

## RESEARCH REPORT

# EVALUATING CROSSDATING ACCURACY: A MANUAL AND TUTORIAL FOR THE COMPUTER PROGRAM COFECHA

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### ABSTRACT

COFECHA is a computer program that assesses the quality of crossdating and measurement accuracy of tree-ring series. Written by Richard L. Holmes in 1982, the program has evolved into one of the most important and widely used in dendrochronology. It is important to note that COFECHA does not perform all the necessary steps in crossdating. Rather, the program is a tool that helps the dendrochronologist assess the quality of crossdating and measurement accuracy. The ultimate decision whether or not a tree-ring series is successfully crossdated must lie with the dendrochronologist and not with the software. Therefore, the program is most useful after initial crossdating is accomplished using visual or graphical techniques (such as skeleton plots), and the rings have been measured. The proper use of COFECHA adds a high degree of confidence that tree-ring samples have been crossdated correctly and measured accurately, ensuring that the environmental signal is maximized. In this paper, I describe the use of COFECHA through all necessary steps, and discuss the meaning of the initial questions posed at program start-up, the various options available in the main menu, the various sections of the output from COFECHA, and interpretation of the diagnostics of crossdating and measurement accuracy. I demonstrate methods used to help crossdate undated series, and offer tips on taking full advantage of the various options available in the program.

### INTRODUCTION

COFECHA is a computer program written in ANSI standard Fortran-77 by Richard L. Holmes of the Laboratory of Tree-Ring Research at the University of Arizona (Holmes 1983). The first version of COFECHA (an invented Spanish word meaning "co-date" or "cross-date") appeared in early 1982, and has since evolved through continuous feedback from users based on their experience with widely diverse data. This evolution has resulted in a program that is extensively powerful in its diagnostics and functions, but its operation and the interpretation of its output remain complex. This paper will include thorough, up-to-date, step-by-step descriptions of the procedures and options with detailed examples. It is written as a guide and tutorial that a student or new user of the program could follow to learn the program's functions and its many unique features. The purpose

of this paper is to (1) carefully examine the various options available in COFECHA, (2) discuss how to interpret the many diagnostics, and (3) describe ways to take advantage of these options and diagnostics to ensure successful crossdating.

COFECHA uses segmented time series correlation techniques to assess the quality of crossdating in measurement series. Crossdating is essentially a "high-frequency" process. In most temperate geographic regions, year-to-year variations in ring widths are more important for successful crossdating than low-frequency, longer-term trends. Such low-frequency trends, however, can be used when dating species with more complex ring series. Examining only the high-frequency variance proportional to ring widths mathematically simulates human perception on visual examination of a tree-ring series for crossdating.

Another important function of COFECHA is its assessment of measurement accuracy. The pro-

gram will detect “outlier” ring measurements that lie in the outer portions (“tails”) of the distribution of all rings for all series in any given year. These rings are flagged and listed in the output, and should be visually inspected and possibly re-measured to ensure that the original measurements are accurate. Often, such rings represent anomalous ring patterns that occur due to a local injury to the tree or when the ring boundary is unclear or obscured. Occasionally, however, these flagged rings represent measurement errors.

The level of correlation among correctly crossdated ring measurement series may differ with tree species, geographic area, site homogeneity, amount of stand competition, and degree of disturbance. Through time, a given tree may suffer differing amounts of stress from competition with other trees for light and moisture, competition for moisture with ground cover, access to soil by the roots, and disturbances such as wildfires and insect outbreaks. For these reasons, COFECHA does not provide precise accept/reject criteria for making objective decisions to determine whether a series has been crossdated correctly throughout. Rather, COFECHA is intended to assist data quality control by thoroughly examining all series from the first to the last value (the end of a series which extends beyond all others cannot be checked). Furthermore, the program should not be used as a substitute for visual crossdating on the wood sample. The ultimate decision concerning whether or not a tree-ring series is dated must lie with the dendrochronologist based on both graphical and statistical techniques. It may be used, however, to assist in deciding to accept or reject tree-ring series or portions of series for inclusion in a site chronology.

### DATA FORMATS

Program COFECHA (as well as all other programs in the Dendrochronology and Dendroecology Program Libraries) will read data in several ASCII formats, among them the standard formats for ring measurements and indices established by the International Tree-Ring Data Bank (ITRDB), known also as the Tucson formats. Ring measurement (also called “Tucson” or “Decadal”) format is most commonly used for ring measurements,

while Index format is most commonly used for tree-ring master chronologies. Ring measurement format is automatically created from most measurement programs currently in use, such as MEDIR and MeasureJ2X. COFECHA can read data files in either 0.01 or 0.001 mm precision. The conversion programs CONVERT5 and CORING can transform measurements from the TRIMSTRL and CATRAS programs into measurement format. If the format of your data is different, you may be able to change it with Program FMT, or you may need to reformat it in some other way. COFECHA cannot directly read spreadsheet (column or case-wise) format. The file should be converted first to ring measurement format with Program FMT.

