A comparison of chronologies from tree rings

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Received May 1, 1989

Accepted August 22, 1989

RIITTERS, K. H. 1990. A comparison of chronologies from tree rings. Can. J. For. Res. **20**: 76–83.

Forty-five-year ring width index chronologies were estimated by five mean-value functions applied to 183 ring width series from four similar sites. The effects of autocorrelation on the comparisons among mean-value functions were explored by fitting Box–Jenkins models to individual-tree index series prior to pooling (prewhitening), and to the pooled chronologies obtained from the mean-value functions (postwhitening). Among the mean-value functions tested, the principal component scores and the biweight yielded the highest cross correlations between chronologies from different sites, whereas the average, the median, and the median polish did not perform as well. Prewhitening and postwhitening tended to decrease both intersite correlations and correlations between chronologies from different mean-value functions for the same site.

RIITTERS, K. H. 1990. A comparison of chronologies from tree rings. Can. J. For. Res. **20** : 76–83.

Des index chronologiques de cernes âgés de 45 ans ont été estimés par des fonctions de cinq valeurs moyennes appliquées à 183 séries de cernes provenant de quatre sites similaires. Les effets de l'autocorrélation dans les comparaisons entre les fonctions de valeurs moyennes ont été explorés en ajustant les modèles Box–Jenkins aux séries d'index d'arbre individuel avant le regroupement (« prewhitening ») et après le regroupement (« postwhitening ») des index chronologiques obtenus des fonctions des valeurs moyennes. Parmi les fonctions de valeurs moyennes testées, les composantes principales indices et pondérations avaient les plus fortes corrélations entre les index chronologiques des différents sites alors que la performance de la moyenne, de la médiane et de la médiane ajustée était moins significative. Le nonregroupement (« prewhitening ») et le regroupement (« postwhitening ») ont pour effet de diminuer les corrélations inter-sites et les corrélations entre les index chronologiques des différentes fonctions de valeurs moyennes pour le même site.

[Traduit par la revue]

Introduction

Dendroecologists use dendrochronology techniques (Fritts 1976) to study historical relationships between forest growth and environmental factors. A basic consideration is the analytical decomposition of tree ring width series into components that are attributable to specific environmental sources (Graybill 1982; Cook 1987). The classical procedure (Fritts 1976) starts by "detrending" each tree's series. Detrending converts a series into a time sequence of residuals from a suitable smoothing function. Depending upon the smoothing function, detrending more or less removes the variation in ring widths corresponding to biological growth trends, long-term environmental trends, and certain growth disturbances (Cook 1987). The detrended ring widths are then standardized into ring width indices, which are simply the weighted residuals from the detrending function (Monserud 1986). The detrending and standardizing procedures produce stationary (Box and Jenkins 1970) ring width index series. These can then be analyzed, combined, or correlated with other series of ring width or environmental data (Fritts 1976).

Two important components of the subsequent analysis are the mean-value function (the algorithm by which individual series are combined to form chronologies) and time-series analysis (the method used to adjust for autocorrelation in ring width index series). Recent literature reveals substantial variety in methodology, and comparisons of the possible techniques are needed to find methods that yield comparable and replicable results (Graybill 1982). The objective of this paper is to compare chronologies obtained by five mean-value functions, with two types of time-series analysis, for a particular set of tree ring width data.

Rationale

The classical mean-value function is the annual average of the ring width index values from a collection of individual tree series (Fritts 1976). Other methods that have been tested include principal component analysis (e.g., Peters et al. 1981; Jacoby and D'Arrigo 1989; Cook 1989) and robust mean-value functions such as the median and the biweight (Cook 1985, 1987). The present study compares chronologies estimated by those four algorithms, and by a new approach that is based on a median polish algorithm.

Autocorrelation is a methodological issue because tree ring width series usually exhibit serial correlation as a result of physiological preconditioning within trees (Fritts 1976). Proper accounting for autocorrelation is necessary for most statistical analyses (Monserud 1986), and it sometimes improves the efficiency of the mean-value function (Cook 1987). The earliest methods applied first-order autoregressive (AR) models. Cook (1987) reviews the dendroecological applications of the general autoregressive moving average (ARMA) techniques of Box and Jenkins (1970) and the even more general Kalman linear dynamic models (Harvey 1984).

