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COMPARING TREE-RING CHRONOLOGIES AND REPEATED TIMBER INVENTORIES AS FOREST MONITORING TOOLS

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Abstract. Historical information on forest growth is essential to evaluate and understand change in managed and unmanaged forests. Two ground-truth nondestructive sources of information on interannual to interdecadal changes are (a) repeated timber inventories and (b) tree-ring chronologies. I present here a case study of how those two types of data can complement and benefit each other. At the Gus Pearson Research Natural Area, a ponderosa pine stand near Flagstaff (Arizona, USA), timber inventories were repeated by the U.S. Forest Service from 1920 to 1990. The analysis of those data has revealed a decline of individual tree growth over the 20th century, attributed to increased stand density. Monthly precipitation and temperature at the study area showed no overall trend from 1910 to 1990. Tree-ring data collected at the area after 1990, and spanning the last few centuries, were compared to the inventory data to represent growth trends. Periodic basal area increment computed from forest inventories showed parallel trends but higher absolute values (especially for small pines) than periodic basal area increment computed from increment cores. Among selected ways of developing a tree-ring chronology, average ring area closely matched repeated forest inventories for 20th century trends and revealed that decadal-scale growth rates in the 1900s have been anomalous compared to the previous 300 years. The mensurational and dendrochronological approaches to forest monitoring showed advantages and disadvantages. Repeated forest inventories quantified growth of individual trees and of the entire stand, thus providing a complete picture, even in retrospect; but they had longer-than-annual resolution, and covered only the last decades. Dendrochronological data quantified annual xylem growth of individual trees over their whole life span, thus placing recent growth trends into a much longer historical perspective; but they had limited spatial coverage and could lead to different trends depending on the type of standardization option. Overall, the combination of both approaches is recommended for evaluating changes of forest growth at multiannual scales.

Key words: Arizona; biomonitoring; dendrochronology; dendroecology; forest health; growth trends; Pinus ponderosa; *ponderosa pine; stand dynamics; timber inventories; tree-ring chronologies.*

Introduction

Forest health monitoring relies on retrospective information to distinguish between "normal" and "abnormal" conditions in the status and trends of ecological parameters and processes (Franklin 1989, Kolb et al. 1994). Because of both economic relevance and ease of measurement, tree growth is probably the parameter that national forest agencies, such as the U.S. Forest Service, have monitored at the most detailed spatial scale for the longest time (e.g., Powell et al. 1993). Identification of long-term patterns in forest growth is a primary objective of basic and applied research, with direct implications in forest management and silviculture, as well as in ecological, paleoclimatological, and global change studies. Time series of remotely sensed vegetation growth indices for circumpolar terrestrial ecosystems have recently been used to infer changes in the seasonal carbon cycle associated with global changes in surface air temperature (Myneni et al. 1997). Two ground-truth, nondestructive sources of information on the history of tree growth are (a) repeated forest inventories, studied by forest mensurationists, and (b) tree rings, studied by dendrochronologists. Traditionally, mensurationists are interested in future, absolute, average values of stand growth, and have focused on quantifying and predicting timber resources in relation to site characteristics and management practices (Clutter et al. 1983). On the other hand, dendrochronologists are interested in past, relative, year-to-year values of tree growth, and have concentrated on reconstructing environmental variables such as precipitation, temperature, air pressure, streamflow, drought severity, sunshine, and on dating past events such as fire, insect outbreaks, volcanic eruptions, landslides, floods, windthrows, earthquakes, frosts, and others recorded in annual xylem layers of selected trees (Hughes et al. 1982, Jacoby and Hornbeck 1987, Bartholin et al. 1992).

Relatively little research has focused on comparing and combining forest inventories and dendrochrono-

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logical records. Differences in the mensurational and dendrochronological approaches have hindered communication between the two fields, and much debate has focused on trend identification (NCASI 1987). Dendrochronologists standardize ring-width series to remove individual growth variability related to stem size and cambial age, sociological status, occasional scars, and other factors, while retaining patterns and trends that are in common among trees. Hence, dendrochronological standardization can be defined, in the broadest sense, as the method used to combine all tree-ring samples into a single, average chronology. Mensurationists avoid computing dimensionless ring indices and prefer to transform ring widths into ring areas, or basal area increments, to quantify temporal trends (Hornbeck et al. 1988). It has been suggested that environmental signals in ring-width series should be statistically analyzed without producing an average chronology (Van Deusen 1990, Visser and Molenaar 1990), or that an individual-tree approach should be preferred (LeBlanc 1992). In practice, when trend detection relies on tree rings without climatic data (e.g., Hornbeck et al. 1988, Swetnam and Lynch 1989, Cook 1990, Reams and Huso 1990), or when dating is a major objective of the study, it may still be necessary to produce an accurate representation of average tree-ring patterns.

The degree to which tree-ring chronologies capture variability related to multiannual processes, either climatic or stand-driven, depends on the length of the individual specimens (Cook et al. 1995), but is also likely to depend on the tree species and its surrounding environment. For instance, red spruce in the eastern United States shows a high correlation between detrended ring width, whole-stem ring width, ring area, and wood volume indices, but age- and stand-related growth trends differ (LeBlanc 1990). Still, for that forest species, ring width is an extremely good indicator of annual stem wood volume increment when trees are older than 50–100 yr (LeBlanc 1996). Thammincha (1981) found good agreement between his annual ring-index series for southern Finland and the data from National Forest Inventories. He was also able to improve accuracy of stand growth predictions by including information on interannual variation derived from tree-ring data. Recently, chemical markers in tree rings have been targeted as potential indicators of forest health (Lewis 1995), and the French National Forest Office has adopted dendrochronological methods to provide information on the past history of forest stands included in its permanent plot network for forest ecosystem monitoring (Lebourgeois 1997). In other European countries, tree ring sampling is not allowed in permanent plots for fear of damaging existing trees (Köhl et al. 1996). Bräker (1996) was then restricted to comparing growth trends from forest inventories of a regularly thinned stand with dendrochronological trends derived from cross sections of the felled trees.

