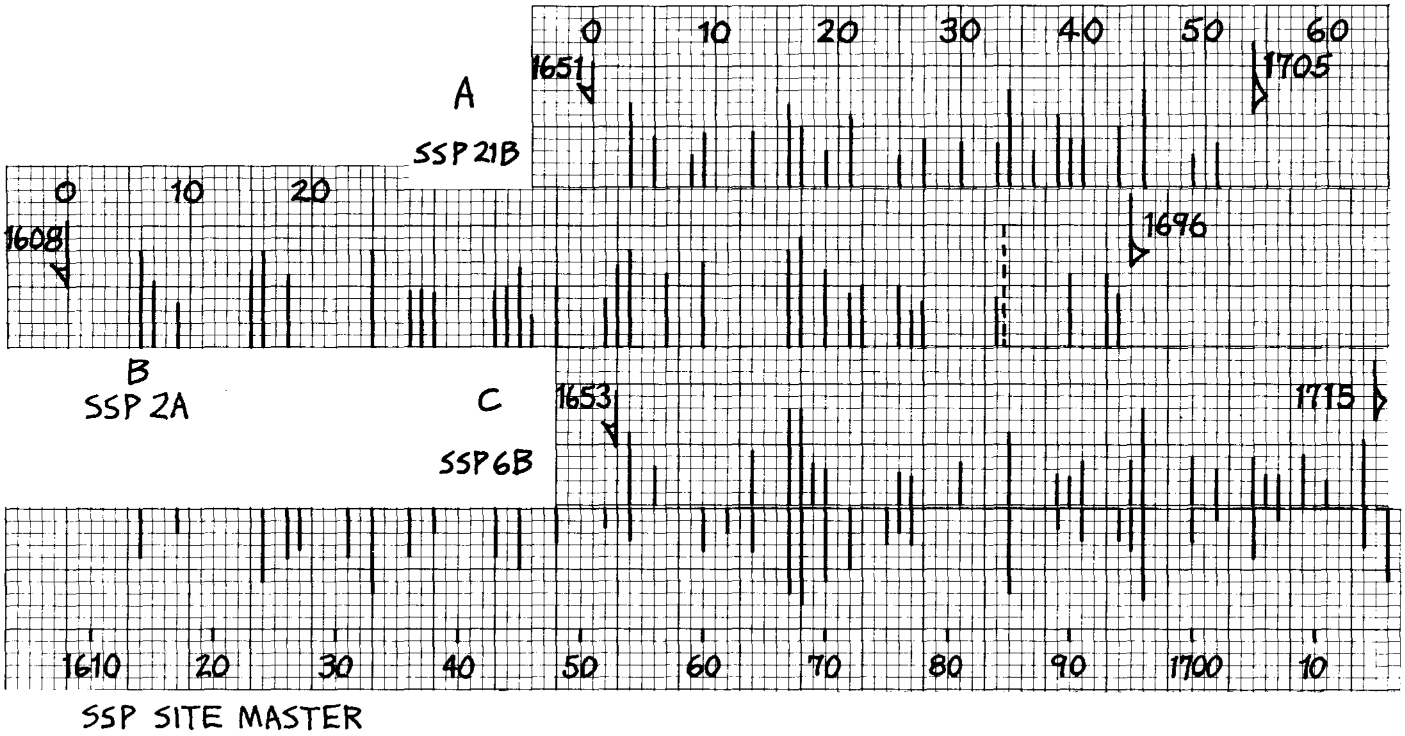


Figure 18—Skeleton plots for SSP cores and composite plot. Plot for core B has been corrected for missing ring.

Skeleton plots can be used to correct for a false ring in a tree-ring sequence (figs. 20–23). Here, an extra drawn line was included in the skeleton plot because a false ring was misidentified as an actual ring, causing the plotted ring sequence to be out of agreement with other plots.

Cores from three Douglas-firs in the Santa Catalina Low site near Tucson, AZ, are shown in figure 20. Construct skeleton plots for the tree-ring series in these cores, try to match their patterns, and then compare your results with the plots in figure 21. The plots agree from rings 5 to 38 on core A, rings 10 to 33 on core B, and rings 0 to 43 on core C. Core B apparently contains a narrow ring that does not appear on the other two cores. Reexamine core B; you may see that what was mistaken for a ring boundary is actually a latewood band with an indistinct boundary. If the intra-annual latewood bands cannot be identified, however, you must rely on the cross-dating and comparison of skeleton plots among trees on the site. One fairly large ring occurs in most trees on the site in that year, rather than the two narrow rings that were mistakenly identified as annual rings. If you look at other cores, you will see that some rings for this year contain faint intra-annual bands. The skeleton plot for core B is corrected by crossing out the drawn line for the false ring and moving the skeleton plot for core B as shown in figure 22. Again, the dating of the skeleton plots can be confirmed by comparing them to the master skeleton plot for the Santa Catalina Low site (fig. 23).

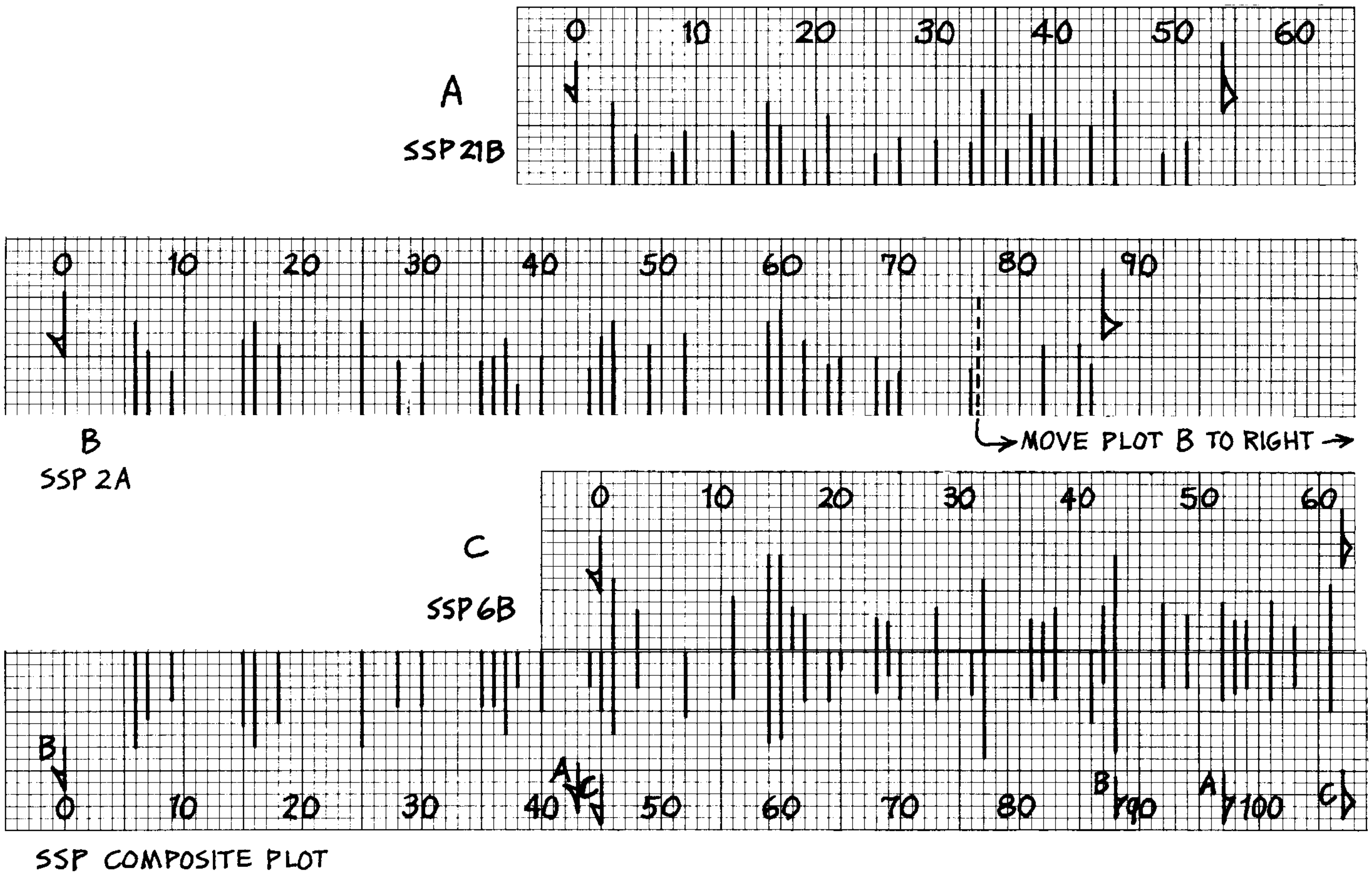


Figure 19—Cross-dating of corrected skeleton plots with the SSP site master.