The present study compares chronologies obtained by using ARMA models for "prewhitening" and "postwhitening" in conjunction with the five mean-value functions. Box and Jenkins (1970) introduced prewhitening as the removal of the time-dependent structures within series of data, prior to computing cross correlations among series. In dendroecology, it is possible to apply ARMA models either before or after computation of the mean-value function. In this paper, prewhitening refers specifically to the application of ARMA models to individual tree ring width index series, and postwhitening refers to their application to ring width index

Printed in Canada / Imprimé au Canada

TABLE 1. Site descriptions

Site No.	Site	Age (years)	Basal area (m^2/ha)	Tree density (no./ha)	Avg. dbh (cm)	Soil
CM8	Cherry Mt. 8	107	28.2	1490	15.2	Sandy, fairly dry
FS3	Fort Smith 3	65	25.3	1981	12.4	Sandy, dry to moist
FS6	Fort Smith 6	88	18.8	1104	14.4	Sandy, fairly moist
FS11	Fort Smith 11	132	21.8	546	15.2	Sandy, fairly dry

NOTE: Descriptions are after Sweda and Umemura (1979).

chronologies after computation of the mean-value function. Prewhitening is the preferred alternative because sufficient replication or a robust mean-value function is needed to dampen the influence of individual trees on the postwhitening ARMA model (Cook 1987). But postwhitening is not an uncommon technique (e.g., Biondi and Swetnam 1987; Federer et al. 1989; Ord and Derr 1989) and therefore warrants inclusion in this study.

The comparisons in this study will be made in terms of the zero-lag cross correlations from the cross-correlation function (Box and Jenkins 1970), which are simply the Pearson correlations among chronologies. Strictly speaking, correlation analyses assume independent observations, and spurious and inflated cross correlations may be obtained if autocorrelation is present (Chatfield 1975). Monserud (1986) and Yamaguchi (1986) illustrate the problem of using nonzero-lag cross correlations to cross-date autocorrelated and "floating" ring width index series (Fritts 1976). However, the practical importance of autocorrelation effects on the zero-lag cross correlation is not well defined. Monserud (1986) found little change in the zero-lag cross correlation after prewhitening, and Biondi and Swetnam (1987) noted an increase after postwhitening.

Intuitively, qualitative comparisons of zero-lag cross correlations can be made despite autocorrelation if the series are the synchronized outcomes of identical processes subject to the same input function. This rationale apparently explains the common practice of using the zero-lag cross correlations among autocorrelated ring width index series as a measure of the similarity of climate. In the intuitive model, climate is the input function, and the common assumption is that trees respond similarly to climate (i.e., that they process the input in the same way) and that the series are accurately cross-dated. If cross correlations are low, the implication is that the input function (in this case, climate) is different. But, as pointed out by Monserud (1986), strict comparisons are dangerous when autocorrelation is present. The reason is that the usual estimators of the sample variances (and therefore of the sample correlations) may be biased (Kmenta 1971).

Furthermore, in ARMA modeling, the underlying process is identified and is used to convert the data to a time series of residuals from that process. The residuals by definition become the output from a different process. Correlations between whitened and nonwhitened chronologies do not have much meaning because the equality of the underlying processes can no longer be assumed. On the other hand, the correlation of prewhitened and postwhitened chronologies is statistically valid, and it indicates whether the two ARMA procedures model the underlying process in the same way. In addition, it is always valid to correlate chronologies obtained by different mean-value functions for the same whitening procedure.

In some situations, synchronized chronologies come from several sites for which similarity of the underlying processes and input functions can be assumed. In these cases, the relative magnitudes of the intersite zero-lag cross correlations may yield insights about the relative abilities of alternate methods to preserve the hypothesized similarity among sites. Methods that yield consistently high correlations across a range of site pairs may be most useful when the pooling of data from different sites is contemplated.

Methods

Tree ring width index series

Sweda and Umemura (1979) reported a study of radial increment growth in even-aged jack pine (*Pinus banksiana* Lamb.) stands near Fort Smith, Northwest Territories, Canada. Stands were located on uniform, flat, glacial deposits of sand and gravel material on the Great Slave Plain at elevations between 200 and 300 m. Fort Smith has short, hot summers and long, cold winters (Sweda and Umemura 1979). Understory vegetation was typically *Hylocomium* spp. and *Pleurozium* spp. on the wetter sites and *Arctostaphylos* spp. and *Vaccinium* spp. on the drier sites. In the summer of 1977, increment cores were taken from all trees within fixed-area plots at nine sites. The annual radii were measured on each core to the nearest 0.001 cm. Site and stand data for the four sites used in the present study, as reported by Sweda and Umemura (1979), are given in Table 1.

