

RESPONSE OF TREE-RING DENSITY TO CLIMATE IN MAINE, U.S.A.

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ABSTRACT

Cores of red spruce (*Picea rubens* Sarg.) from three upper-elevation sites in Maine, U.S.A., were X-rayed, and minimum and maximum wood densities as well as ring widths were mechanically recorded. The 200- to 300-year series of maximum densities at the three sites show remarkable inter-site similarity. Maximum density and total ring-width series from one site, Elephant Mt., were standardized. Response functions, which measure tree-growth response to climatic variables, were calculated for each of these two series. The ring-width response function explained 66% total variance, of which 34% was explained by climate. The maximum density response function explained 70% total variance, 67% of which was explained by the same climatic variables. Thus, the climate signal from maximum densities is stronger, and perhaps more season-specific, than that of ring widths.

Des échantillons de "red spruce" (*Picea rubens* Sarg.) de trois stations situées à la plus haute altitude dans le Maine ont été étudiés par les méthodes densitométriques (RX). Les densités maximales et minimales ainsi que l'épaisseur totale de chaque cerne ont été mesurées. Les séries longues de 200 à 300 ans montrent d'un site à l'autre, une similitude remarquable des densités maximales. Ces densités maximales et les séries d'épaisseur des cernes d'une site, Elephant Mt., ont été standardisées. Les fonctions de réponses qui mesurent la réponse de la croissance aux variables climatiques ont été calculées pour chacune de ces séries. La fonction de réponse fournie par l'épaisseur des cernes expliquait 66% de la variance totale dont 34% étaient expliqués par le climat. La fonction de réponse obtenue en utilisant la densité maximum explique 70% de la variance totale, dont 67% sont expliqués par les mêmes variables climatiques. En conclusion, le signal climatique transmis par la densité maximum est plus puissant et peut être plus spécifique d'une saison que celui fourni par l'épaisseur totale de cerne.

Bohrkerne aus Rotfichten von drei hochgelegenen Standorten in Maine/U.S.A. wurden röntgenografisch untersucht und daraus die minimale und maximale Holzdichte sowie die Breite der Jahresringe abgeleitet. Die 200 - 300 jährigen Zeitreihen der maximalen Jahrringdichte zeigten zwischen den drei Standorten eine beachtliche Ähnlichkeit. Die Reihen der Maximaldichte und Jahrringbreite der Fichten des Standortes Mt. Elephant wurden standardisiert. Für beide Zeitreihen wurden "response functions" (Reaktionsmuster) berechnet, die einen Ausdruck für die Reaktion des Baumwachstums auf Klimaeinflüsse darstellen. Die Funktion für die Ringbreiten erklärt 66% der Gesamtstreuung, wobei 34% auf das Klima zurückgehen. Die Funktion für die maximale Dichte erklärt 70% der Gesamtstreuung, wobei 67% durch klimatische Faktoren verursacht wurden. Somit ist das klimatische Signal in der maximalen Holzdichte stärker und eventuell mehr jahreszeiteinspezifisch als das der Ringbreiten.

INTRODUCTION

Dendroclimatic studies in the American Southwest have been successful in part because of the growth-limiting effects of low precipitation and high temperatures. There is thus a strong climate/growth relationship which is visible in the year-to-year variations in tree-ring widths. In contrast, the northeastern U.S. enjoys ample precipitation for most of the year, and temperatures are usually moderate in the summer. Tree growth is more commonly limited by competition from surrounding trees for sunlight, moisture, and nutrients, and the tree-growth/climate relationship is harder to establish. Thus, dendroclimatic studies using ring widths from eastern U.S.