### STARTING COFECHA

When COFECHA is first run, it asks for a job identification. A unique set of alphanumeric symbols should be entered to help identify the data set or the project (*e.g.* “ELMA” for “El Malpais”). This string will form the first 1 to 5 letters of all output files created in this run. The program then asks for the file containing the ring measurement series to be tested. If the file does not reside in the folder in which COFECHA resides, the user must enter the complete path on the computer to the measurement file (*e.g.* “c:\malpais\elma.rwl”). COFECHA will then display the first eight lines of the data file, identify the likely data format, and ask the user to verify the format. If the format is identified correctly, simply press the return key. Otherwise, press “N” and the program will list the various formats that can be selected.

The user is then asked to enter the name of the file containing the measurement series that are undated. If the crossdating was unsuccessful for one or more series, or if the crossdating is uncertain, these series can still be measured, starting each series with the year “1,” and placed in a separate data file. COFECHA will use the master dating series created from the file of dated series entered first to suggest possible dating placements of each undated series. If there is no file of undated series, press return. The user is then asked to enter a title for the run. If no title is needed, simply press the

return key, and the COFECHA Main Menu is presented in the next screen.

## THE COFECHA MAIN MENU

The Main Menu shows the current setting of parameters for running the program. Default choices are initially set by the program. Any of these values may be changed by first typing the number appearing at the left, then responding with the modification desired. When no additional changes are to be made, pressing the return key begins processing of the data. Often, very few or no changes need be made to the default values. Either upper or lower case letters may be used in responding to prompts. The program may be terminated at any prompt by typing a *forward* slash (“/”).

### Option 1: Rigidity of the Spline for Filtering

The first option prompts the user to select the rigidity of the spline curve used in removing the low-frequency trend in each series. Much like an architect’s spline, this curve is flexible, derived from a complex mathematical formula. Spline curves are useful for detrending because they can be fit to virtually any trend found in tree-ring series. Experience with data sets from several regions suggests that the optimum job of discovering errors is usually accomplished by using the default spline rigidity of 32 years, with 50% frequency response at a wavelength of 32 years. The resulting interseries correlations and standard deviations of the detrended series were found to be generally highest using this spline rigidity (Table 1). The 32-year response period represents a “window” of years, somewhat like the window of years used in calculating a moving average. A more flexible spline of a shorter length could remove too much of the environmental signal that contributes to the formation of common ring patterns. A less flexible spline may not remove enough of the low-frequency trend, causing series to retain undesirable signals (e.g. competition, local disturbances) that may mask crossdating. The actual ring width for any year is divided by the value predicted from

**Table 1.** Resulting average interseries correlations and average standard deviations of detrended series from an actual tree-ring measurement data set, demonstrating the effects of different spline lengths when assessing crossdating accuracy. The interseries correlations are highest with the 32–35 year spline lengths, while standard deviations are highest with the 40–50 year spline lengths.

Spline Length	Interseries Correlation	Standard Deviation
10	0.552	0.416
20	0.574	0.439
25	0.580	0.447
28	0.581	0.450
32	0.582	0.453
35	0.582	0.455
40	0.581	0.458
45	0.579	0.458
50	0.579	0.458
60	0.578	0.453
75	0.578	0.451
100	0.577	0.445

the spline for the same year, resulting in a dimensionless annual index.

COFECHA will then list a table that displays the variance retained at various wavelengths of the selected spline rigidity. The “wavelength cutoff” is an important property of the spline curve fit to the series being tested. The selected spline rigidity is automatically programmed in COFECHA to retain 50% of the variance in the tree-ring series. For example, 50% of the variance (the amount of scatter about the mean of the series) will be retained for the default 32-year spline. However, only 1% of the variance will be retained for wavelengths in the tested series of 100 years or longer (Cook and Peters 1981). This demonstrates the effectiveness of the spline curve for removing low-frequency trends. For a spline rigidity of 10 years, 1% of the variance will be retained for wavelengths of 31 years or longer. If a very flexible spline is selected, COFECHA will warn the user that autoregressive modeling is not recommended. If desired, the user can select “no detrending” by entering a negative number for the spline rigidity. This will cause the program to test the associations between series using the untransformed measurement values.

### Option 2: Segment Length to Examine

The second option allows the user to select the segment length to be tested, as well as the amount of overlap in succeeding segments. The default setting is to test succeeding 50-year segments with 25-year overlapping periods. A correlation coefficient is first calculated for the first 50-year segment of the series being tested versus the master chronology. COFECHA will then advance 25 years and calculate the correlation coefficient for the next 50-year segment versus the master reference chronology. For example, the first segment to be tested for a series might be the segment 1850–1899. The next segment to be tested would therefore be 1875–1924. Successive segments are lagged 25 years, giving a 50% overlap.

The default segment length of 50 years lagged by 25 years is adequate for measurement series that average 100 years in length or longer. These default values, however, may not be desirable for a data set in which the average series length is less than 100 years. A good rule to help determine the optimal segment length in these cases is to select a segment length that is approximately half the average length of all series being tested. For example, if the majority of series average 80 years in length, then a segment length of 40 years or shorter could be chosen. A segment length under 30 years is not generally recommended, as it tends to yield spurious high and low correlation values. The length of segments may be increased to 100 years or more for long series in species with relatively weak crossdating or widely separated key crossdating years, such as *Sequoiadendron giganteum*.