In each of the four stands, samples were drawn of 50 trees that were larger than the average stand diameter in 1977. Competition almost certainly limited radial growth of all plot trees in the past (Table 1; Sweda and Umemura 1979). The larger trees were chosen to minimize the occurrences of sudden and transitory changes in radial growth patterns due to releases from competition. A further simplification was that only the radii for the years 1931 through 1976 were used. During this time period, the biological growth trend (compounded by stand density effects) was generally decreasing for all trees. It was thus possible to use a relatively simple detrending model and thereby focus the comparisons on the mean-value functions and ARMA procedures.

The tree ring width series could not be subjected to the usual cross-dating procedures (Fritts 1976). Although missing or multiple rings are always a concern in dendroecology (Fritts 1976), there was no basis for verifying the needed adjustments, even if automated procedures (e.g., Munro 1984; Van Deusen 1990) were applied. The original cores were not available for visual comparisons, and

TABLE 2. Summary of Box–Jenkins model selections

A. Prewhitening

		No. of tree chronologies							
Site No.	Total no.	White noise	AR(1)	AR(2)	AR(3)	AR(4)	AR(5)	AR(6)	ARMA(1,1)
FS3	43	7	24	3	1	3	0	1	1
FS6	46	8	28	7	2	0	0	1	0
FS11	49	25	12	2	6	0	2	1	1
CM8	45	10	24	2	5	2	0	1	1
Total	183	50	88	14	14	5	2	4	3

B. Postwhitening

		No. of site chronologies					
Site No.	Prewhitened	MA(1)	AR(1)	AR(2)	AR(3)	AR(4)	AR(5)
FS3	No	5	0	0	0	0	0
	Yes	1	1	1	0	0	2
FS6	No	0	0	5	0	0	0
	Yes	0	0	5	0	0	0
FS11	No	0	5	0	0	0	0
	Yes	0	0	3	1	1	0
CM8	No	0	5	0	0	0	0
	Yes	0	4	1	0	0	0
Total	No	5	10	5	0	0	0
	Yes	1	5	10	1	1	2

a master chronology (Fritts 1976) apparently does not exist for jack pine in that geographic area (G. C. Jacoby, personal communication). Instead, a few nonconforming series were rejected on the basis of a rigorous preliminary comparison. The final sample sizes for each stand are given in Table 2.

The following procedure was used to find a standardized ring width index series for each tree. First, the radius data were differenced to obtain a series of ring widths (i.e., annual radial growth rates) for the years 1932–1976. A detrending model (Monserud 1986) was then fitted to each tree's ring width series (RW_t) over time (t):

$$RW_t = B0\, t^{B1}\, e^{-B2t}$$

where $B0$, $B1$, and $B2$ are parameters to be estimated. The model provided a satisfactory fit to the ring width series for all trees as judged by the fit statistics and by visual inspections of the residuals.

The standardized ring width index for a given tree at time t (I_t) is the weighted residual from the fitted growth trend (Monserud 1986):

$$I_t = \text{observed } RW_t/\text{predicted } RW_t$$

If the detrending model is appropriate, the I_t values are distributed with unit mean and constant variance. Plots of I_t over time for each tree were inspected to verify the standardizing procedures, and the calculated index values were entered into subsequent analyses.

Mean-value functions

Five basic mean-value functions were tested: the arithmetic average, the median, the biweight (Mosteller and Tukey 1977), the year effect from a two-way (trees by years) median polish (e.g., Tukey 1977), and the standardized first principal component scores (e.g., Cooley and Lohnes 1971). The biweight was estimated by an iteratively reweighted, least-squares algorithm (Goodall 1983). The algorithm used a tuning constant of 6, and the scale factor was the median absolute deviation. Convergence was assumed when the change in the biweight was less than 0.01 of its standard error (Iglewicz 1983). Three or four iterations were typically required, and the change in the biweight at the final iteration was of the order of ± 0.001 index units.