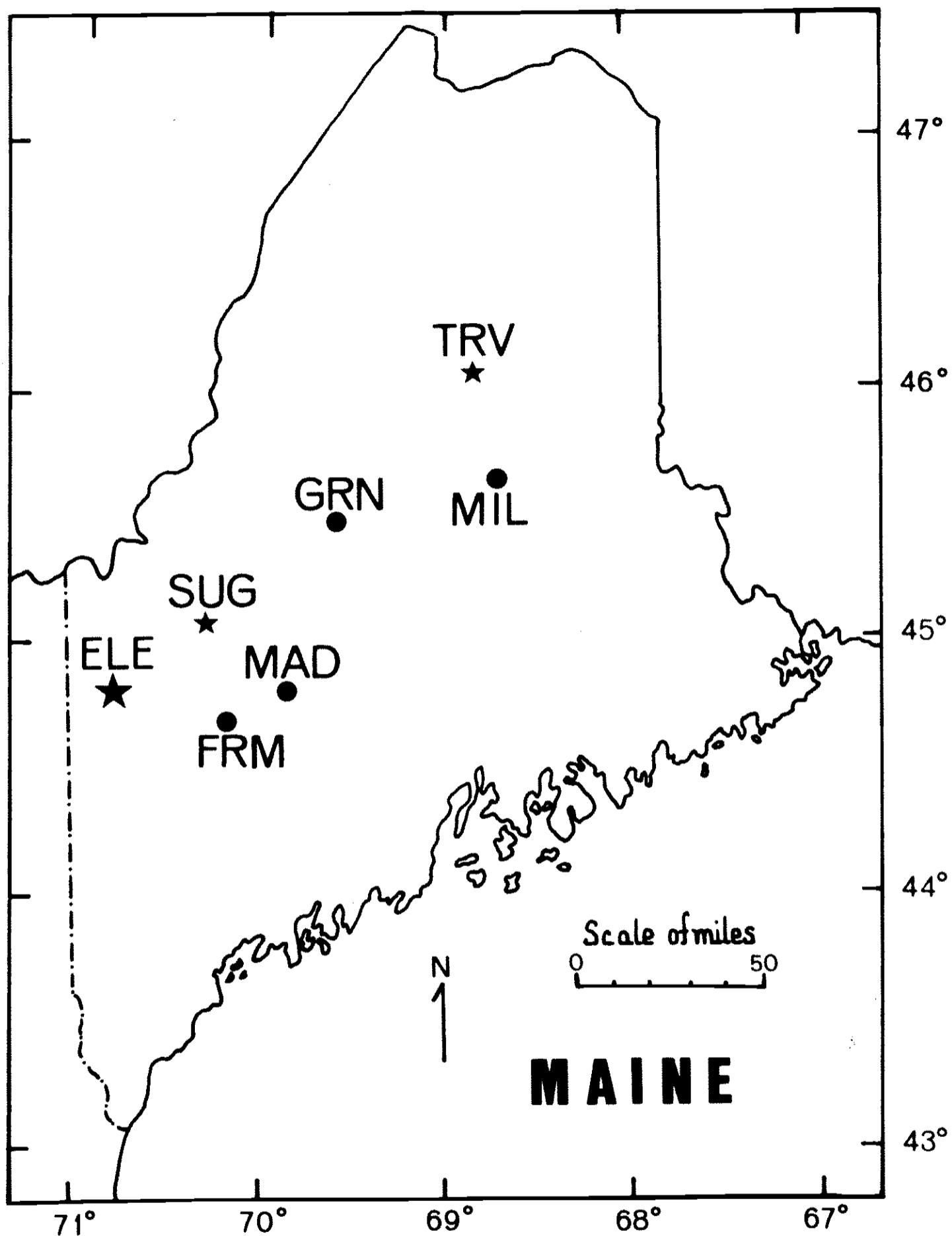


Figure 1. Location of tree-ring chronologies (stars) and stations of climatic data (dots), Maine, USA.

Tree-ring sites:	TRV	=	Traveler Mountain
	SUG	=	Sugarloaf Mountain
	ELE	=	Elephant Mountain
Climatic stations:	MIL	=	Millinocket
	GRN	=	Greenville
	MAD	=	Madison
	FRM	=	Farmington

trees have been few, hampered largely by a lack of belief in the climatic potential of tree-ring widths from humid areas.