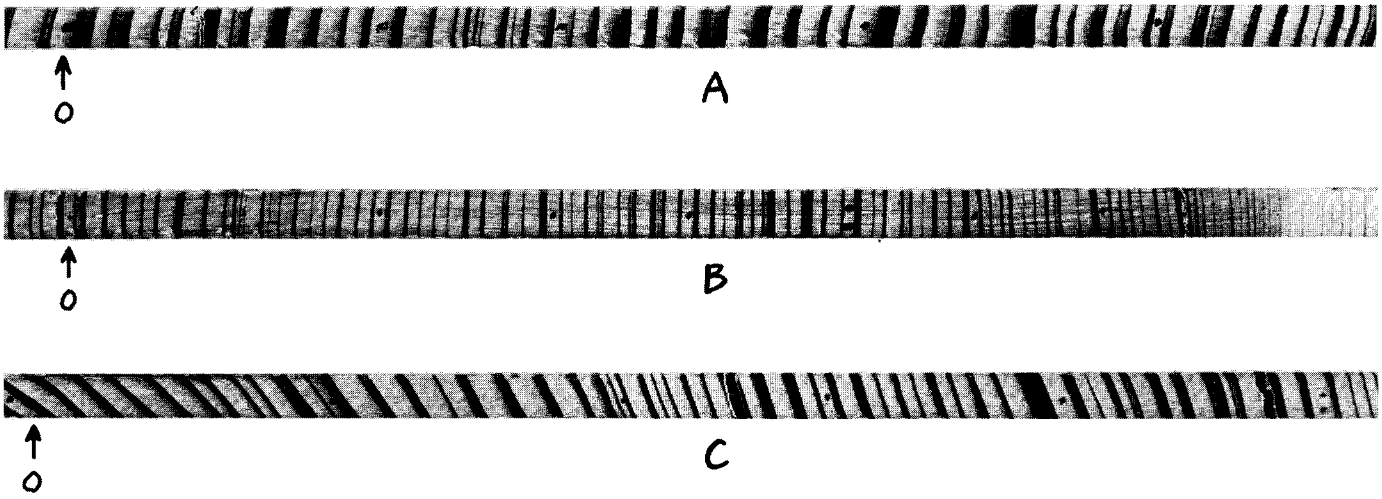


Figure 20—Increment cores from three Douglas-firs, Santa Catalina Low site, Arizona.

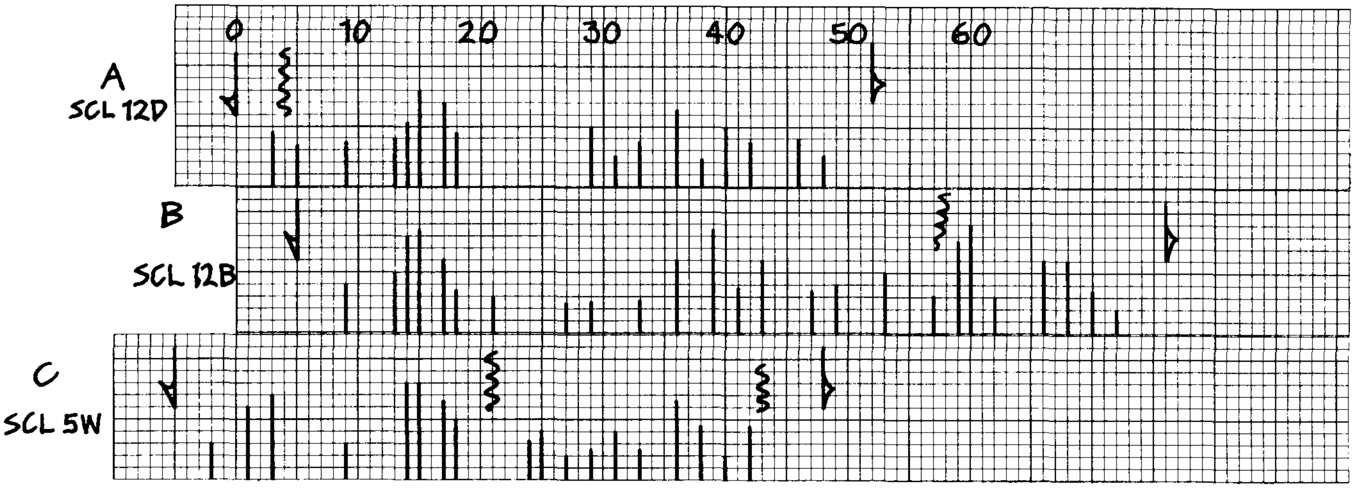


Figure 21—Skeleton plots for three Santa Catalina Low (SCL) cores.

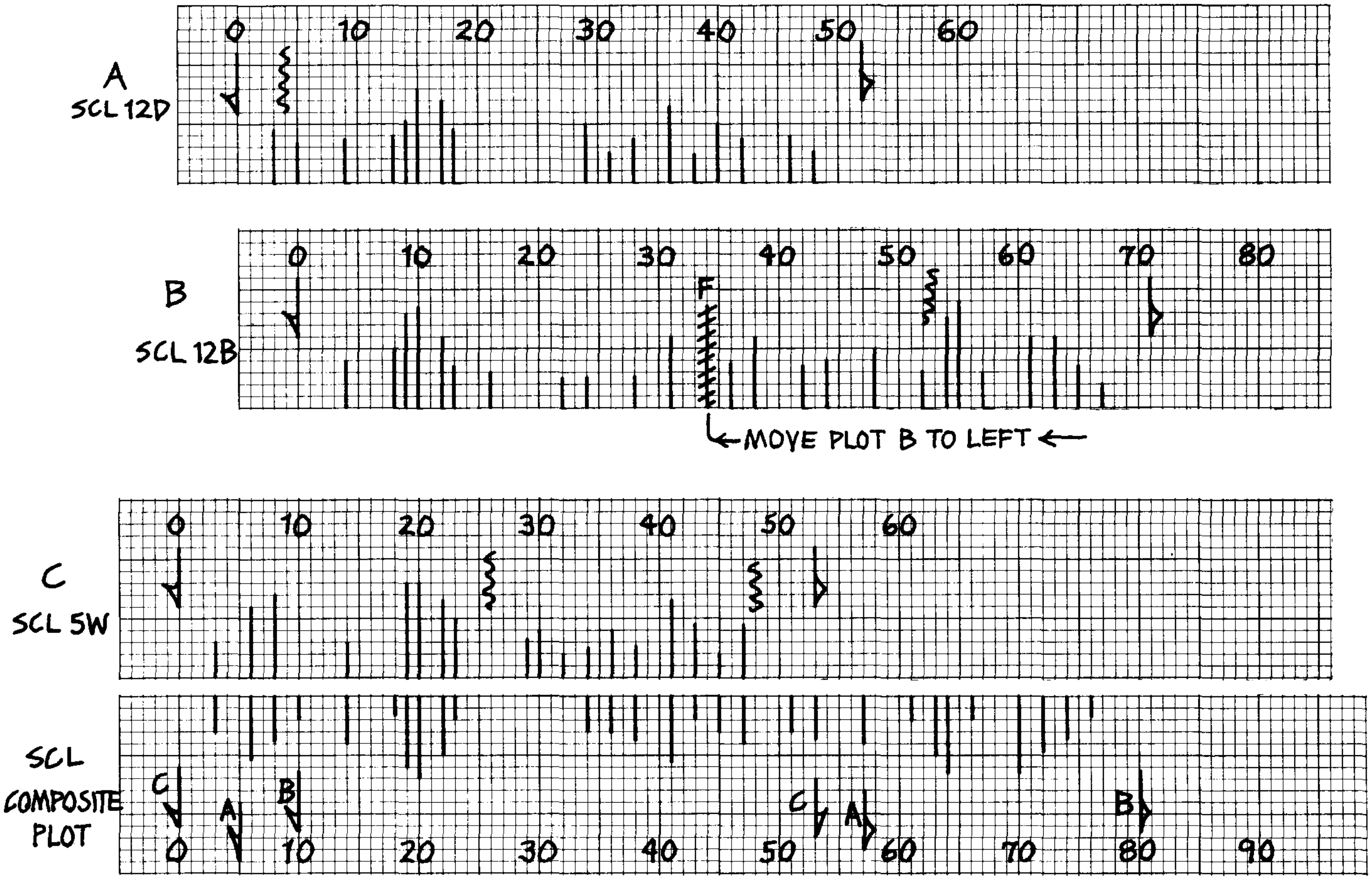


Figure 22—Skeleton plots for SCL cores and composite plot. Plot for core B has been corrected for false ring.