The median polish has not been applied before as a mean-value function in dendroecology. This algorithm alternately subtracts row and column medians from a two-way (years by trees) table of ring width index values until further changes are of an arbitrarily specified small size. Two complete polishing cycles (Tukey 1977) were applied. The polished table contained residuals from the two-way median polish fit. The chronology was estimated by the fitted marginal effects corresponding to years.

Principal component analysis was applied by finding the first principal components from the correlation matrix of the ring width index series. The resulting eigenvectors were examined to verify that the component was measuring an average and common tendency of all series. The corresponding standardized (zero mean and unit variance) principal component scores were estimated and used as the chronology.

Box–Jenkins models

The objective of the ARMA model-building process is to remove the time-dependent autocorrelation structure from a series of data, reducing the residuals to a series of "white noise" (Box and Jenkins 1970). An ARMA(p,q) model is said to be of order p, q, and has p autoregressive parameters and q moving average parameters. ARMA models of increasing order are tested until a parsimonious model is obtained;

there is usually an element of subjectivity in the procedure. The tests for model selection include visual inspections of the autocorrelation function, the partial autocorrelation function, and the inverse autocorrelation function (Box and Jenkins 1970); tests of significance of model parameters; and a general lack of fit test (Ljung and Box 1978). The residuals from the fitted ARMA model constitute a new series with the time dependency removed.

In the present study, the individual tree ring width index series were prewhitened by fitting a Box–Jenkins model to remove any time-dependent autocorrelation structure. The mean-value functions were then applied to the prewhitened series, and separately to the nonwhitened series, yielding a total of 10 chronologies for each site. Those chronologies were then postwhitened by fitting Box–Jenkins models to them, and the residuals from those models became 10 more chronologies. In this way, a total of 20 chronologies were estimated for each site.

Correlations

The Pearson correlations (zero-lag cross correlations) among the chronologies obtained by the 20 methods for the same site are called method correlations. The intersite Pearson correlations among chronologies for the same method are called site correlations. The method correlations were calculated for all pairs of methods for each site separately and for all sites combined. The results were similar for the different sites, and so the combined analysis will be reported. The site correlations were then calculated for all six pairs of sites for each of the 20 methods. The methods were then ranked in order of decreasing site correlation for each pair of sites. The ranking was done over all 20 methods, and within each of the four subsets defined by the whitening procedure (i.e., nonwhitened, prewhitened only, postwhitened only, and prewhitened and postwhitened).

Results and discussion

Box–Jenkins models

All candidate series of ring width indices were judged to be stationary by examination of the autocorrelation function, and so Box–Jenkins models were appropriately considered. Surprisingly, 27% of the individual-tree series were white noise without further modeling (Table 2). This result is unexpected because there is a biological rationale for the presence of autocorrelation. A reviewer noted that this result could be due to the relative shortness of the time series studied. With $n = 45$ years, the approximate 95% confidence interval for the parameter of the AR(1) model (for example) covers 30% of the available parameter space. This forces the rejection of AR models that would account for moderately weak but real autocorrelation.

When the hypothesis of white noise could be rejected (as in 73% of the series), the most common choice of models for prewhitening was AR(1) (i.e., autoregressive, order 1), followed by AR(2) and AR(3) (Table 2). Relatively few individual-tree series required a model with more than three parameters. The moving average (MA) model was never a good choice.

The common selection of AR(1) models here agrees with the results of Meko (1981) and Tessier (1984, as cited in Biondi and Swetnam 1987). In contrast, both Rose (1983) and Monserud (1986) selected ARMA(1,1) models for most of their series. Cook (1985) considered only AR models and usually selected from one to three parameters. A reasonable synthesis of the evidence to date is that MA models are almost never chosen, and usually three or fewer parameters are needed for AR or ARMA prewhitening models.

TABLE 3. Simple statistics for site FS6 site chronologies

Mean-value function	Mean	SD	Min.	Max.
Nonwhitened				
Avg.	1.00	0.10	0.80	1.24
Median	0.98	0.10	0.77	1.21
Biweight	0.98	0.10	0.77	1.22
Median polish	0.01	0.10	−0.20	0.23
Component score	0.00	1.00	−1.92	2.35
Prewhitened				
Avg.	1.00	0.05	0.91	1.12
Median	0.99	0.05	0.91	1.11
Biweight	0.99	0.05	0.91	1.11
Median polish	0.00	0.05	−0.08	0.12
Component score	0.00	1.00	−1.85	2.33
Postwhitened				
Avg.	1.00	0.08	0.82	1.23
Median	0.98	0.08	0.80	1.14
Biweight	0.98	0.08	0.81	1.16
Median polish	0.00	0.07	−0.17	0.16
Component score	0.00	0.76	−1.69	2.37
Prewhitened + postwhitened				
Avg.	1.00	0.04	0.92	1.09
Median	0.99	0.03	0.92	1.08
Biweight	0.99	0.03	0.92	1.08
Median polish	0.00	0.03	−0.06	0.08
Component score	−0.01	0.71	−1.70	1.90