And yet, reconstruction of the past few hundred years of climate over North America cannot be complete without the eastern picture. Reconstructions of eastern U.S. climate from a grid of western U.S. tree-ring chronologies have been attempted (Fritts, Lofgren, and Gordon 1979), but they are not as reliable as they would be if as many data were available from the East. I have previously tried to reconstruct temperature and precipitation in the East from several well-replicated eastern ring-width chronologies: the results are encouraging, but stronger growth/climate correlations are desirable (Conkey 1979).

Recent dendroclimatological studies in areas of ample moisture have included measurements of tree-ring density, as well as widths, of high-altitude conifers. Maximum (latewood) density values were found to be highly correlated with mean maximum August temperatures and runoff in Canada (Parker and Henschel 1971). The values of yearly maximum density in Swiss alpine trees were found to be related to summer temperature (Schweingruber et al. 1978). Although the eastern U.S. is not as cold or as high in elevation as either of these sites, moisture levels are similar, and there is obvious variation in latewood densities. I therefore felt this technique should be applied and tested with eastern U.S. conifers. This paper presents preliminary results obtained in a study of the contribution of tree-ring densities to analyses of climate in the eastern U.S.

THE SITES

Location of three sites of tree-ring collections in Maine, U.S.A., are indicated by a star on Figure 1: (1) Traveler Mountain, north of Katahdin in Baxter State Park, (2) Sugarloaf Mountain, a well-known ski resort near Kingfield, and (3) Elephant Mountain, actually on the col between Elephant and Blue Mountains along the Appalachian Trail north of Rumford. The Traveler and Sugarloaf Mountain sites are at the upper elevational limit of upright tree growth and thus approximate the environmental conditions of the Swiss conifers. Circles on the map (Figure 1) denote climatic stations, data from which were made available by Harold Borns and W. R. Baron from the University of Maine at Orono. Monthly precipitation totals and temperature averages extending back into the late 1800's are the data from Millinocket, Greenville, Madison, and Farmington. The site I have worked with so far is Elephant Mountain, in conjunction with data from Farmington. In addition, I am screening all the climatic data for temporal and spatial homogeneity.

The Elephant Mountain site is in direct contrast to the typical southwestern tree-ring site. Rainfall averages 40 or more inches (1016 mm) per year, little sunlight can penetrate the canopy to dry things out, the ground is not steeply sloped to allow for rapid run-off, the trees are not stunted by severe conditions, and they do not show the "spike top" of old age that is common in western North America. And yet the trees are old by eastern standards: the chronology is over 300 years long.

METHODS

Cores of red spruce, *Picea rubens* Sarg., were collected from the three mountainous sites in Maine. The cores were prepared and analyzed densitometrically at the Swiss Federal Institute of Forestry Research, Birmensdorf, Switzerland. The cores are first carefully sawn and acclimated to assure constant size and hygroscopic conditions,

and they are then x-rayed. A narrow beam of light is then passed through the x-ray films, ring by ring, and the brightness is recorded. The measured densities are calibrated to represent actual wood density. (see Schweingruber et al. 1978 for a summary of procedural details.) Five parameters of each yearly ring were recorded mechanically: (1) maximum latewood density, (2) minimum earlywood density, (3) earlywood width, (4) latewood width, and (5) total ring width.

One of the three sites has been further analyzed. The two parameters of total ring width and maximum density were separately standardized, producing two series of indices, and these were analyzed in cross-correlations and analyses of variance. Each chronology was also used in a modified form of multiple linear regression called a "response function", determining possible ring-width or density response to various climatic variables (Fritts 1976). The results of these preliminary analyses are presented here, as an indication of what more we may learn about eastern U.S. climate in the past 300 years through the study of the tree rings' density instead of, or in conjunction with, their widths.

RESULTS AND DISCUSSION

A photomicrograph (Figure 2) of part of one core shows a complacent ring-width series, fairly typical for the eastern U.S.; there is little variation in width from year to year. But the density profile of the same rings in the lower portion of Figure 2 shows much greater variation. The wood of the ring for each year exhibits a steady increase in density: the cells in the earlywood are large and thin-walled, and they decrease in size and increase in wall thickness as the season progresses. In the case of spruce, maximum density is reached near the end of the growing season, and the break in density from one year to the next is an abrupt change from high to low values. The values of the yearly peaks of maximum density change from one year to the next, showing more variation than the ring widths. This variation is remarkably constant from one tree to the next within each site, allowing for crossdating much easier than with ring widths alone. Variation in density thereby represents a stronger signal of climate.