In this paper, I present a case study demonstrating how repeated forest inventories and tree-ring chronologies can augment and benefit each other for accurately detecting and evaluating changes of forest growth at multiannual scales. Climatic forcing of such changes is investigated by analyzing long-term trends in precipitation and temperature data collected at the study area, the Gus Pearson Research Natural Area near Flagstaff, Arizona. Since temporal trends derived from forest inventories have already been reported (Biondi 1996), emphasis is placed on trends derived from dendrochronological data. Different standardization methods for producing tree-ring chronologies are graphically compared for evaluating their ability to replicate growth trends derived from the forest inventories.

Materials and Methods

Study area

The study was conducted on the Gus Pearson Research Natural Area, a 800 × 400 m permanent plot established in 1908 within unmanaged ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. var. *scopulorum*) in north-central Arizona. Ponderosa pine forests around Flagstaff occupy a crucial place in the history and development of modern dendrochronology. It was in these forests, in 1901, that A. E. Douglass began collecting wood specimens to test the hypothesis that annual tree growth, as measured by ring width, was influenced by climate, and therefore could be used to reconstruct past climatic fluctuations (Douglass 1919, Webb 1983). At about the same time, in 1908, G. A. Pearson was sent to Arizona by the Forest Service to study natural regeneration of ponderosa pine (Pearson 1942, 1950). In order to evaluate the impact of management practices on ecological processes, he established the permanent plot that now bears his name. Today, the Gus Pearson Research Natural Area is part of the Fort Valley Experimental Forest, within the Coconino National Forest. Although it is one of the longest, individual-based forest monitoring data sets in the world, it was decommissioned in 1987 (Covington et al. 1997), and one can only hope that budget considerations will not affect its preservation.

Forest inventories in digital format were obtained from the U.S. Forest Service. All pines with diameter at breast height (1.3–1.5 m; dbh) >8.9 cm (3.5″) were first tagged and measured in 1920, and then remeasured every 5 yr from 1920 to 1960, and every 10 yr from 1960 to 1990. At every inventory, ingrowth (pines whose dbh had exceeded the minimum value for tagging) was added to the database, and mortality (pines that had died) was recorded. The study area is now divided in 29 plots that were neither thinned nor burned during the period covered by the forest inventories. Additional details on inventory data are given by Avery et al. (1976). Spatial and temporal patterns of tree and stand growth derived from the repeated inventories have revealed a decline of individual tree growth over the 20th century (Biondi et al. 1994, Biondi 1996). Because of the rapid increase in density during the 20th century (Fig. 1), large trees have experienced, on average, greater reduction in growth over time, and greater chances of dying, than small trees. During previous centuries, stand structure in southwestern ponderosa pine was maintained at low-density levels by frequent, low-intensity fire (Weaver 1951, Cooper 1960, Dieterich 1980, White 1985). Fire suppression programs in the 1900s allowed pine regeneration to grow into larger size classes, thereby occupying the space in and around clumps of much older trees, which experienced a relatively abrupt change in competition processes (Biondi 1996).

Tree-ring data

Dendrochronological sampling consisted of two increment cores extracted from the stem of 58 tagged pines growing on the 29 plots. Two pines, one above and one below 50-cm dbh in 1990, were randomly selected on each plot in order to stratify the sample by two size classes. The 50-cm dbh cutoff was used to mimic the distinction between large ponderosa pines, called ''yellow pines'' because of the orange and light brown color of their outer bark, and small pines, called ''blackjacks'' because of the dark grey, almost black color of their outer bark (Schubert 1974). Two increment cores were extracted from each tree ~1.0 m above ground level and 180° from each other whenever possible. Pines on plots 1–14, 16, and 27, i.e., those reported in Avery et al. (1976), were first sampled in 1987 (T. W. Swetnam, University of Arizona, 1990, *personal communication*), and later resampled to extend their tree-ring record until 1990. A total of 116 wood cores was collected between November 1990 and July 1991. Coordinates of each cored pine were ob-