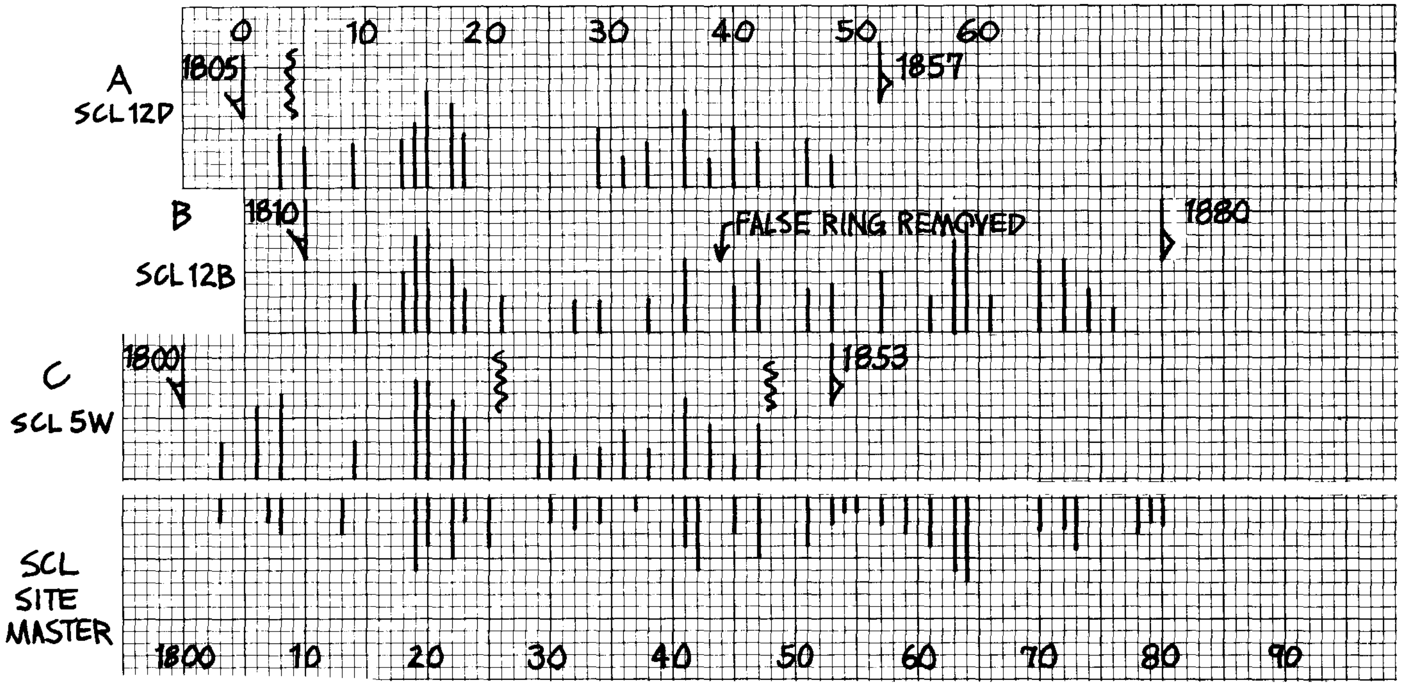


Figure 23—Cross-dating of corrected skeleton plots with SCL site master.

The examples (figs. 16–23) intentionally simplify correcting for missing and false rings. Often, more than one missing or false ring will occur in the ring sequences of many trees from a collection. With patience, practice, and perseverance, however, you can cross-date tree-ring series and determine actual calendar dates for every ring in each series.

Measurement of Ring Widths

Efficient and precise measurement of annual tree-ring widths is best accomplished with a sliding-stage micrometer interfaced with a microcomputer (Robinson and Evans 1980). Individual rings are measured by moving the samples on the sliding stage under a binocular microscope set up with a crosshair in one ocular lens (fig. 24). Measurements are recorded in the microcomputer and subsequently on a magnetic disc by pressing a button when the crosshair is lined up on the ring boundaries of successive rings. Several different systems combining sliding-stage micrometers with microcomputers are now commercially available.

Checking original measurements by remeasuring a portion of the tree-ring sample is advisable. Even the most conscientious and experienced technicians suffer eye fatigue and lapses of attention that can result in error. Experienced technicians can duplicate ring-width measurements of conifer species with a mean absolute difference of about 0.05 mm between original measurements and remeasurements (Fritts 1976). Appropriate statistical tests can be devised to determine if differences between original measurements and remeasurements are within an acceptable range.[3]

After the tree-ring samples are measured, the data files stored on disks should be transmitted via modem or direct connection to magnetic tape or disk files on an appropriate mainframe or minicomputer system. The tree-ring programs used in the remaining analyses and the necessary storage space for tree-ring data require more memory (about 200 kilobytes) than is currently available in most microcomputers.

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[3] Burns, J. M. A guide to measuring tree-ring widths. Unpublished manuscript. Tucson, AZ: Laboratory of Tree-Ring Research, University of Arizona; 1979. 36 p.

Standardizing and Developing Tree-Ring Chronologies

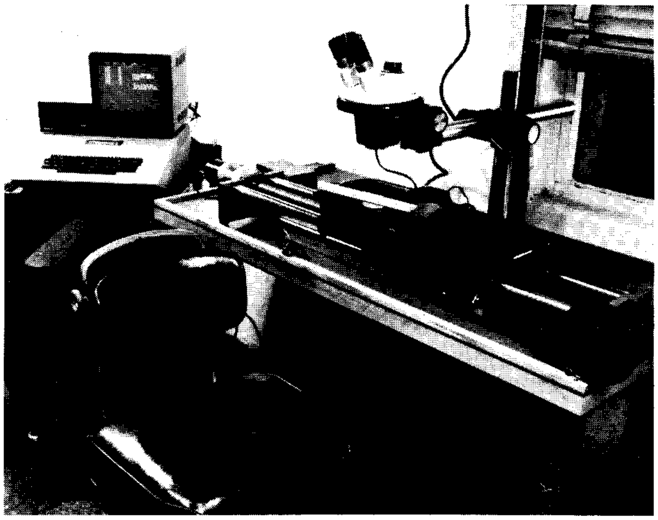

Figure 24—Sliding-stage micrometer/ microcomputer for measuring tree rings.

As trees grow older and increase in circumference, the average width of the annual rings generally decreases. The rate of decrease is specific to each tree and is a function of aging, genetic potential for growth, bole geometry, site conditions, and stand history. This individual growth trend must be removed or "standardized" to compare or average growth of different-aged trees (Fritts 1971, 1976). The expected growth of the tree without environmental variation is approximated by fitting a curve to the ring-width series of a core. Each ring-width value is then divided by the value of the curve for that year, producing an index of tree growth as a function of variation in environmental factors (Fritts and others 1969).

When ring-width series are standardized, the mean and variance of the inner part of each series is made comparable to the outer part. Thus, the rapid, vigorous growth of youth and the slower, steadier growth of old age are scaled to about the same mean and variance. Because all indexed tree-ring series will have a mean of about 1.0, index series from trees of different ages can be averaged together to form site chronologies. If ring-width series from trees of different ages were averaged together before being transformed into indices, the resulting series would have peaks of higher variance and larger ring-widths wherever the younger trees entered the series (Fritts 1971).

Three computer programs are used to generate standardized tree-ring series and their descriptive statistics. Details of these programs are discussed in an operating manual,[4] and descriptions are also provided by Fritts (1976), Graybill (1979), and Graybill and others (1982).

RWLIST—Listing Tree-Ring Series

RWLIST lists all ring widths and produces plots of 20-year averages of each core's ring widths. Output from this program should be used to check the original data for errors in measurement or input and to determine from the 20-year plots the type of growth curve to be fit to the ring widths. Curve-fitting decisions for short or fluctuating ring-width series may be difficult to make using only the RWLIST

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[4] Graybill, D. A. Program operating manual for RWLIST, INDEX, and SUMAC. Unpublished manuscript. Tucson, AZ: Laboratory of Tree-Ring Research, University of Arizona; 1979.

plots because the 20-year averages often obscure certain growth trends. The host tree-ring series will typically show fluctuating growth, so a simple computer program should be used to plot all of the complete ring-width series for the host trees. These plots can be used to observe overall growth trends for the curve-fitting decision. TRPLOT, another program available from the Laboratory of Tree-Ring Research, is specifically designed to plot ring widths and ring-width indices.