In addition, this yearly variation in magnitude of maximum density is coherent among all three sites, even at distances of more than 200 km. Figure 3 shows maximum density averaged over all the cores at each site for the last 125 years of record. The similarity is striking, and is much greater than between any two series of eastern tree-ring width chronologies that I have seen. Similarity at such wide distances is due to large-scale environmental factors, such as climate.

Two parameters of ring data, total ring widths and maximum densities, were selected from the Elephant Mountain site for further study. Each series was standardized, deriving indices by fitting exponential or polynomial curves in the case of the ring widths, and straight lines to the densities, and then dividing by the value of the curve (Fritts 1976). The indices were averaged for the two sampled cores from each tree and for all trees to produce each of the two chronologies (Figure 4). At present there is considerable debate among dendrochronologists about the validity of deriving indices from polynomial curve fits. Because of statistical constraints of polynomial curve derivation, the curve does not always adequately match tree growth, and climatic information may also be inadvertently removed. For some species, decrease in ring width with age approximates a negative exponential curve, so that such a curve has some biological meaning, but polynomial curve-fitting, now standard procedure with non-arid-site trees, is being reexamined and improved upon. The maximum density

series showed very little of the narrow and wide periods of growth seen in the ring widths, and I was able to merely standardize with straight lines, an advantage amid controversies.

The upper time series in Figure 4 shows the ring-width indices. Both high- and low-frequency variation are visible, and persistence is strong. Conditions which cause a ring to be narrow in one year tend to carry over their effect on growth of following years, and the first-order serial correlation (the correlation of one series with itself at one lag) for this series is 0.61.

The lower time series in Figure 4 shows the maximum density indices. Compared to the ring-width series, the maximum densities show less low-frequency variance, less persistence. Indeed, the first-order serial correlation is only 0.18. When serial correlation is high, increased difficulties are encountered in assigning a climatic cause in any one year to the ring of that year. Density does not integrate conditions over such a long time as ring widths seem to, and yearly values appear to be more specific.

Each series was subjected to an analysis of variance. This analysis, as adapted for tree-ring work, separates the total variance of a chronology into three components: (1) that variance which is in common to the whole site, to all samples together, approx-