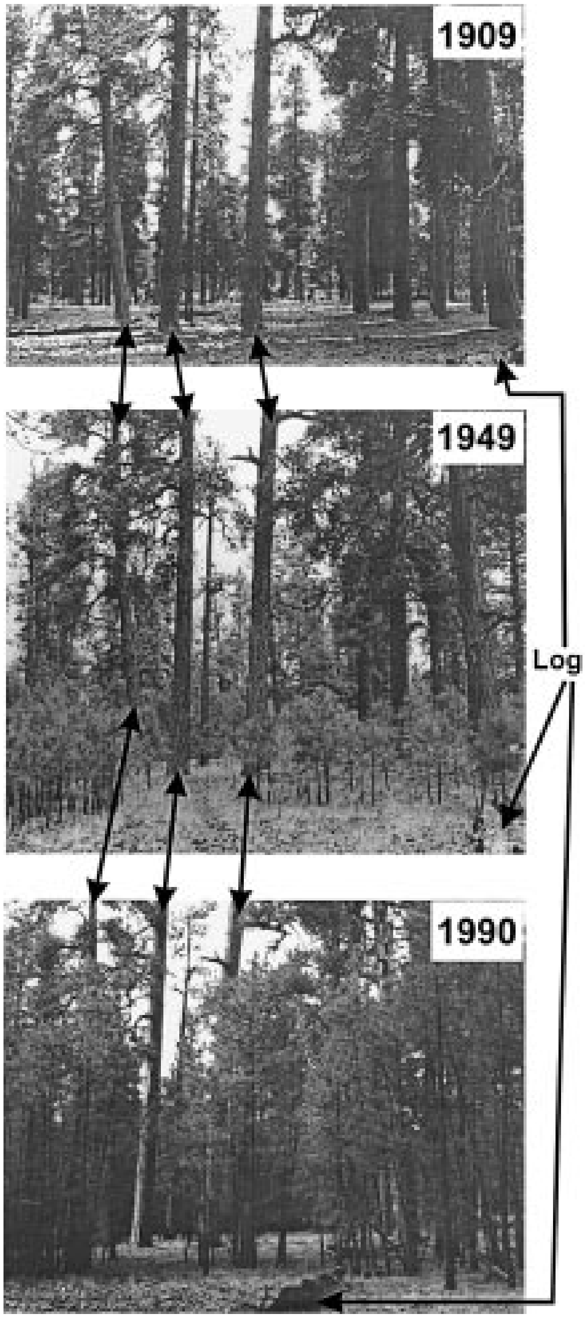

FIG. 1. Repeated ground photos taken at the study area (C. C. Avery, School of Forestry, Northern Arizona University, Flagstaff, 1991, *personal communication*) illustrate historical stand dynamics. The downed stem (Log) and the overstory pines (arrows) were present throughout the 20th century. The 1909 photograph was first published by Pearson (1931:8), then by Covington and Moore (1994) together with the 1949 and 1990 photographs. Covington and Moore (1994) gave credit for the 1909 and 1949 photo to G. A. Pearson (who died in January 1949), and for the 1990 photo to Frank Ronco.

Top (1909): The ponderosa pine forest is open, park-like, with clumps of trees scattered across the landscape. Such features are consistent with reports of early explorers of the American Southwest. The last spreading fire occurred in 1876 (Dieterich 1980), but almost no herbaceous understory is

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present, most likely because of overgrazing, reported in the Flagstaff area during the 1880s (Cooper 1960). **Middle** (1949): Fire suppression programs started shortly after 1900, and pine regeneration exploded. Given their size, saplings visible in the foreground probably originated in 1919, when abundant ponderosa pine reproduction was reported over the Colorado Plateau (Schubert 1974, Savage et al. 1996). Many other successful regeneration pulses have occurred during the 20th century (Pearson 1950). Density increased from 1920 to 1990 by increasing the number of pine groups rather than their horizontal dimension (Biondi et al. 1994). In the absence of fire, stand patchiness was maintained by seed dispersal mechanisms (Biondi 1994). **Bottom** (1990): Today the Gus Pearson Natural Area is a dense, multistoried stand, formed by an uneven-aged mosaic of even-aged pine clusters. As in a number of other Southwestern ponderosa pine forests, pine crowns form a patchy but continuous fuel ladder from sapling and pole thickets to the tallest, oldest individuals (Kolb et al. 1994, Covington et al. 1997). Individual growth rates have declined over the 20th century, especially among large pines. Mortality of large pines has also increased over time, most likely because of root-level competition from small pines (Biondi 1996).

tained in the field using compass and measuring tape. At the laboratory, size of sampled pines was tested for spatial autocorrelation using geostatistical methods (Isaacs and Srivastava 1989, Myers 1991).

All increment cores were air dried, glued to wooden mounts after vertically aligning the xylem tracheids, mechanically sanded, then polished by hand with progressively finer sandpaper. Ring patterns were visually cross-dated (Stokes and Smiley 1968) using a binocular microscope. Crossdating was independently verified by another researcher, then ring widths were measured to the nearest 0.01 mm by means of a sliding micrometer with a computer interface for data acquisition (Robinson and Evans 1980). Dating accuracy was verified using the computer program COFECHA (Holmes 1983).

In dendrochronological studies, once cross dated rings are measured, it is necessary to reduce them into a manageable representation of short- and long-term historical patterns. Tree growth varies on multiple time scales, from interannual to interdecadal, and various numerical methods have been proposed to preserve (or discard) this information in the final tree-ring chronology. Such methods are grouped under the term ‘‘standardization’’ in the dendrochronological literature (Douglass 1919, Schulman 1956, Fritts 1976, Hughes et al. 1982, Cook and Kairiukstis 1990), and they are intended to minimize growth variation due to phenomena acting at the individual tree level. I considered four methods of producing an average tree-ring chronology. The selected methods are only a fraction of those proposed in the literature, but they are different enough to represent the issues involved in growth trend detection from dendrochronological data. Autoregressive modeling (Box and Jenkins 1976, Biondi and Swetnam 1987) was not considered because the emphasis in this paper was placed on interpreting, rather than removing, low-frequency variability. Separate tree-ring chronologies were developed for pines with 1990 dbh ≥50 cm and with 1990 dbh <50 cm. The methods can be summarized by the following equations:

$$\omega_t = [\oplus_i(wy_1^{-1}s^{-1})_{it}] + \alpha \qquad (1)$$

with ω_t = chronology value at year t; $\oplus_i$ = biweight robust mean (Mosteller and Tukey 1977) of the i values, $i = 1, \ldots, n_t$ (n_t is the number of measured specimens that included year t); w = cross dated ring width (mm); y_1 = modified negative exponential or straight line (Fritts et al. 1969); s = cubic smoothing spline with 50% variance reduction at a 128-yr period (Cook and Peters 1981); α = difference between 1.000 and the arithmetic mean of the robust-mean chronology. These are the default options of the ARSTAN software program (Cook and Holmes 1996).

$$\omega_t = n_t^{-1} \sum_i (wy_2^{-1})_{it} \qquad (2)$$

with Σ_i = summation of the i values, $i = 1, \ldots, n_t$; y_2 = modified negative exponential or straight line with slope ≤ 0. This is the most widely known method, as first proposed by Douglass (1914), and later made popular by Fritts (1976).

$$\omega_t = n_t^{-1} \sum_i [\log(w_{it} + k) - y_{2it}] \qquad (3)$$

with k = constant added to avoid taking the logarithm (log) of zero. This method is based on an exponential model (Biondi 1992, 1993); taking the logarithm of ring widths is equivalent to plotting ring-width series on semilogarithmic paper, a method commonly adopted by European dendrochronologists (Schweingruber 1988:51).