Occasionally, the ring widths of an individual tree may show growth variation unlike that of all other trees at the site. The cause may have been factors that affect only that tree, such as lightning strikes, fire scars, or broken tops. Nonhost trees with atypical growth patterns that cannot be removed by the indexing procedure should be eliminated from the analysis because the nonhost chronology is intended as a control to represent average expected tree growth at the site. Inclusion of atypical tree-ring series could significantly affect the index values of the final nonhost chronology, especially if the number of samples included is low (10 trees or less).

Determining if the budworm was actually the cause of atypical growth fluctuations in host trees may be impossible; so unless individual host trees cannot be confidently dated or indexed, they should be included in the analysis. Identification of budworm effects and measurement of growth reduction (described in a later section) is based on individual host-tree chronologies, providing additional opportunity to identify atypical growth patterns.

INDEX—Indexing Tree-Ring Series

The program INDEX converts each core's ring-width measurements to ring-width indices by fitting growth curves to the ring-width series with a least-squares technique, and then dividing each ring-width value by the value of the growth curve for that particular year. The resulting ring-width indices have a mean of about 1.0, a minimum value of 0.0 (a missing ring), and a maximum value that rarely exceeds 4.0. The series of ring-width indices from a core is called a "core chronology." The researcher specifies the type of curve to be fitted by the program, based on the resemblance of the ring-width series to one of several mathematical functions.

Five curve-fitting options are (1) a negative exponential function (or straight line with negative or zero slope), (2) a horizontal line, (3) a straight line with any slope, (4) a negative exponential function (or straight line of any slope), and (5) a polynomial function. The two negative exponential options will fit straight lines of specified slope if fitting the negative exponential curve within the limits set by the program is impossible.

Ring-width series from three trees are shown in figure 25A. The ring-width series of cores CPN211 and CPN212 have a typical negative exponential shape and were fitted with an exponential curve. The ring widths of cores CPN101 and CPN102 were fitted with a horizontal line, and CPN071 and CPN072 were fitted with straight lines of negative slope.

The polynomial option (not shown) will generally result in a closer curve-fit of tree-ring series that have abrupt periods of increasing or decreasing growth. This option should be used cautiously because it may remove low-frequency variation that represents important environmental information. If some trees in the nonhost site show growth surges or releases (assumed to be unrelated to climate) not common to other trees in the site, the polynomial may be used to standardize those series. This procedure is commonly used to emphasize climatic information but should be used carefully and only on nonhost trees. The ring-width series and fitted curves should be plotted to determine whether the curves actually fit the presumed nonclimatic surge or release.

Deleting the first one or more decades from a ring-width series may be necessary for better fitting of the growth curves. Ring widths near the pith commonly increase for a few years before they begin the more typical gradual decrease. Deleting the beginning portion is advisable because the fitted curve may underestimate the peak ring-width values, resulting in artificially high indices. Truncation may be unnecessary if the sampled core did not include rings near the pith. Regardless of whether ring-width series are truncated, the series should include enough measurements preceding outbreaks so that the fitted curve will be determined by these "normal" periods.

After ring widths have been processed through INDEX, the indices should be carefully examined. Consecutive index values greater than 4.0 may

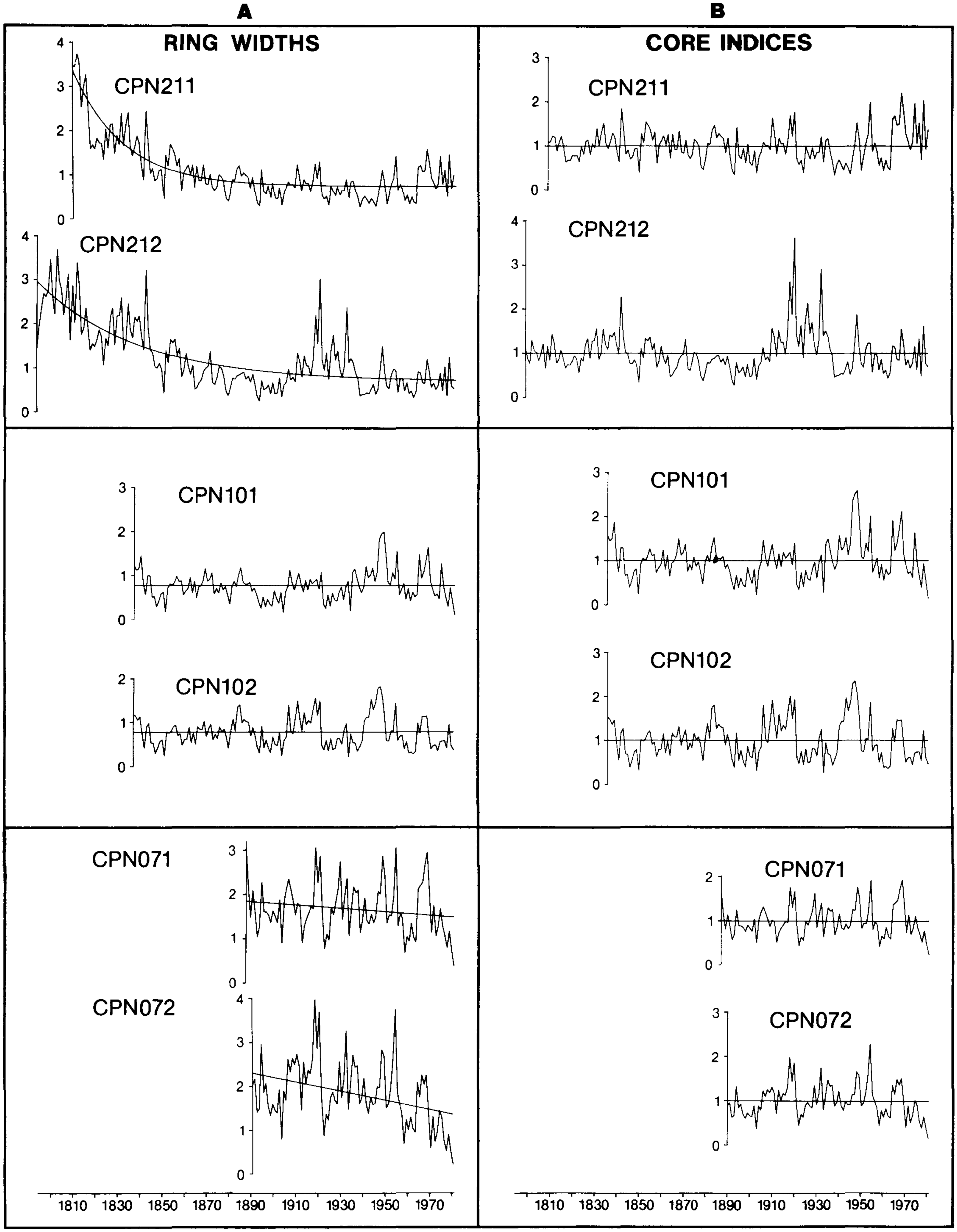
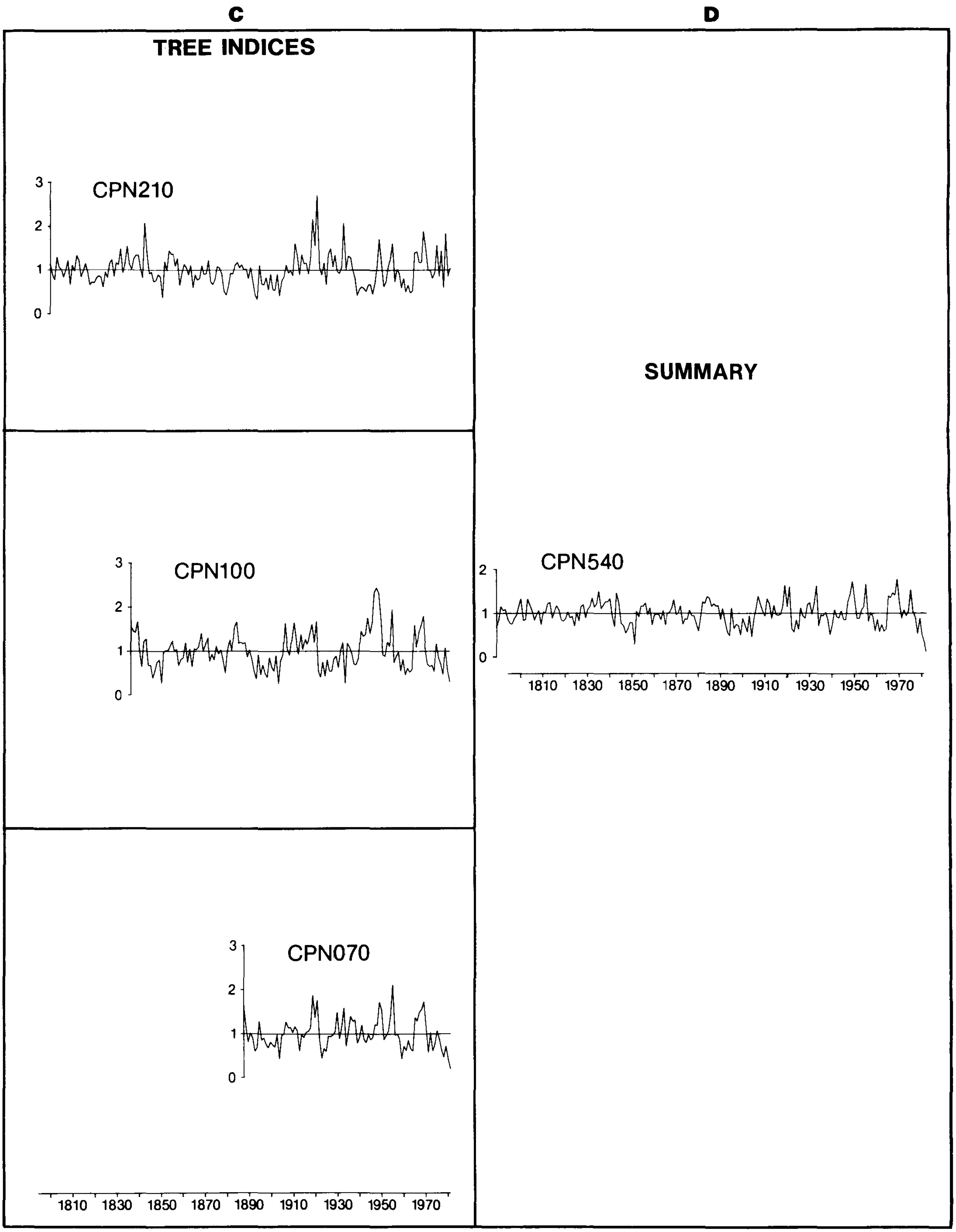