None of the nonwhitened or prewhitened chronologies was white noise after estimating the mean-value functions (Table 2). Prewhitening affected the number of parameters required for postwhitening. Only one parameter was required to postwhiten 15 of the 20 nonwhitened chronologies, and never more than two parameters were needed. In contrast, at least two parameters were required for 14 of the 20 prewhitened chronologies, and up to five parameters were sometimes needed.

The model selected for postwhitening depended upon the site. For example, all 10 chronologies for site FS6 were described best by AR(2) models, whereas AR(1) models were chosen for 9 of the 10 chronologies for site CM8. MA(1) models were the best choice for 6 of the 10 chronologies for site FS3, but in those cases, the AR(1) model was always a very close second choice. In comparison, Biondi and Swetnam (1987) usually chose ARMA(1,1) or AR(2) models, Ord and Derr (1989) usually chose either AR models with fewer than three parameters or else a higher order MA or ARMA model, and Federer et al. (1989) chose AR(1) models for their three chronologies.

Another effect of prewhitening was observed in the principal component analysis. The loadings (i.e., signs and magnitudes) associated with different-tree series are measured by the eigenvector coefficients for each principal component. When all loadings are similar and have the same sign, the associated principal component score can be interpreted as measuring an average tendency of all tree series (e.g., Cooley and Lohnes 1971). This is a desirable outcome in forming chronologies. Whereas the eigenvector coefficients were all positive for the nonwhitened series, they were

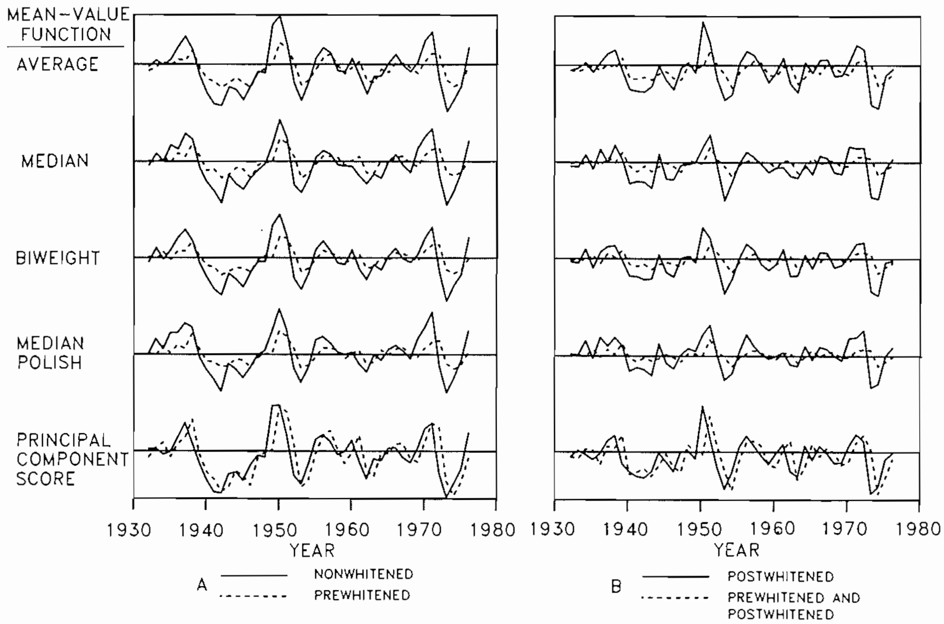

FIG. 1. Jack pine site chronologies for site FS6. It is possible to compare Figs. 1A and 1B.