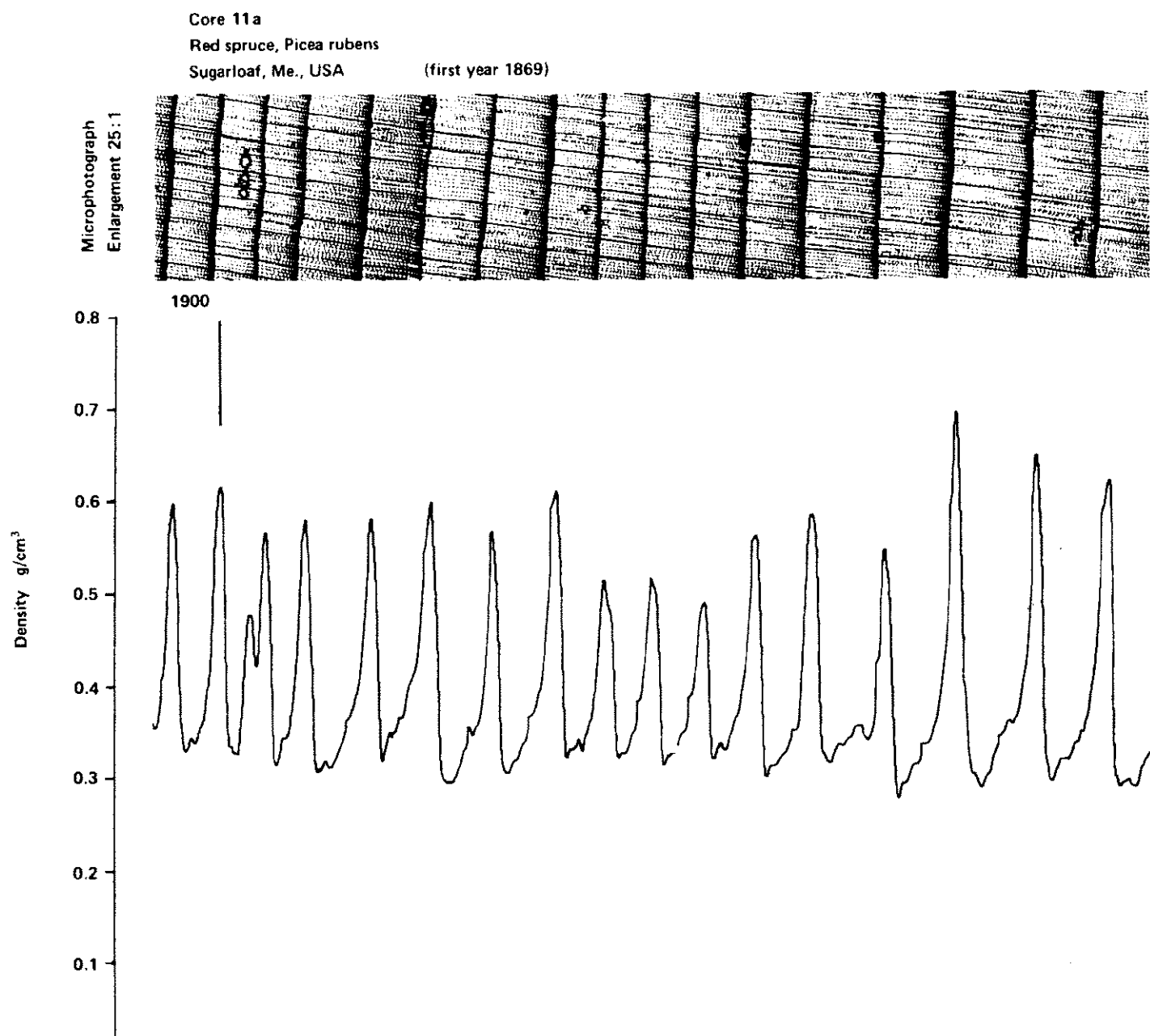


Figure 2. Density profile of a section of a core from Sugarloaf Mountain *Picea rubens*. The line plot (below) is of density in grams per cubic centimeter, and is aligned with a photomicrograph (top) of that core. Reduced for reproduction.

imating the climatic signal of the chronology, (2) that variance which is in common only to an average of the samples for individual trees (usually two cores per tree), and (3) that variance which is individual to the samples within the trees (Fritts 1976). Typical values for the variance common to the group, or climatic component, for ring-width data in the East average 28.9% (DeWitt and Ames 1978). At Elephant Mountain for ring widths it is 39%, and for the maximum density chronology it is 47%. This latter figure compares favorably to the average of 60% in stressed, arid-site ring-width chronologies (DeWitt and Ames 1978).