Figure 25—The program INDEX fits growth curves to tree-ring-width series from individual cores (A), and produces a new index series for each core (B). The program SUMAC averages the two cores from each tree into tree-index series (C), and as a final step, all core-class series are averaged into a summary or final chronology (D).


C
D
TREE INDICES
SUMMARY
CPN210
CPN100
CPN070
CPN540
0
1
2
3
1810
1830
1850
1870
1890
1910
1930
1950
1970

indicate that an inappropriate curve-fitting option was chosen, or that portions of the series should have been deleted. Other curve-fitting options should be tested to reduce the incidence of numerous very large or small index values that appear to be an artificial result of curve-fitting rather than an inherent trend.

INDEX produces a table of the index values for each ring of each core series. It also produces a set of statistics describing the standardized series. These statistics include mean ring width, mean index value, and standard deviation of the indices. The mean index value should be close to 1.0 in a well-standardized series. The number, percent, and calendar year of absent rings are indicated. Also shown is the curve-fitting option used and coefficients of the fitted curve.

Three additional statistics descriptive of the index series are mean sensitivity, standard deviation, and first-order autocorrelation. Mean sensitivity is a measure of the year-to-year variability of ring widths and is calculated as the mean percentage change from each measured yearly ring value to the next (Douglass 1936, Fritts 1976). The more ring width varies from year to year, the greater the sensitivity. Mean sensitivity is the average sensitivity of a series and ranges from 0 (no variation) to 2.0 (a zero ring-width value next to a nonzero value). Series with high standard deviation frequently have high mean sensitivity.

First-order autocorrelation is the correlation of each ring width with the preceding ring width. This value quantifies the association of ring widths with preceding values, or the nonrandomness of the time series. Environmental factors causing long-term growth effects, such as climatic trends or insect infestations, increase the autocorrelation value. Series with high first-order autocorrelation frequently have low mean sensitivity and standard deviation.

Fritts and Shatz (1975) summarize these three descriptive statistics for four western conifer species. They list the range of statistics obtained for a large number of chronologies from the Western United States and discuss possible interpretations of high and low values.

Finally, INDEX produces a plot of the 20-year mean ring widths and the fitted growth curve. The closeness of the fitted growth curve to the actual ring widths shows on this plot. The researcher may wish to plot the complete ring-width series with the expected growth curve overlain on the ring widths, particularly in the host-tree cores (fig. 25B). TRPLOT includes this option.

SUMAC—Averaging Tree-Ring Series

SUMAC averages tree-ring chronologies from a site in several ways. Core chronologies are first averaged into tree chronologies (fig. 25C). For purposes of analysis, the core chronologies are divided into two classes (when only two cores are collected per tree), usually designated arbitrarily as the first and second cores of a sampled tree. This affords the opportunity to explore, for instance, the effects of slope or exposure on two different sides of a tree. The classes are averaged into two core-class chronologies (or as many classes as cores per tree); as a final step, the core-class chronologies are averaged into the final site chronology. This is equivalent to averaging tree chronologies into the final site chronology (fig. 25D). The site can also be subdivided into one or more groups. For example, groups may be lightly, moderately, and heavily defoliated trees. All of the above-mentioned statistics are generated for all chronologies.

After averaging all of the tree-ring series, SUMAC generates an analysis of variance (ANOVA). This procedure and interpretations of the results are described by Fritts (1976) and Graybill and others (1982). Briefly, the output from the ANOVA is a table listing the proportions of variance in the final chronology contributed by the site chronology, the trees within the site, the core classes, and the individual cores. If most of the trees at a site are responding to similar environmental factors, the site-chronology component will be the largest. If the trees are responding to individual microsite factors (for example, variance in the degree of defoliation), the variance contributed by individual trees, individual cores, or both may be large. The variance contributed by the core classes should be purely random unless the core classes were collected systematically. Variance attributable to differences between groups would be given if any groups were designated.

SUMAC also generates a cross-correlation analysis that compares the correlation of chronologies during the interval common to all chronologies (for example, all chronologies having indices for the period 1866 to 1982) and during subperiods. The length of subperiods and chronologies to be correlated (cores, trees, sites, groups) may be designated by the user. For example, two series may be similar in one 20-year period (high correlation), and dissimilar in another (low correlation). This similarity could be caused by a similar response to climate in the first period and to different amounts of defoliation during an outbreak in the second period.

The standardizing programs with options for ANOVA and cross-correlation analysis provide a versatile tool for tree-ring research. Many different combinations of tree-ring chronologies can be developed and their variance and correlation characteristics analyzed. Thus, the programs can be adapted and applied to a variety of study designs and research objectives. We emphasize again, however, that reliable results depend on careful indexing (curve-fitting), thorough inspection of the output for errors and inconsistencies in data, and thoughtful consideration of the variance and correlation statistics.

Comparing Host and Nonhost Chronologies

When the standardization procedures are completed, the individual host-tree chronologies should be graphically compared with the final nonhost site chronology. The statistics of host and nonhost chronologies should also be compared.

The host/nonhost comparison is a preliminary procedure that should be carried out before the host tree-ring indices are transformed with the TRMCLM program, which uses the nonhost site chronology to correct host-tree chronologies for climate and other environmental effects. These procedures are explained in the next section. Objectives of the host/nonhost comparison are to determine if (1) the effects of current or past budworm outbreaks are detectable as a decrease in the growth of individual host trees with no corresponding decrease in the nonhost chronology; (2) the growth trends of host and nonhost trees are generally similar, with the exception of budworm outbreak periods; and (3) the statistics of host and nonhost chronologies are generally similar, with the exception of differences that may be expected as the result of budworm effects. A reasonable basis exists for correcting the host tree-ring series with the TRMCLM program if the above conditions are observed.

The nonhost site chronology is used for comparison because it represents the average expected growth of trees within the study area. By comparing each host-tree chronology with the nonhost site chronology, the researcher may be able to identify specific instances of budworm-induced growth reduction. Plots of all individual host-tree chronologies should be graphically compared with the nonhost site chronology because variation will occur in the effects of budworm on each tree.

The graphical comparison of host and nonhost tree-ring series should reassure the researcher that observed periods of growth reduction in host trees were not caused by climatic events. Budworm outbreaks may occur during droughts, but differences between host and nonhost growth will probably still be apparent. Graphical comparisons with climate data may be useful. If past outbreaks of budworm are to be identified, the researcher should attempt to verify that periods of growth decline in the host trees correspond to documented outbreaks recorded by forest entomologists, managers, or other observers. Documentation of insect problems is rare before about 1900; therefore, researchers should be cautious about interpreting earlier periods of growth reduction as being induced by budworm.