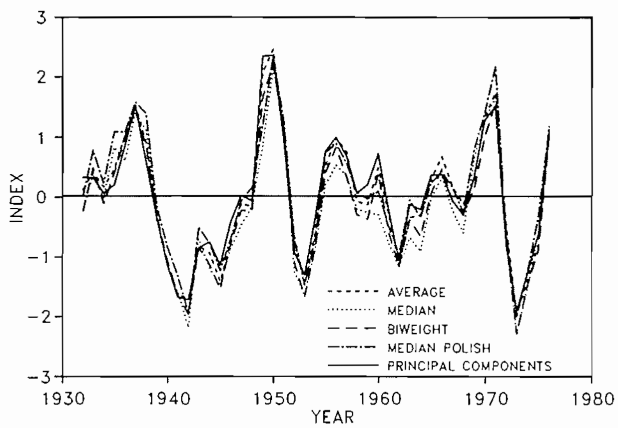

FIG. 2. Comparison of mean-value functions for nonwhitened chronologies for site FS6.

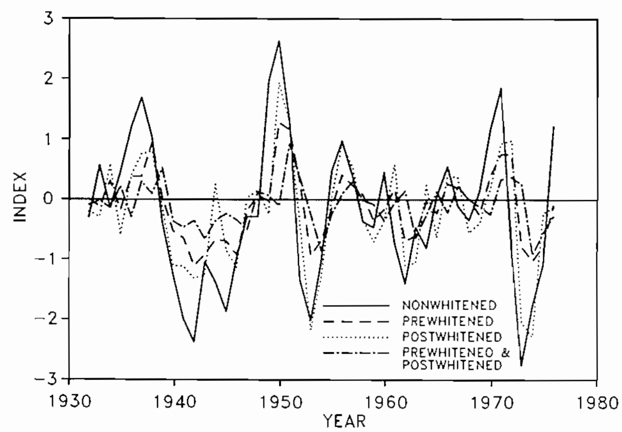

FIG. 3. Comparison of biweight site chronologies for site FS6.

sometimes negative for the prewhitened series. It is problematic to interpret what is being measured by the principal component scores for those prewhitened chronologies without some theoretical justification.

Mean-value functions

The differences in the means, standard deviations, and extremes of the chronologies obtained by the various methods are illustrated by site FS6 in Table 3. The average, median, and biweight retain the centering of ring width indices near unity and give approximately the same standard deviations, minima, and maxima. As calculated here, the median polish and principal component scores methods center the chronologies near zero and rescale the standard deviations or the extremes. Prewhitening and postwhitening did not appreciably change the centering of the chronologies, but they did reduce both the standard deviations and the ranges.

Correlations among methods

The gross visual trends in the chronologies appeared similar over time, as illustrated by the results for site FS6 (Fig. 1). A direct visual comparison of the mean-value functions for nonwhitened chronologies for site FS6 (Fig. 2) suggests that except for differences prior to 1940 and around 1960, the five methods yielded similar results. This general conclusion was reached for the whitened chronologies also (the figures are not shown). But a visual comparison of the different whitening procedures for the biweight mean-value function (Fig. 3) revealed more inconsistency. The visual evidence suggests that the choice of method to account for autocorrelation has more effect on the chronology than the choice of mean-value function.

The full set of cross correlations among methods (Table 4) helps to sort out some of the patterns illustrated in the figures. Along the diagonal, the blocks of correlations labeled *a* through *d* quantify the similarities obtained among the mean-value functions for the same whitening procedure. Overall, these correlations are rather large (block *a* is comparable to Fig. 2), but they appear to decrease with additional whitening, especially prewhitening (compare blocks *a* through *d*). This suggests that the choice of mean-value function is more important when prewhitening index series than when postwhitening index chronologies.