Yearly Maximum Density at three sites in Maine

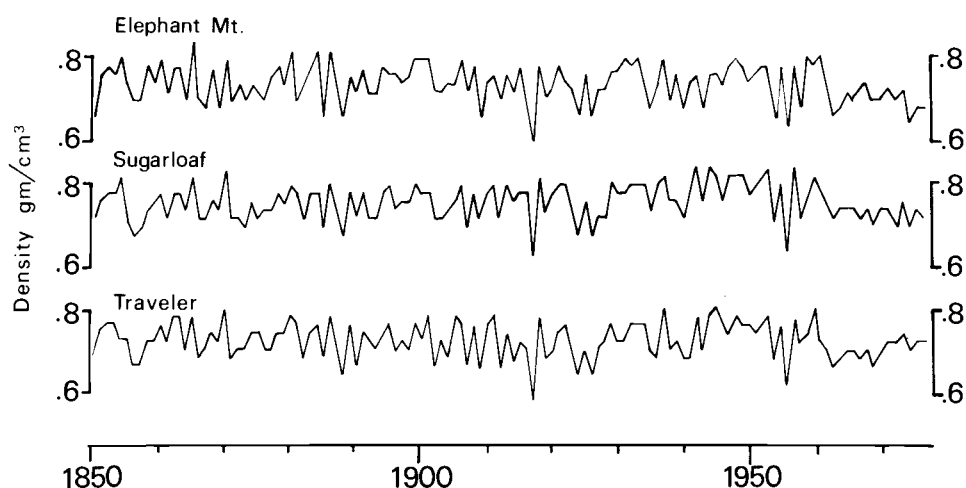


Figure 3. Yearly maximum density at three sites in Maine, USA. Each series is the average maximum density.

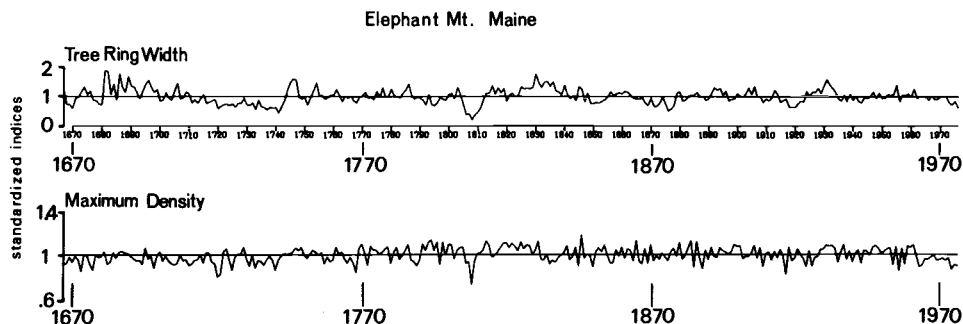


Figure 4. Time series of the standardized indices of the tree-ring widths (top) and tree-ring maximum densities (bottom) from the Elephant Mountain site, Maine, USA. Note the difference in vertical scale of the two series.

A response function was calculated for each of the two chronologies from Elephant Mountain (Fritts 1976). In the first instance, the *ring-width* indices of Elephant Mountain comprised the dependent variable for 72 years of data, 1905-1976. This was regressed on principal components of monthly temperature and precipitation values from Farmington (distance = 50 km.), for 16 months prior to and including each growing season, June of year $t-1$ (where t is the year of calibration) through September of year t , plus three values of prior tree-growth indices from years $t-1$, $t-2$, and $t-3$. The step of the regression shown in Figure 5 accounted for 66% of the total variance, of which 34% was described by the climatic elements. Vertical bars are the 95% confidence limits for each response function estimate. Those months of temperature or precipitation that relate significantly to growth (i.e., those values whose confidence limits do not cross the zero line), either negatively or positively, indicate which climatic variables are most likely to be important to the growth of the rings. This response function indicates that large rings are correlated with low temperatures in July, August, and October of the previous year (an inverse relationship), and with high temperatures in December and January, and May, July, and September of the current growing season (a direct relationship). Precipitation shows a significant correlation to growth only in the previous year. The strongest influence on growth is related to the high first-order serial correlation we saw before; prior growth at one lag shows a high, direct correlation to ring width.

Figure 6 shows the response function for Farmington temperature and precipitation and Elephant Mountain *maximum density* indices. The total variance explained at this step of the regression is 70%, slightly higher than the ring-width analysis. However, 67% of the maximum density variance is due to these climatic variables, as opposed to only 34% of the ring-width variance seen in Figure 5. Prior density values have little importance, again reflecting the low first-order serial correlation.

I expected to find that maximum density would be responsive to late growing season conditions since it occurs at the end of the yearly ring, and, indeed, there is a positive response to August and September temperature and a negative response to August and September precipitation. High maximum density occurs, then, under hot, dry conditions in late summer, conditions probably related to water stress within the tree (Kramer 1964). The unfavorable water balance possibly discourages cell enlargement, and the photosynthates go instead into cell-wall thickening (Zahner 1963). Schweingruber and others (1978) also report a direct response of maximum density in the Swiss Alps to summer temperature, but a somewhat weaker inverse response to precipitation in late summer than I find at Elephant Mountain.