An optional technique for improving host and nonhost graphical comparisons is to transform the tree-ring series with a low-pass filter (fig. 26). A low-pass filter effectively removes the year-to-year variations (high frequencies) in the host and nonhost series that may obscure the effects of budworm, while retaining the long-term variations (low frequencies) that are probably more characteristic of budworm outbreaks or other nonclimatic effects on growth. Budworm is more likely to affect tree growth in the long term (longer than about 3 or 4 years) because outbreaks usually last from 5 to 15 years (Carlson and McCaughey 1982, Johnson and Denton 1975).

The low-pass filter is similar to a running or moving-average filter because it smooths the tree-ring series. A digital low-pass filter, however, uses a set of symmetrically weighted values that are multiplied by each index value, resulting in a filtered series that retains characteristics of phase and amplitude much better than a simple moving-average filter (see Mitchell and others 1966, p. 46–57; and LaMarche and Fritts 1972, p. 22–25). An additional advantage is that the wavelengths to be preserved in the series can be adjusted by the number and value of weights used in the algorithm. A digital filter computer program, FILTTRL, routinely used at the Laboratory of Tree-Ring Research, can be either a low-pass or high-pass filter. The high-pass filter effectively removes long-term variation and preserves only high-frequency variations.

Plots of host (Douglas-fir) and nonhost (ponderosa pine) low-pass filter values are compared in figure 27. Growth trends are generally similar, with the exception of identified periods of budworm outbreak (from USDA Forest Service records). In some periods, host and nonhost growth trends are similar in shape but one curve may rise above or fall below the other. Interpreting such discrepancies is difficult

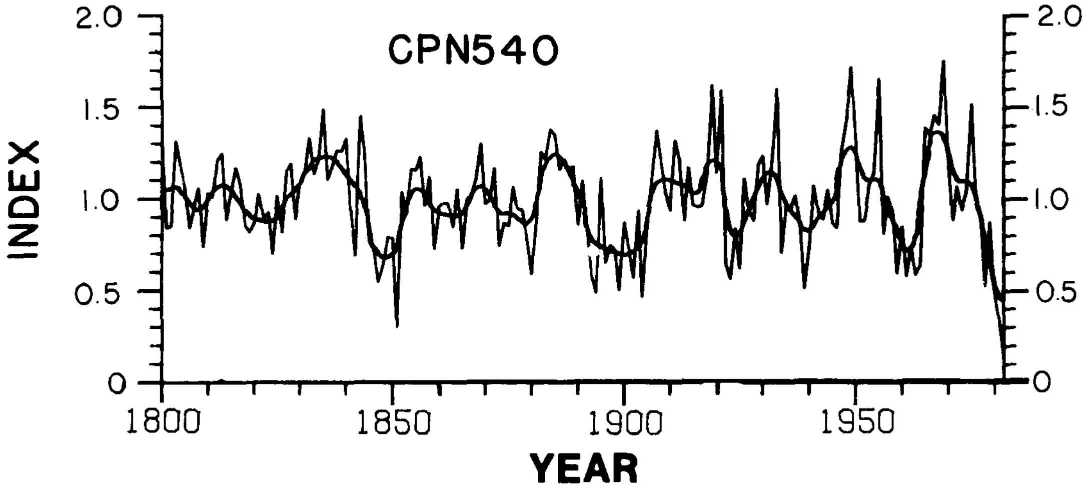


Figure 26—Site chronology (about 17 trees averaged after 1900) of Douglas-firs from Capulin Canyon, NM. The smooth line represents the low-pass filter values that were generated by applying a filter with 13 weights. This filter passes variance with wavelengths greater than about 8 years.

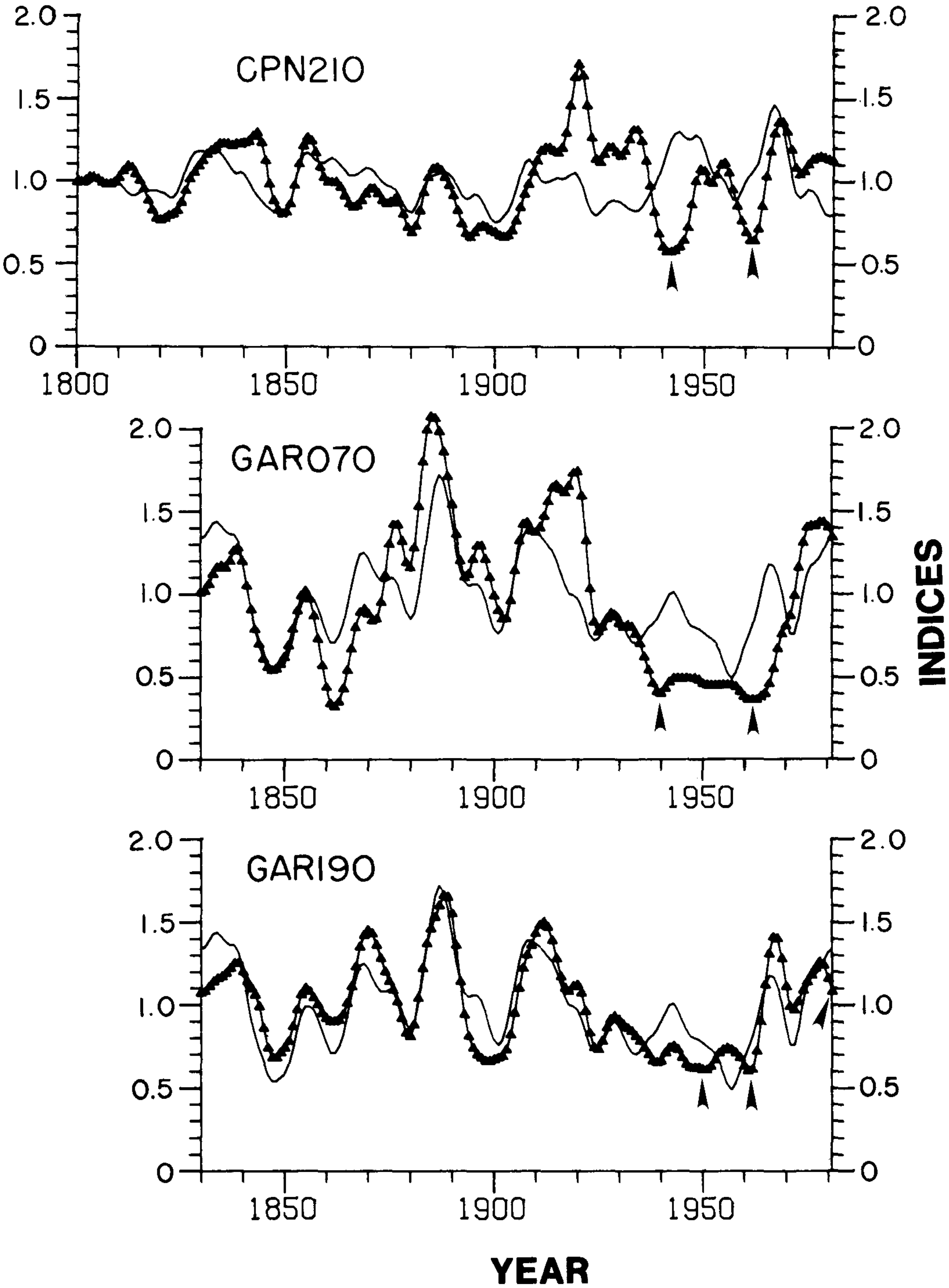


Figure 27—Comparison of low-pass filter values between individual Douglas-firs (lines with triangles) and site chronologies of ponderosa pine (lines) from Capulin Canyon (CPN) and Garcia Park (GAR), NM. Arrows indicate periods of growth reduction in Douglas-fir corresponding to documented outbreaks of budworm.

because they may result partly from differences in variance characteristics of the chronologies (for example, one chronology may have a higher standard deviation than the other). Therefore, the best evidence of a period of budworm outbreak is a noticeable difference in direction of trend between the chronologies in conjunction with forest-insect records. Sometimes observed discrepancies in the host/nonhost comparisons can be traced to individual samples and growth anomalies specific to those trees. The period of high growth in the tree CPN210 (fig. 27) around 1920 is the result of a much higher growth rate on only one side of the tree as reflected in the ring widths and indices for core CPN211 (fig. 25).