$$\omega_t = n_t^{-1} \sum_i a_{it} \qquad (4)$$

with a = ring area (cm^2) computed from w assuming a circular cross section, as follows:

$$a_t = \frac{\pi}{100} w_t \left(w_t + 2 \sum_{i=0}^{t-1} w_i \right) \qquad (5)$$

with w_0 = distance (mm) between the stem pith and the innermost measured ring; when a core did not include the pith, w_0 was estimated using circles (Applequist 1958). This method of producing a tree-ring chronology was first proposed by Phipps (1979), and has been commonly applied in dendroecological studies (Phipps and Whiton 1988, Jordan and Lockaby 1990, Peterson et al. 1993). A modification of this procedure, whereby past diameters are estimated by subtracting ring width from current outside bark diameter, has been proposed by LeBlanc (1993, 1996).

For direct comparison, periodic basal area increment of the sampled pines was computed from the repeated dbh measurements of forest inventories and from dendrochronological data. The two ring-area series from the same pine were averaged to quantify current annual basal area increment. The 10-yr periodic basal area increment (PBAI) was then computed as the 10-yr sum of the current annual basal area increment. The difference between estimates of wood increment from forest inventories and from dendrochronological series was computed as follows:

$$\mathrm{MD}(\%) = \frac{\sum_{i=1}^{n_i} \sum_{t=1}^{n_t} \left(100 \frac{\mathrm{PBAI}_1 - \mathrm{PBAI}_2}{\mathrm{PBAI}_1} \right)_{it}}{n_i n_t} \qquad (6)$$

with MD = mean difference; PBAI_1 = 10-yr periodic basal area increment computed from ring-area series; PBAI_2 = 10-yr periodic basal area increment computed from forest inventories; n_i = number of pines; n_t = number of time intervals.

Climatic data

Twentieth-century trends in precipitation and temperature were studied using the Fort Valley station, which well represents the climatic regime of ponderosa pine forests over the Colorado Plateau (Schubert 1974: 10–12). Daily meteorological data recorded at the study area include maximum and minimum temperature, total precipitation, and amount of snowfall (NOAA 1990*a*). The station was moved from its first location, at 2255 m, to a slightly lower one, at 2239 m, between July and August 1946, but data were continuous (NOAA 1990*b*) and homogeneous. Because of the large amount of missing data, snowfall data were not used in the final analyses. Monthly summaries were produced from the daily data and checked against published monthly summaries (NOAA 1990*b*). Statistical significance of monotonic temporal trends was tested using the univariate, nonparametric, Mann-Kendall test (Kendall and Gibbons 1990). From 1910 to 1990, climate at the study area was characterized by cold snowy winters, May–June droughts, and July–August monsoon rainfall.

The climatic regime at Flagstaff was compared to that at Fort Valley for testing data homogeneity (Fritts 1976:254), and then used to estimate missing values in the Fort Valley record. The climatic regime at Flagstaff, based on monthly data for the 1900–1990 period, is very similar to that at Fort Valley. The warmest, coldest, wettest, and driest months are the same at both stations, and correlation is very high ($P < 0.001$) in every month, although it decreases in July and August because of frequently localized thundershowers. On average, Flagstaff is a little warmer and a little drier than Fort Valley, which is ~100 m higher in elevation. According to Pearson (1931:34), Fort Valley is colder than Flagstaff because it is closer to the high San Francisco Mountains. Also, both stations are located in a cold air drainage, as shown by temperature inversion in fall and winter (Pearson 1931:32).

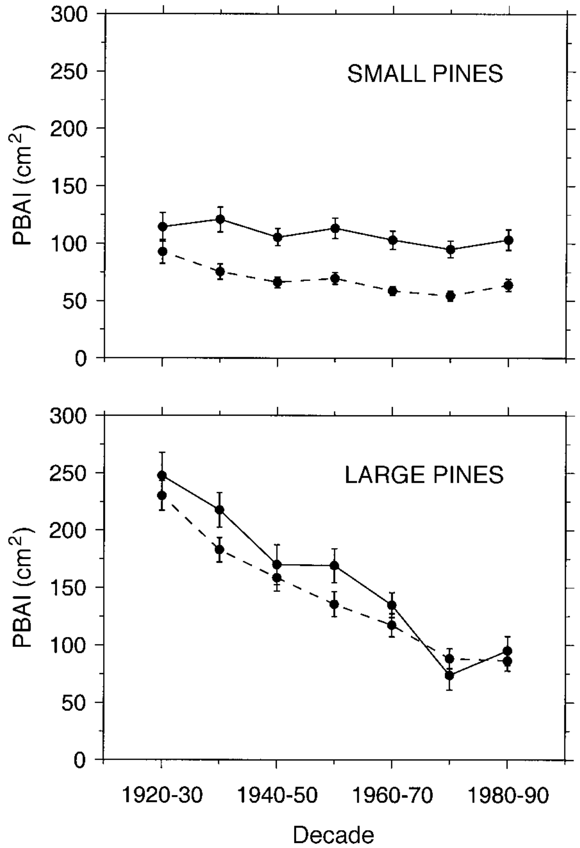

FIG. 2. Periodic basal area increment (PBAI) of pines with 1990 dbh below 50 cm (SMALL PINES) and above 50 cm (LARGE PINES). Standard error bars (±1 SE) are also plotted to show variability and significance of parameter estimates. Values computed from repeated forest inventories (——) show similar fluctuations to, and usually exceed, those computed from increment cores (– – –).

RESULTS

Tree characteristics

Cored pines were not affected by spatial autocorrelation because omnidirectional sample variograms of stem dbh and of tree height fluctuated randomly with respect to distance (Biondi 1994). Increment cores were dated and measured up to ring-year 1990. Because most cores did not extend back further than 1570, measured ring widths ranged from 1570 to 1990. The total number of measured rings was 20 197: 16 408 belonged to large pines and 4509 to small pines. No dating errors were identified after running the COFECHA program, even though some cores had low correlations with the rest of the sample. Running COFECHA on the combined data set ($N = 116$) or on each of the two data sets for large and small pines ($N = 58$ each) produced indistinguishable results in terms of dating.