It is interesting to note that there are responses at other times of the year as well. A strong response is seen in May, positive to both temperature and precipitation. Maximum density is high when springs have been warm and wet — a different type of relationship than that seen in late summer. Explanations may be tied to still-untested relationships of maximum density to earlywood widths or minimum densities. It is reasonable that conditions which allow production of high amounts of photosynthates to contribute to latewood cell density result from optimal photosynthetic conditions earlier in the growing season (Larson 1969). Maximum density is also inversely related to June temperatures of the previous year and to December and January precipitation, and directly to temperatures in February and April. These could represent various preconditioning phenomena.

The response functions of the total ring widths (Figure 5) and maximum densities (Figure 6) do not contradict one another in any monthly response. The widths

03/28/79 4856TOT/FARM

6STEP 17 F= 1.10, PCL= .337, RR= .664

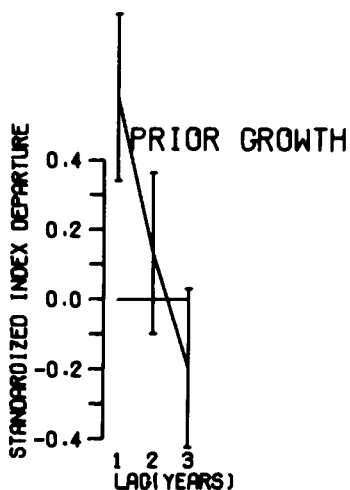
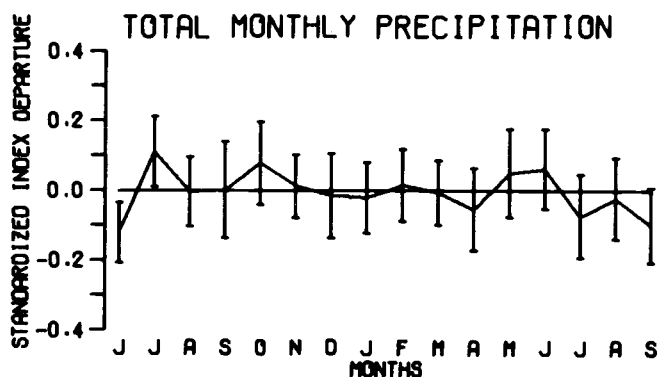
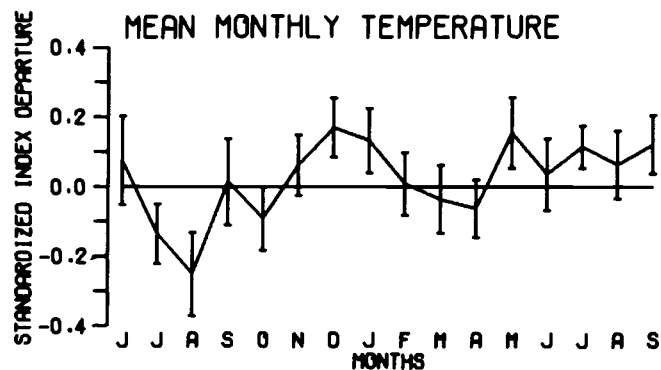


Figure 5. Results of step 17 of a response function analysis: total ring width indices from Elephant Mountain, Maine, regressed on principal components of monthly temperature and precipitation values from Farmington, Maine, and three years of prior growth indices. The vertical bars are the 95% confidence limits. Total variance at this step is 66%; that variance due to climatic factors alone is 34%.