The variance and autocorrelation characteristics of the host and nonhost series should be closely examined and compared before using TRMCLM to measure impact. In general, the mean sensitivities and standard deviations should be similar, although TRMCLM is designed to account for these differences. The host-tree chronologies will probably have higher first-order autocorrelation than the nonhost trees because of the effects of the budworm. If the nonhost chronology statistics show sudden increases in autocorrelation during the common period (up to five orders of autocorrelation are computed in SUMAC), or patterns very different from those observed for the host chronologies, the nonhost chronology probably should not be used because these statistics may indicate species or site-specific characteristics not shared by the host trees.

The correlation of host and nonhost chronologies can also be examined using a special run of the SUMAC program. Correlations should be relatively high during preoutbreak periods and lower during outbreak periods.

Correcting Host Tree-Ring Indices

The graphical comparison of the host and nonhost chronologies should provide some evidence that budworms have caused radial-growth reduction in the host trees. But the question remains: How much growth reduction during the identified periods of outbreak resulted from budworm defoliation? Host trees may also have been responding to other environmental factors, such as drought, that may have caused growth reductions. The purpose of TRMCLM is to remove from the host tree-ring chronologies environmental effects common to both host and nonhost chronologies, so that more precise estimates of growth reduction can be derived from the corrected host series.

The TRMCLM program corrects a host-tree chronology by first scaling residuals from the nonhost site chronology to the same variance as the host-tree chronology to be corrected. These scaled residuals are called the "predicted residual indices" (PRI). The PRI's are then simply subtracted from the host-tree indices to produce the "corrected indices" (CI). The computer program accomplishes these procedures with the following equations:

$$\mathrm{PRI} = \frac{\mathrm{SDEV(H)}}{\mathrm{SDEV(NH)}}\,(\mathrm{INDEX(NH)} - \mathrm{MEAN(NH)});\ \text{and}$$

$$\mathrm{CI} = \mathrm{INDEX(H)} - \mathrm{PRI}.$$

SDEV(H) and SDEV(NH) are the standard deviations for the host and nonhost series, INDEX(H) and INDEX(NH) are each index value of the host and nonhost series, respectively, and MEAN(NH) is the mean of the nonhost series (about 1.0).

The TRMCLM program was first developed by Nash and others (1975) for a study of the effects of copper-smelter pollutants on tree growth in central Arizona. The strategy of their study was somewhat different from ours. They intended to remove the effects of climate from the affected trees; for a control, they developed a regional chronology composed of tree-ring chronologies from several surrounding sites averaged together. We collected control-tree samples (nonhost trees) near to or within the host-tree site, so that microsite effects as well as climate are removed from the host tree-ring chronologies. If satisfactory nonhost control trees cannot be found within a budworm study area, researchers should consider the regional chronology strategy as an alternative.

The TRMCLM technique is based on two major assumptions. First, host and nonhost trees are assumed to be responding similarly to environmental influences other than budworm. The validity of this assumption is crudely tested during the graphical and statistical comparisons (previous section). In general, two different species growing in the same area will respond in a relatively similar manner to climate, but exceptions will occur because of differing phenological characteristics or other factors (Fritts 1976).

The second assumption is that nonhost trees are assumed to be unaffected by budworm. This is probably valid where the nonhost trees are from pure stands or stands never defoliated by budworm. As previously mentioned, however, nonhost trees growing with defoliated host trees may benefit from reduced competition. This effect may result in an overestimate of host-tree growth reduction. Where no alternative is possible but to obtain control samples from defoliated mixed stands, the researcher should look for a consistent increase in the growth of nonhost trees during documented budworm outbreaks.

Plots of three corrected Douglas-fir tree-ring series from northern New Mexico are shown in figure 28. Ponderosa pine was the nonhost species used to correct the individual tree series. Identified periods of budworm outbreaks during the mid-1940's and early 1960's have the lowest indices recorded for the entire length of the chronologies. The effects of the most recent outbreak, which began in this study area in the late 1970's, was just beginning to appear in these three trees in 1980.

Measures of Growth Reduction

The corrected host-tree indices can be used in many ways to quantify budworm-induced growth reduction. We will briefly describe four different measurements and rates of growth reduction similar to those first devised by Brubaker and Greene (1979).

All these measurements are based on the simple relation of tree-ring index values to the chronology mean. The mean of a tree-ring chronology can be considered the expected growth of the tree (or trees) in the absence of variations in growth-limiting factors. This is conceptually sound because the indices are derived by fitting an expected growth curve to a ring-width series based on the inherent biological aging and increasing circumference of the tree. Given this theoretical basis, the growth reduction (or increase) during any given year is simply the difference between the mean of the corrected series and the corrected index value for that year.

Maximum Growth Reduction for One Year—This is the largest growth reduction for a single year during a budworm outbreak period. It is computed by subtracting the minimum corrected index value during the outbreak from the expected growth value (mean of the corrected series = 1.0).

Five-Year Growth Reduction—This is the average growth reduction for a 5-year period, centered on the minimum corrected index year during an infestation. It is computed by summing the corrected index values for the 5-year period, subtracting the sum from 5.0 (the sum of expected indices during that period), and then dividing by 5.0.

Maximum Rate of Growth Reduction—This is the largest growth reduction between 2 years during an outbreak period. It is computed by finding the largest difference between consecutive corrected index values.

Rate of Growth Reduction or Recovery—This is the slope of the least-squares regression line computed for corrected index values preceding or following the year of maximum growth reduction for an outbreak. The last index value greater than or equal to the expected value, and indices up to and including the maximum growth-reduction year are used in the regression for computing rate of growth reduction. The first index value greater than or equal to the expected value and preceding indices back to and including the year of maximum growth reduction are used in the regression for computing rate of growth recovery.

Each of the growth-reduction measurements can be converted to percent reduction from expected growth by multiplying the computed values by 100.

Undoubtedly, different measurements can be devised to quantify amounts and rates of growth reduction. For example, average growth reduction could be computed for periods of different lengths corresponding to observed duration of outbreaks. Many ways to illustrate the results are also possible; one example (fig. 29) shows growth-reduction measurements from individual host trees using histograms.

When interpreting these measurements, researchers should remember that radial-growth measurements from the base of defoliated trees may underestimate growth reduction in the crown portion of the stem, and that growth reduction may lag 1 to 3 years behind the onset of defoliation and continue for 1 to 2 years after defoliation has ceased (Alfaro and others 1982,