Pine ages at coring height ranged between 59 and 160 yr for trees <50 cm dbh in 1990, and were >111 yr for trees with 1990 dbh ≥50 cm. The oldest sampled pine exceeded 600 yr of age, and was a large dominant surrounded by thickets of small pines. Its dbh increased from 95.0 cm in 1920 to 105.4 cm in 1990. Several locally absent rings were identified in its two cores; rings formed earlier than 1600 were initially dated against the Flagstaff chronology (Douglass 1940, 1947) retrieved from the Laboratory of Tree-Ring Research collections. Crossdating was reliable back to 1487; I dated the first visible ring as AD 1380 ± 5. Since the first visible ring did not include the pith, and the two cores were not taken at ground level, the true age was probably 30–50 yr greater, up to an estimated 660 yr in 1990. Maximum reported age of southwestern ponderosa pine is ~750 yr (Swetnam and Brown 1992).

Long-term trends

Periodic basal area increment (PBAI) computed from increment cores showed trends parallel to those computed from forest inventory data (Fig. 2). Growth rates of large pines declined more than those of small pines. Based on forest inventories, large pines had larger

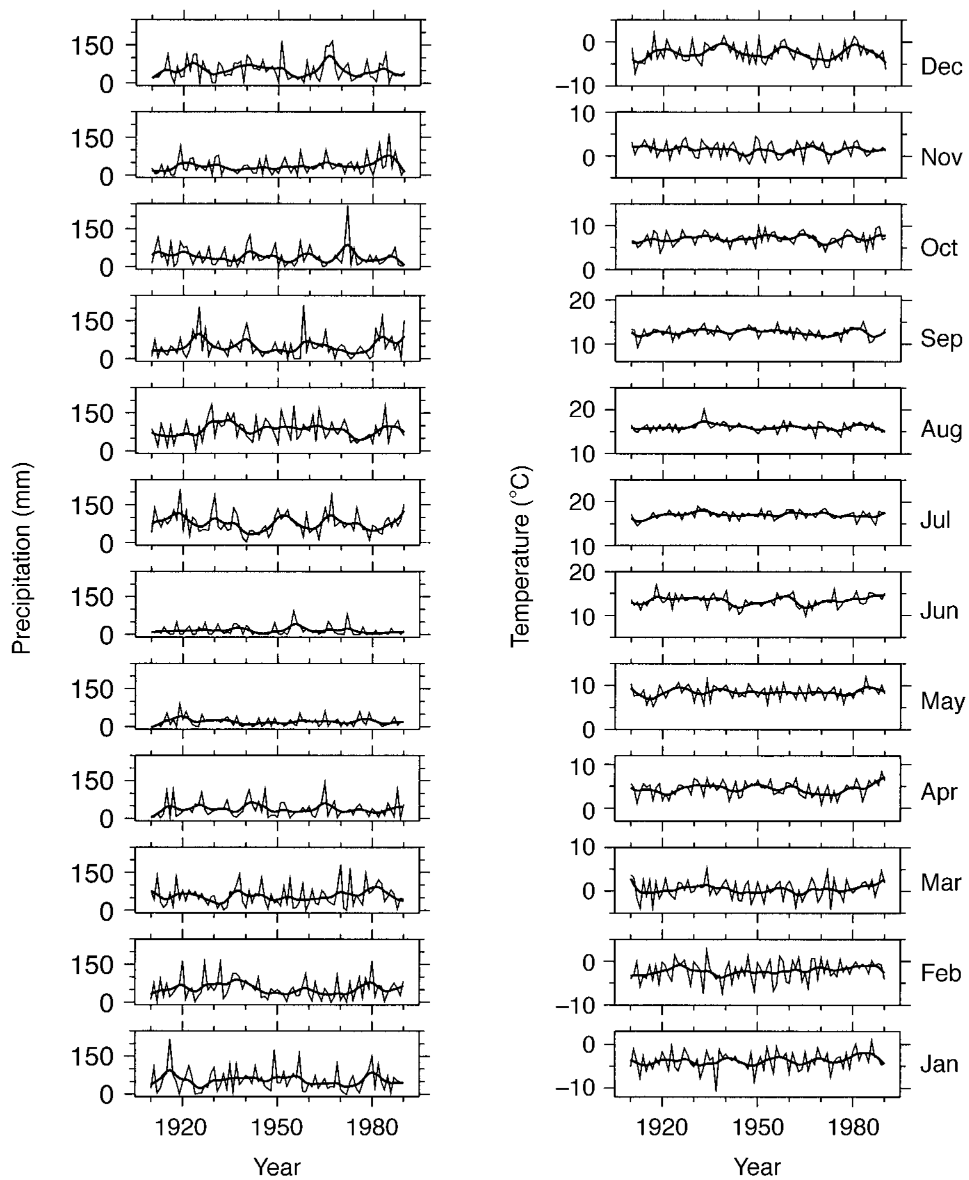

FIG. 3. Time-series graphs of monthly total precipitation and mean temperature at the study area from 1910 to 1990. Decadal-scale variability (thick, smooth line) was superimposed on the annual variability (thin, jagged line). No overall trend is present.

PBAI than small pines until the last decades, when the situation reversed (also see Biondi 1996). Based on tree rings, PBAI of large pines remained larger than that of small pines throughout the 1900s (Fig. 2). This difference in absolute PBAI values was related to the difference between PBAI computed from forest inventories and from dendrochronological data. Such difference was greater for small pines (MD = −61%) than for large pines (MD = −8%).