03/28/79 1856MAX/FARM

6STEP 16 F= 1.02, PCL= .665, RR= .699

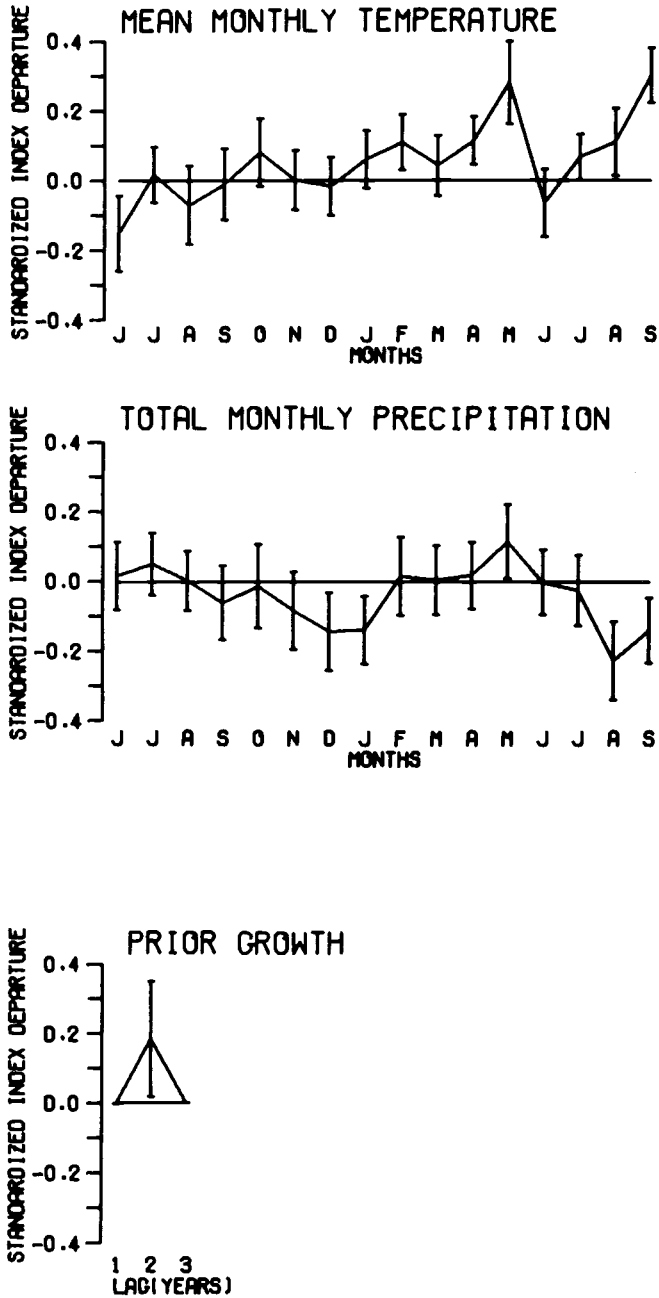


Figure 6. Results of step 16 of a response function analysis: yearly maximum density indices from Elephant Mountain, Maine, regressed on principal components of monthly temperature and precipitation values from Farmington, Maine, and three years of prior maximum density indices. The vertical bars are the 95% confidence limits. Total variance at this step is 70%; that variance due to climatic factors alone, 67%.

integrate conditions over a larger time period and the densities have a more specific response; both together may be able to provide a more complete picture of past climate in the East than we now have from ring widths alone.

ACKNOWLEDGEMENTS

This research has been undertaken with support from a Fulbright-Hays — administered, Swiss Government Grant for predoctoral research to the author, from National Science Foundation Grant No. ATM/77-19216 A01 to The University of Arizona (H. C. Fritts, principal investigator), and from the School of Forest Resources and the Institute of Quaternary Studies, University of Maine at Orono. I would like to thank Fred Knight, Harold Borns, and Bob Baron of the University of Maine for climatic data and logistical support, Bob Brakenridge for field assistance, Fritz Schweingruber and staff at the Swiss Federal Institute of Forestry Research for guided use of their facilities, and Linda G. Drew and staff for keypunching and computer help at The University of Arizona. Drafts of the manuscript were thoughtfully reviewed by Harold C. Fritts, William R. Boggess, Bob Brakenridge, Marvin A. Stokes, and Marna Ares Thompson.

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