TABLE 4. Cross correlations among methods (1–20) for all sites combined

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
		(a)					*(e)*					*(h)*					*(j)*			
1.00	0.97	0.99	0.97	0.97	0.84	0.72	0.76	0.71	0.72	0.59	0.54	0.57	0.54	0.58	0.45	0.39	0.44	0.35	0.37	1
	1.00	0.98	0.99	0.95	0.83	0.73	0.76	0.71	0.72	0.58	0.55	0.57	0.54	0.58	0.44	0.38	0.43	0.34	0.37	2
		1.00	0.98	0.96	0.84	0.73	0.77	0.71	0.72	0.59	0.54	0.58	0.54	0.58	0.45	0.38	0.43	0.34	0.37	3
			1.00	0.95	0.83	0.73	0.76	0.72	0.72	0.58	0.54	0.56	0.54	0.58	0.44	0.38	0.42	0.35	0.37	4
				1.00	0.81	0.70	0.74	0.68	0.73	0.56	0.53	0.55	0.52	0.59	0.40	0.35	0.40	0.32	0.36	5
							(b)					*(f)*					*(i)*			
					1.00	0.92	0.94	0.91	0.92	0.76	0.73	0.75	0.73	0.73	0.67	0.58	0.64	0.54	0.59	6
						1.00	0.97	0.97	0.94	0.84	0.84	0.84	0.82	0.81	0.74	0.67	0.71	0.62	0.67	7
							1.00	0.95	0.95	0.81	0.80	0.82	0.79	0.79	0.71	0.64	0.70	0.59	0.66	8
								1.00	0.94	0.83	0.82	0.83	0.83	0.81	0.73	0.65	0.70	0.64	0.67	9
									1.00	0.83	0.81	0.83	0.81	0.83	0.71	0.64	0.69	0.61	0.71	10
												(c)					*(g)*			
										1.00	0.94	0.98	0.95	0.97	0.71	0.58	0.61	0.55	0.58	11
											1.00	0.96	0.98	0.92	0.69	0.60	0.63	0.56	0.59	12
												1.00	0.96	0.95	0.70	0.59	0.62	0.55	0.58	13
													1.00	0.92	0.70	0.60	0.62	0.59	0.60	14
														1.00	0.63	0.53	0.56	0.51	0.57	15
																	(d)			
															1.00	0.86	0.86	0.82	0.82	16
																1.00	0.96	0.91	0.86	17
																	1.00	0.88	0.86	18
																		1.00	0.85	19
																			1.00	20

Key to method numbers

Nonwhitened	Prewhitened	Postwhitened	Prewhitened + postwhitened
1. Avg.	6. Avg.	11. Avg.	16. Avg.
2. Median	7. Median	12. Median	17. Median
3. Biweight	8. Biweight	13. Biweight	18. Biweight
4. Median polish	9. Median polish	14. Median polish	19. Median polish
5. Component score	10. Component score	15. Component score	20. Component score

NOTE: Letters in parentheses denote blocks of correlations as discussed in text.

The marked changes in method correlations for the whitened chronologies in comparison to the nonwhitened cases (blocks *a*, *e*, *h*, and *j* in Table 4) are expected for the reasons mentioned earlier. Yet differences are apparent when comparing the correlations among the different whitening procedures (blocks *f*, *g*, and *i*). This suggests an important interaction between mean-value functions and the procedures utilized for autocorrelation adjustment. The whitening procedures must not be modeling the underlying process in the same way, and the mean-value functions are more or less sensitive to the differences. Of course, it is not possible to determine from these correlations which, if any, whitening method is best. Yet the differences suggest that whitening should be applied thoughtfully, and that several mean-value functions could be tested.

Correlations among sites

There is nothing to prevent comparing site correlations obtained by different mean-value functions for different whitening procedures, and the relative efficiencies of the different mean-value functions can be gauged by these comparisons. But there is a potential problem in comparing nonwhitened chronologies with whitened chronologies, and comparisons must be qualified by an assumption that autocorrelation has no practical effect on the zero-lag cross correlation.

An appropriately qualified comparison of the different whitening procedures can be summarized as follows. Overall, the nonwhitened methods yielded the highest correlations, as reflected in a mean group rank of 6.1 (Table 5). The postwhitened group performed slightly better than the prewhitened group, and both were noticeably better than the prewhitened plus postwhitened group. Whitening did not always reduce correlations. In three site pairs (numbers 3, 5, and 6) the largest site correlation was obtained (by the principal component score) in at least one of the whitened groups. In addition, the average and biweight in the postwhitened group performed better in terms of mean rank overall than the median and the median polish in the nonwhitened group.