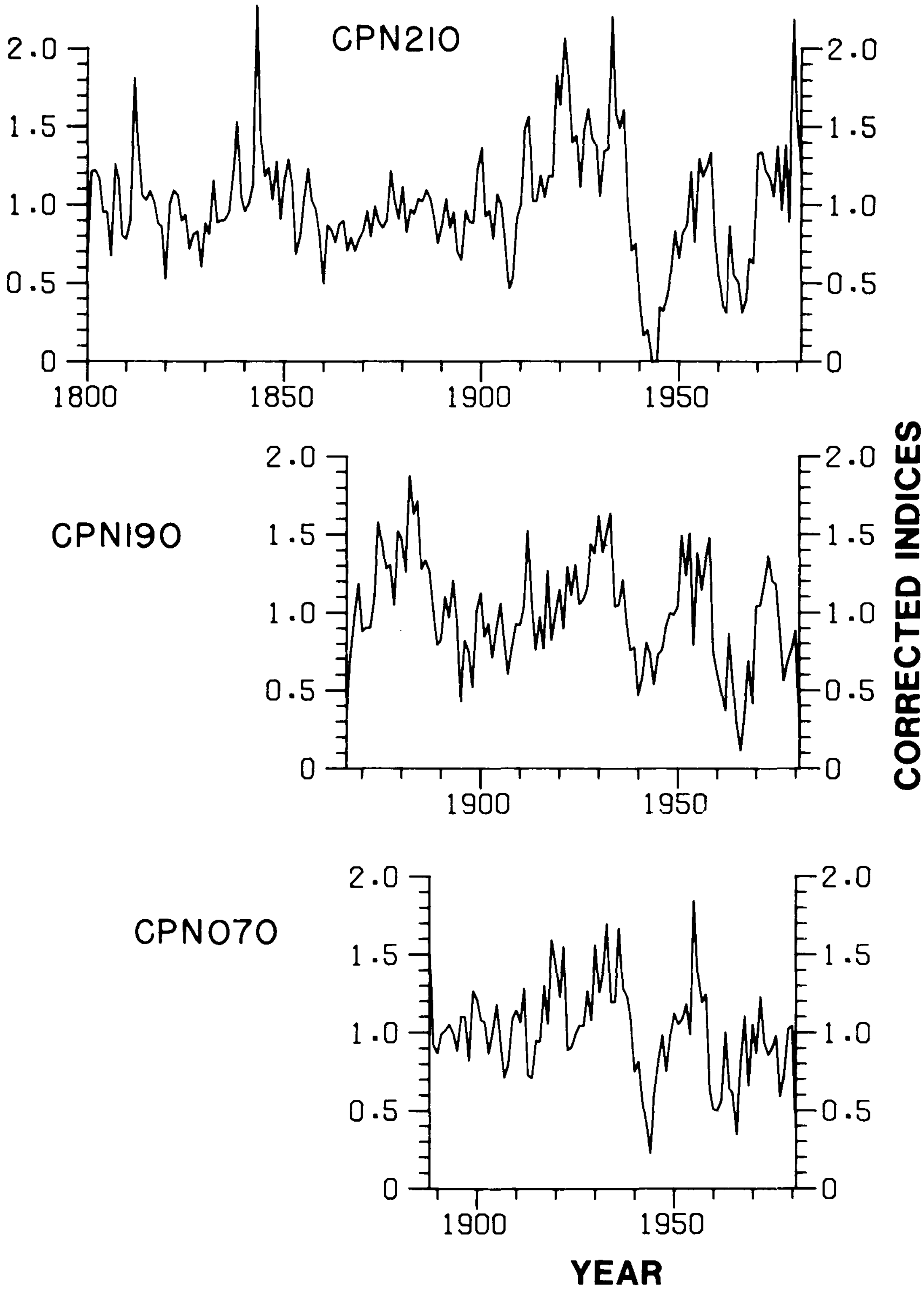


Figure 28—Corrected tree-ring series for three individual trees.

Brubaker and Greene 1979, Duff and Nolan 1953, Mott and others 1957, Kulman 1971, Williams 1967). Additional measurements from positions higher on the stems of defoliated trees can be readily included in the standardizing programs and analyses described in this paper, but this type of sampling may require felling trees and more time for analysis. In any case, more detailed estimates of individual tree- and stand-growth losses may also require measurements of height-growth loss, top-killing, and mortality.

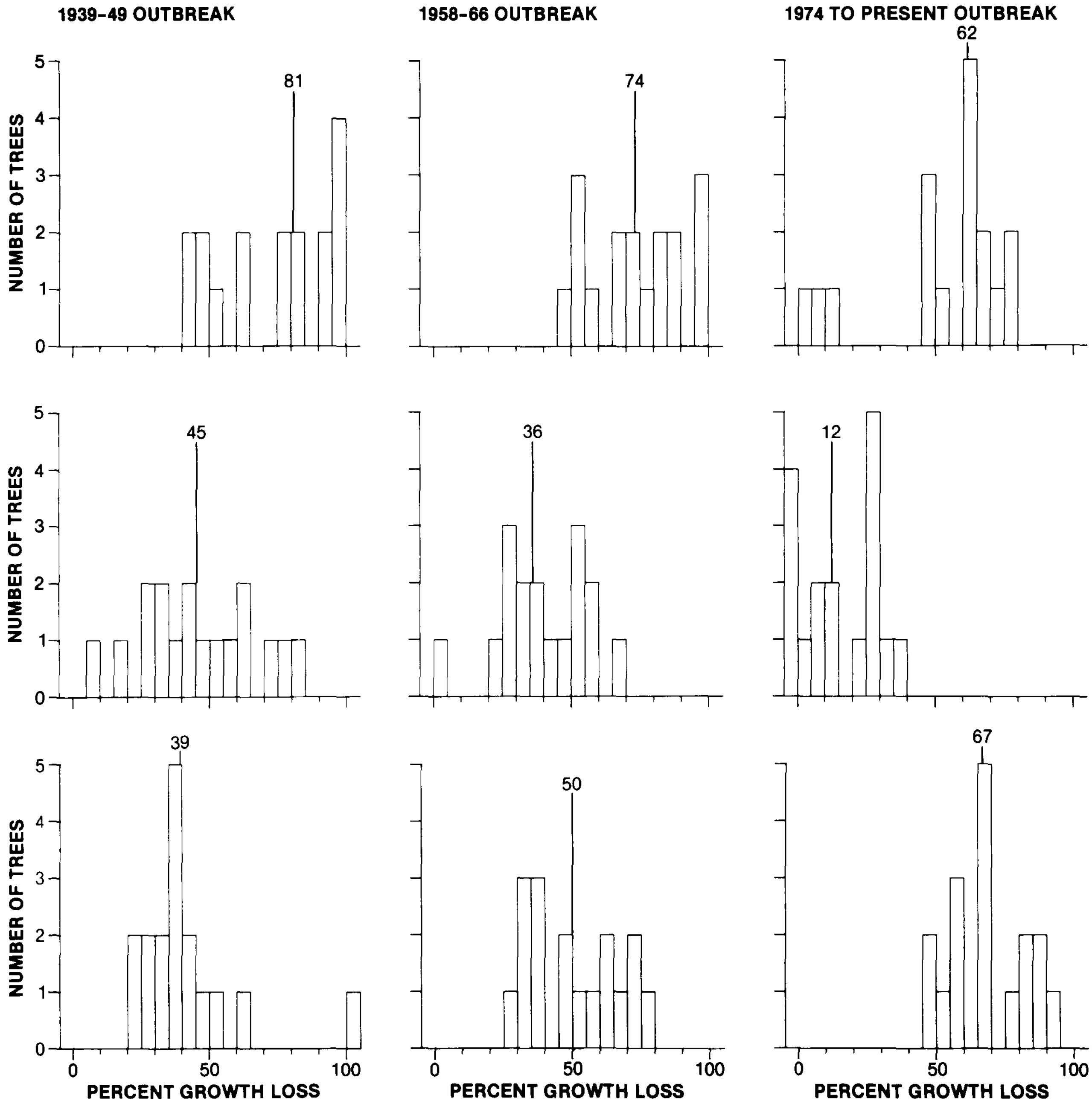


Figure 29—Histograms of three different measures of growth reduction. Row A shows the largest growth reduction for 1 year during three different outbreak periods. Row B shows the average growth reduction for 5 years. Row C shows the maximum rate of growth reduction per year. Median values are indicated with vertical lines.

Summary

The techniques described can be used to obtain improved estimates of budworm-induced radial-growth reductions because cross-dating provides temporal control, standardizing facilitates comparing and averaging tree-ring series from different trees and sites, and correcting host growth with nonhost growth provides climatic and environmental control. We recognize, however, that several limitations remain. Because cross-dating is essential in tree-ring research, our methods are limited to areas where cross-datable species are found. Tree-ring chronologies—and measurements of growth reduction derived from them—are only estimates because tree-ring chronologies are developed from samples of larger populations, standardizing can only approximate the biological growth trends of individual trees, and samples from the base of trees are only relative measures of growth reduction throughout the stem.

A more serious limitation is the bias that may be introduced by using nonhost growth to correct host growth when the two species respond differently to climate, when nonhost trees benefit in some manner from defoliation of the host tree, or when other pests or other nonclimatic factors have differentially affected host and nonhost. If these problems can be avoided or mitigated by careful site selection, sampling, and data analysis, the growth-reduction measurements will be the most reliable and precise estimates now obtainable.

Several applications of radial growth-reduction estimates are immediately useful. For example, percentages of radial-growth reduction could be used by existing inventory systems and models to estimate volume losses in budworm-defoliated stands. Several researchers are currently using or developing stand-projection and prognosis models that use data on radial-growth reduction to predict reductions in forest growth and yield (Wycoff and others 1982, Beveridge and Cahill 1984, MacLean and Erdle 1984, Nichols 1984). As use of these models becomes more widespread, need for region-specific data on radial-growth reduction will increase, both for calibration and for independent verification of their predictions. Regression of data on yearly radial-growth reduction with defoliation data for different species and site conditions may help define predictable relations useful in estimating growth reduction in comparable stands where only defoliation data are available and intensive tree-ring study is impractical.

Developing accurately dated long-term host and nonhost tree-ring chronologies also could identify trends in frequency, extent, duration, and severity of outbreaks (Blais 1983). This information may prove useful in refining simulations and models, as well as providing data for ecological studies of the relations between budworm outbreaks, stand density, species diversity, site history (for example, fire control and logging), and climatic events.

Use of these methods is not limited to the budworm problem. The sections on collecting and preparing samples, skeleton plotting, and standardization are general descriptions of basic procedures applicable to any tree-ring study that dates annual rings and develops tree-ring chronologies. With modifications of sampling and analysis, the filtering, comparison, and correction techniques could be applied to other growth-decline problems—including other defoliating insects, disease, fire, and air-pollution damage. Dendroclimatologists have also developed a diverse array of other statistical tools that may prove useful in extracting nonclimatic environmental information from tree rings. Application of these techniques represents a new and productive development in forest mensuration, with a promising potential for supplying needed ecological and climatic information for understanding and solving forestry problems.

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