No long-term trend was evident in the annual and monthly precipitation and temperature record (Fig. 3), and the Mann-Kendall test for trend was never significant ($P \geq 0.082$). Time-series autocorrelation from one year to the next was not statistically significant for monthly total precipitation, monthly mean temperature, annual total precipitation, and annual mean temperature. Decadal-scale climatic patterns had prompted Glock and Agerter (1969) to infer that a post-1925 decline of ponderosa pine growth at the Fort Valley Experimental Forest was related to a decrease in June–July rainfall after 1923. June–July precipitation, however, reached a minimum in the 1940s, then increased in the 1950s, and by 1959 it was back to its 1923 level (Fig. 3). Furthermore, Glock and Agerter (1969) gave no consideration to the increasing stand density and competitive reduction of individual tree growth.

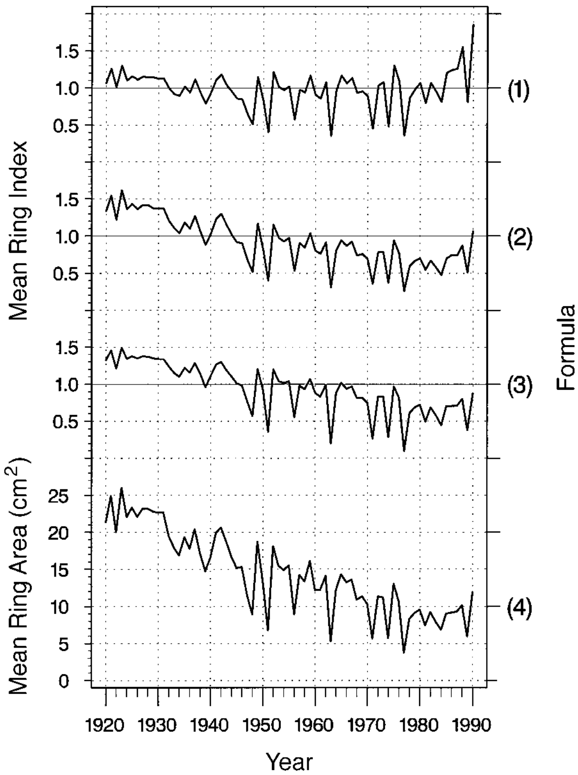

FIG. 4. Tree-ring chronologies from 1920 to 1990 based on tree-ring samples of pines with 1990 dbh >50 cm (LARGE PINES). The four methods [(1) ARSTAN, (2) Fritts, (3) Biondi, and (4) Phipps] used to compute the chronologies are detailed in *Materials and Methods: Tree-ring data.*

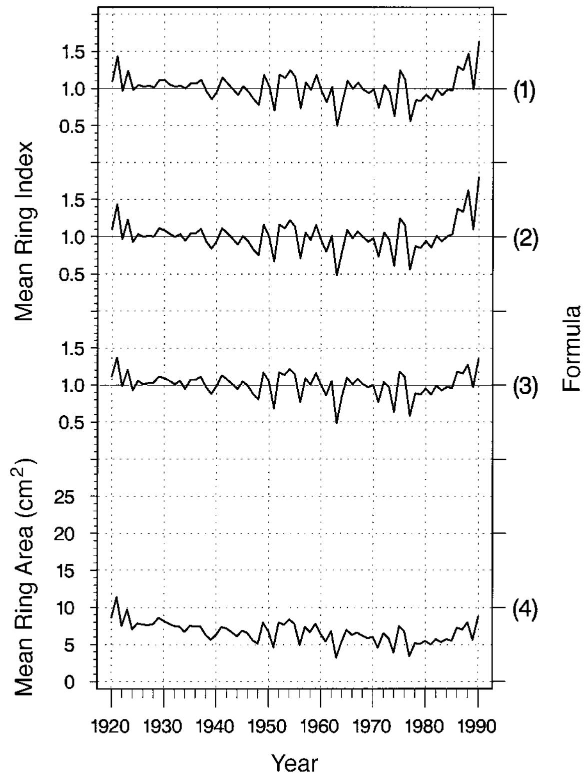

FIG. 5. The same as Fig. 4, but for pines with 1990 dbh <50 cm (SMALL PINES).

Dendrochronological trends during the 20th century depended, in part, on the standardization options (Figs. 4 and 5). Tree-ring chronologies developed by adopting ARSTAN defaults did not show any decline over time; rather they displayed a rapid growth increase after about 1980. Since ring-width series ended in a low-growth period, dividing ring width by a fitted curve value could artificially inflate the final part of the tree-ring chronology (Cook and Peters 1997). A similar growth surge was evident in small pines when method (2) was used, but it was not present in the method (3) chronology (Fig. 5). For large pines, methods (2) and (3) produced extremely similar tree-ring chronologies, and replicated the growth decline evident in periodic basal area increment. Considering the agreement between low-frequency growth patterns derived from forest inventories and from ring-area chronologies, the latter were chosen to represent tree growth at the study area over the past four centuries (Fig. 6). Large pines showed a unique growth surge in the early 1900s followed by a continued decline until about 1980. Small pines showed a less dramatic growth increase in the early 1900s followed by a less dramatic decline up to about 1980, when growth rates began increasing again.

DISCUSSION

Maximum ages of sampled ponderosa pines were greater than those reported by White (1985). In this study, out of 29 randomly selected pines with dbh >50 cm, one was older than 600 yr, and 13 other pines were older than 400 yr. White analyzed a total of 236 pines older than 106 yr, and found that only five of them exceeded 400 yr, with a maximum age of 406 yr in 1980 (White 1985). The pines he sampled were located on two of the 29 plots sampled in this study, and usually one core was taken from each tree. The year of the innermost, crossdated ring was used to define pine age, even though most cores did not include the stem pith (A. S. White, University of Maine, 1992, *personal communication*). The old age of trees at the Gus Pearson Natural Area is even more remarkable if one considers the location and topography of the stand, on both sides of a major highway and on gently undulating terrain. Typical sites for old, climatically sensitive trees are remote areas on steep, rocky slopes (Schulman 1956, Swetnam and Brown 1992).