The principal component score was clearly the best mean-value function within both the nonwhitened group and the prewhitened group, but it was unremarkable within the other two whitened groups. The largest site correlation for any pair of sites was always attained by the principal component score. The biweight was consistently the first or second choice in all groups, and it was tied for the highest correlation for two pairs (numbers 1 and 2) of sites. The median

TABLE 5. Cross correlations among site chronologies for pairs of sites, and rankings of correlation magnitudes

	Site pair						Mean rank		
	FS3 FS6	FS3 FS11	FS3 CM8	FS6 FS11	FS6 CM8	FS11 CM8	Overall*	In group[†]	Of group[‡]
Nonwhitened									6.1
Avg.	0.79	0.66	0.67	0.57	0.59	0.78	5.8	3.3	
Median	0.77	0.68	0.71	0.42	0.56	0.77	8.3	3.8	
Biweight	0.81§	0.69§	0.71	0.59	0.57	0.75	5.0	2.4	
Median polish	0.78	0.68	0.70	0.44	0.54	0.79	8.2	3.6	
Component score	0.81§	0.69§	0.66	0.64§	0.60	0.80	3.4	1.8	
Prewhitened									10.8
Avg.	0.72	0.52	0.72	0.39	0.56	0.65	11.8	3.8	
Median	0.74	0.58	0.68	0.50	0.55	0.61	10.4	2.9	
Biweight	0.72	0.58	0.74	0.42	0.53	0.68	11.5	2.8	
Median polish	0.73	0.56	0.66	0.44	0.52	0.65	13.3	3.8	
Component score	0.77	0.53	0.77§	0.53	0.61§	0.66	6.8	1.7	
Postwhitened									9.4
Avg.	0.68	0.63	0.65	0.61	0.59	0.81	7.7	2.7	
Median	0.67	0.63	0.66	0.45	0.55	0.78	11.6	4.1	
Biweight	0.72	0.65	0.65	0.59	0.58	0.79	7.7	2.3	
Median polish	0.68	0.64	0.65	0.46	0.52	0.80	11.7	3.5	
Component score	0.70	0.64	0.63	0.63	0.56	0.82§	8.3	2.4	
Prewhitened + postwhitened									15.8
Avg.	0.65	0.42	0.60	0.48	0.59	0.48	14.3	2.5	
Median	0.67	0.47	0.63	0.46	0.56	0.40	15.0	2.5	
Biweight	0.67	0.49	0.64	0.38	0.53	0.50	16.8	2.5	
Median polish	0.60	0.41	0.52	0.39	0.53	0.40	18.7	4.2	
Component score	0.57	0.20	0.77§	0.50	0.54	0.37	14.1	3.3	

*Mean rank over all site pairs. The expected value under the null hypothesis of no difference among the 20 methods is 10.5.
[†]Mean rank within each whitening group. The expected value under the null hypothesis of no difference among the five methods in each group is 3.0.
[‡]Mean of the overall mean ranks for each whitening group. The expected value under the null hypothesis of no difference among groups is 10.5.
[§]Largest correlation in each site pair.

polish seems a poor choice overall and was never a contender within any group. The average and median turned in mixed performances.

Conclusion

This comparison of methods was based on a set of tree ring width series that are simpler and shorter than the very long series commonly encountered in dendrochronology. However, dendroecology is being increasingly applied in second-growth, closed-stand conditions (e.g., Hornbeck and Smith 1985; Van Deusen 1987, 1989), and so this kind of comparison is needed. The relatively good performances of the principal component scores and the biweight suggest that these mean-value functions should be tested further. Although there was no evidence to distinguish the new method of median polishing, a firm conclusion regarding its utility cannot be drawn from this limited test.

Despite the biological basis and statistical rationale for autocorrelation adjustments, the application of prewhitening and postwhitening should be a considered procedure. This is so because of the evidence obtained for interactions among mean-value functions and whitening procedures, and for the differences in intersite correlations among prewhitened and postwhitened chronologies. The fact that whitening reduced intersite correlations and in some cases gave chronologies that do not strongly resemble the nonwhitened chronologies is an interesting result that cannot be generalized.

It is worth emphasizing that there is usually a biological reason for autocorrelation, and a statistical reason for eliminating it when the analysis requires estimating variance components, for example, in an analysis of variance or in cross-dating via the cross-correlation function. But autocorrelation adjustment is not a statistical requirement to retain the unbiased expectation of parameter estimates in linear models. Different approaches can be justified for different objectives, and additional comparisons of the possibilities are needed to learn which assumptions are tenable in which situations.

Acknowledgements

The author wishes to thank Robert Monserud and Douglas Shadwick for helpful comments on earlier drafts of this manuscript. Although the research described in this article has been funded wholly or in part by the United States Environmental Protection Agency through Contract 68-02-4444 to NSI Environmental Sciences, it has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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