Basal area increments computed from repeated forest inventories and from increment cores showed similar trends but systematic differences in absolute values, especially for pines with 1990 dbh <50 cm. Since PBAI values computed from forest inventories exceeded those computed from tree-ring chronologies, their difference should not depend on the usually lower-than-

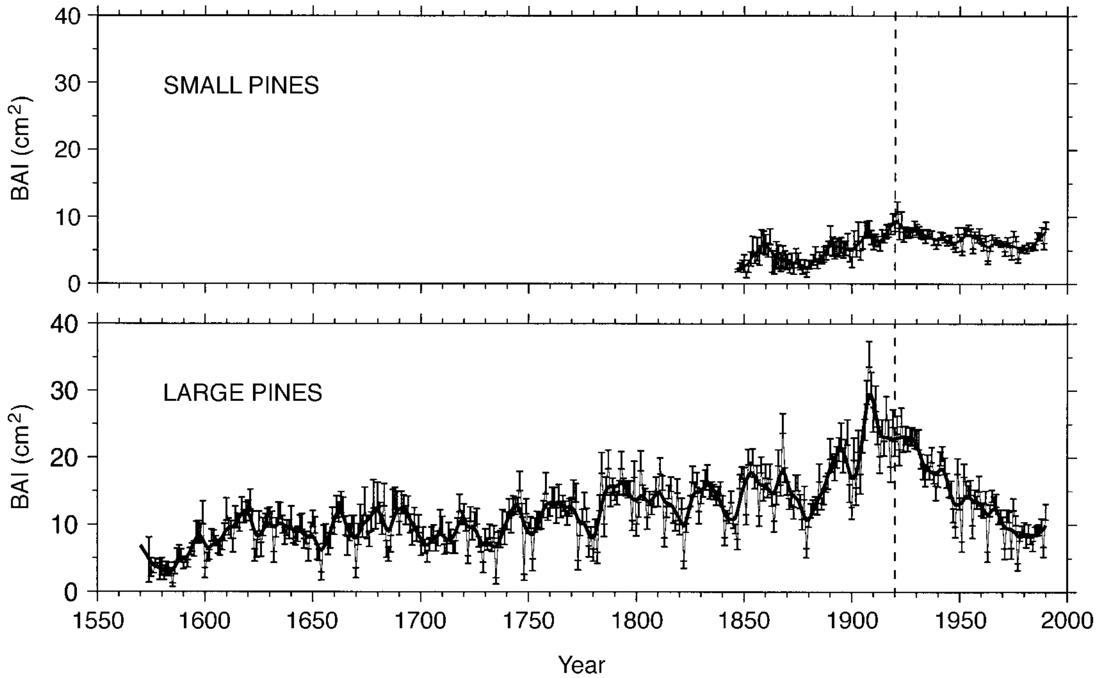

FIG. 6. Tree-ring chronologies for the whole period of available records, computed as the average of ring-area series. Standard error bars (±1 SE) are plotted to show variability of annual values. It is evident that pines with 1990 dbh >50 cm (LARGE PINES) were much older and experienced a greater growth decline in the last century than pines with 1990 dbh <50 cm (SMALL PINES). Tree-ring patterns over the last 400 yr reveal that the 20th century has been unique and suggest that the extreme growth decline experienced by large pines is partly a return to normal growth rates after the growth surge of the early 1900s.

breast-height level at which cores were taken. Several sources of error affect both types of growth rate estimation (Biging and Wensel 1988, Gregoire et al. 1990). Irregularity of the bark surface, noncircularity and nonconvexity of the stem, inclusion of both wood and bark increment, as well as changes over time in instrumentation, height from the ground, operators, and measuring protocols, are factors that can bias the estimation of individual basal area increment from repeated dbh measurements. Such errors may vary with pine size/age; for instance, bark furrows are usually deeper and narrower in blackjacks than in yellow pines. On the other hand, using two increment cores for estimating basal area increment is also problematic because of noncircular growth rings, asymmetric pith location, and other sources of systematic variation of ring width at coring level. Radial shrinking of increment cores after drying is minimal, but it artificially reduces estimated growth rates. Finally, pith location was usually easier to identify in pines with 1990 dbh <50 cm, hence ring-area series were more accurate for small pines than for large pines.

Not all standardization methods used in the present study resulted in similar trends. Mean ring-area series highlighted the difference between large and small pines (Figs. 4 and 5). The 20th century growth decline was steeper in large pines than in small pines, it leveled off after 1970, and, for small pines, began reversing in the last few years preceding 1990 (Fig. 5). Those trends best matched those identified from time-series plots of ring-width series (Biondi 1994), and those detected graphically and statistically for periodic basal area increment of individual pines (Biondi 1996). Among other standardization options, fitting a stiff curve to log-transformed ring widths and then computing ring indices as deviations from the curve generated trends that best agreed with mean ring-area series (Figs. 4 and 5). The modified negative exponential curve reflects expected features of radial increment as a function of stem size in open-grown trees (Fritts 1976). The smoothing cubic spline was proposed to model expected low-frequency variation related to factors acting on individual trees growing in dense, uneven-aged forest stands where shade-tolerant species may respond to release effects (Cook 1987).

The present case study suggests that inferences and comparisons of temporal trends for trees of different age/size should be based on ring-area series, which are less dependent on stem size and cambial age than ring-width series (Phipps 1979, LeBlanc 1990). Furthermore, when ring indices are computed as ratios, end-series computational problems may interfere with the dendrochronological identification of temporal growth trends in recent decades (Biondi 1994, Cook and Peters 1997). Whenever tree-ring data are the only source of information about past tree growth trends, it is then desirable to avoid using ARSTAN default options, especially considering that prediction of future trends weights heavily the most recent portion of the historical record.

Mean ring-area chronologies revealed that the establishment of the Gus Pearson Natural Area coincided with the largest peak of pine annual growth as well as with the beginning of the longest growth decline in the last four centuries (Fig. 6). Of the 29 cored pines with 1990 dbh >50 cm, only one was younger than 130 yr. Therefore, the growth surge experienced by pines with 1990 dbh >50 cm at the beginning of the 20th century could not be caused by young trees entering the chronology around that time. According to Fritts (1991), the 1907–1916 period was the second wettest decade from 1600 to 1960 in the western United States. It is also possible that livestock grazing, which was particularly intense around the turn of the century (Fig. 1), enhanced tree growth by removing the competing grass cover. Even though intertree competition was most likely the primary forcing factor of the growth decline during the 20th century (Biondi 1996), climatic stress may have periodically enhanced or relieved the burden of competitive interactions. For instance, the decrease of pine outgrowth and basal area increment, as well as the increase of pine mortality, accelerated during the 1940s and 1970s (Biondi 1996), both of them periods of intense summer drought (Fig. 3). The recent increase in growth rates of small pines has coincided with an increase of summer precipitation in the 1980s, and dendroclimatic analyses have shown that July monsoon rainfall benefits ponderosa pine growth (Glock and Agerter 1969, Biondi 1994).

When seen in historical perspective, the extreme growth decline experienced by large pines from 1920 to 1990 appears to be, in part, a return of growth rates to their long-term average preceding the growth surge of the early 1900s. Such long-term patterns could not be captured by forest inventories, restricted to the 20th century. The value of this otherwise unavailable information about past growth history justifies the cost of dendrochronological data. Repeated forest inventories are extremely expensive because they are labor intensive, and require the establishment and maintenance of permanent plots, with associated long-term investment of resources for record keeping and updating. In comparison, the cost of dendrochronological data is minimal, and certainly lower than the cost of, for example, Geographic Information Systems (GIS) data and technologies, which are now routinely used for forest management purposes. Until a rigorous cost–benefit analysis is undertaken, the often heard claim that dendrochronology is ''too expensive'' to be added to forest inventory methods does not seem warranted.

Overall, the mensurational and dendrochronological approaches to forest monitoring have advantages and disadvantages. Previous studies (Biondi 1994, 1996) have shown that repeated forest inventories quantify growth of individual trees and of the entire stand, thus providing a complete picture, even in retrospective, of growth dynamics. It is then possible to ascertain if there is a difference between growth trends of individual trees and of the forest stand they belong to. Ingrowth, the direct outcome of successful tree regeneration (Shifley et al. 1993), and mortality, both of them highly variable processes, can be derived from the inventories. Furthermore, when combined with spatial information, forest inventories are a powerful tool to evaluate spatial processes, either alone or in combination with temporal ones (Biondi et al. 1994). On the other hand, inventory data on permanent plots are usually collected at 5-to-10-yr intervals. Hence, interpolation between successive inventories is needed to compute yearly growth values (Eriksson et al. 1990), but because of the smooth pattern of interpolated annual growth rates, the effect of year-to-year environmental variation on tree growth remains undetected. Furthermore, simple correction schemes to convert dbh outside bark to dbh inside bark may result in estimation errors if bark percentage of dbh changes with the age of the tree or with other factors.

Dendrochronological data provide an accurate representation of year-to-year growth patterns, and can be used to empirically quantify the influence of regional forcing factors, such as climatic regime, upon annual wood production (Graumlich 1989). An advantage of dendrochronology for historical reconstructions and trend detection is dating accuracy, as obtained by means of crossdating. Indeed, Fritts and Swetnam (1989) define dendrochronology as ''the systematic use of tree-ring crossdating, a procedure that uses variability of ring characteristics to establish the exact year in which each ring was formed.'' They describe and discuss applications of crossdating in ecological studies, and point out that significant estimation errors can arise when ring counting is preferred to crossdating. Numerical, graphical, and visual techniques of crossdating have been developed to accurately assign calendar years to xylem layers (Douglass 1941, Stokes and Smiley 1968, Baillie and Pilcher 1973, Holmes 1983, Wigley et al. 1987, Yamaguchi 1991, Van Deusen and Reams 1993). Crossdating is not commonly used in forest mensuration studies, but its practical importance should not be overlooked. For instance, accurate measurements of tree age translate into more refined data on forest stand growth, which in turn allow more efficient utilization of forest resources (Zeide 1993). In this study, cores collected from pines with 1990 dbh >50 cm included 194 locally absent rings (1.2% of the total number of measured rings). It is unknown how many more errors would have been made without proper surface preparation, visual and numerical crossdating. Considering that the majority of ring widths from 1950 to 1990 ranged between 0 and 0.6 mm for pines with 1990 dbh >50 cm (Biondi 1994), it is reasonable to infer that routine measurement of tree ages by ring counting in the field would have missed most rings formed in the last decades.

Compared to forest inventories, tree-ring records usually have limited spatial coverage, hence they cannot provide a complete picture of stand growth. On the other hand, forest inventories are restricted to the last century, but the longevity of tree species and the pace of stand dynamics in the midlatitudes require a much longer record to disentangle variability at multiple time scales, from annual to decadal to centennial. For instance, the identification of abnormal decline in tree radial growth has to be preceded by the definition of the normal, or expected, decline caused by the biological trend (Federer and Hornbeck 1987, Fritts and Swetnam 1989). Dendrochronological data can provide a long-term perspective on natural variability of individual tree growth, thereby giving managers additional information for evaluating recent trends. In this study, ring-area chronologies agreed with repeated forest inventories during their period of overlap, and then revealed that decadal-scale growth rates in the 1900s had been anomalous compared to the previous three centuries. Such long-term perspective is the most compelling reason to recommend the development of tree-ring chronologies whenever forest inventories are used as monitoring tools for evaluating growth trends at multiannual scales.

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