### Option 3: Autoregressive Modeling

The third option from the Main Menu allows the user to toggle on or off autoregressive (AR) modeling when processing the measurement series. Tree-ring series are highly autocorrelated. Persistence in ring widths carries over from one year to the next because climatic factors to which trees are responding are also persistent from year to year. This property introduces a low-frequency trend that may mask the year-to-year, high-frequency variation required for accurate crossdating.

AR modeling removes persistence that may remain after the spline is fit to the measurement series and the series is detrended. By default, AR modeling is performed by COFECHA, but can be omitted by the user if persistence in the ring series is considered non-problematic.

### Option 4: Transformation of Series to Logarithms

The fourth option allows the user to turn on or off log-transformations of the detrended, AR-modeled measurement series. The purpose of log transformations is to weigh proportional differences in ring measurements more equally. The logarithm of each detrended value in the series is taken after adding a constant of one-sixth of the mean of the series. The constant is added to avoid the possibility of taking the logarithm of zero (*i.e.* negative infinity) in the case of a locally absent ring. A minor disadvantage, however, is that a log transformation creates a distribution of indices that is negatively skewed. By default, log transformations are performed by COFECHA, but can be omitted by the user.

### Option 5: Critical Level Used in Correlation Analyses

This option allows the user to (1) set the critical level for the correlation coefficient used when COFECHA tests segments against the master dating chronology, and (2) choose which type of correlation coefficient to use. The primary statistic used in COFECHA is the correlation coefficient, also known as the *r*-value, which has a range between  $-1.0$  (perfect inverse relationship between two series) and  $+1.0$  (a perfect direct association). A value near zero indicates no association between two time series.

Two types of correlation coefficients can be used when statistically testing the strength of association between two series. The Pearson product moment correlation coefficient is used to test the linear relationship between two numerical (quantitative) data sets. The Pearson coefficient (*i.e.* *r*-value) is more commonly used in tree-ring analyses, and is a parametric measure of linear asso-

**Table 2.** Critical correlation coefficients at the 99% confidence level, associated with selected segment lengths.

Length of Segment	Correlations at 99% Confidence Level
10	0.7155
15	0.5923
20	0.5155
25	0.4622
30	0.4226
35	0.3916
40	0.3665
50	0.3281
60	0.2997
70	0.2776
80	0.2597
90	0.2449
100	0.2324
120	0.2122

ciation between two variables. The Spearman rank correlation coefficient is calculated once the values in the series being tested and the master dating series have been transformed from their original units into their respective rankings. This coefficient is most often used when assessing association between ordinal (qualitative) data sets, between a numerical (quantitative) data set and an ordinal data set, or when the distribution of data in numerical data sets is not normally distributed. The Spearman coefficient is therefore non-parametric, but can be used to test linear associations. If the tested tree-ring series crossdates with the master dating series for a given segment, the association should be very good, resulting in a positive and statistically significant correlation coefficient.

Because crossdating should be precise, the 99% one-tailed confidence level is used by default in COFECHA (Table 2). Any negative correlation is unacceptable, no matter how high its level of statistical significance. Any segment correlating with the master below the correlation associated with the 99% level will be flagged by COFECHA, and these segments should be carefully re-inspected.

### Option 6: Saving the Master Dating Series

The master dating series developed by COFECHA can be saved for later runs or for plotting.

When attempting to date individual undated series, the master dating series can be input as the dated series during the initial start-up of the program rather than the file containing the ring measurement series. This saves computational time and simplifies the output for easier interpretation. When this option is selected, the user can choose to save the master series in either Compact format or Spreadsheet format (two column, year and index). If selected, the master dating series is saved in a file using the job identification entered during the initial start up of the program (*e.g.* "ELMACOFMAS").

### Option 7: Listing Ring Measurements in the Output

The ring measurements themselves can be listed in the COFECHA output when diagnosing problem segments or possible measurement errors. By default, COFECHA does not list actual ring measurements. Occasionally, however, a listing of the ring measurements in the output may help diagnose problem segments or possible measurement errors. This option is also useful to initially document the measurement file and to help permanently archive the ring measurements themselves. For especially long series in a measurement file, this option will create a significantly larger output file.

### Option 8: Parts of the Output to Print

COFECHA output contains eight parts intended to help diagnose any potential problem areas in each series, as well as to help document the ring measurement series. Often, several runs of COFECHA are required to thoroughly diagnose and assess a data set. Subsequent runs need not contain all parts of the output. For example, when correcting problem segments on a series by series basis, subsequent runs of COFECHA do not necessarily have to contain the title page, histogram, master dating series, or bar plot initially printed in the output. This greatly simplifies the output and makes interpretation easier. After all corrections are made, however, and the dendrochronologist is satisfied with the crossdating and measurement

quality of the tree-ring data, a full run of COFECHA should be made to confirm and document the correct crossdating of the site collection.

The parts of the COFECHA output are:

- Part 1: Title page, options selected, summary, absent rings by series.
- Part 2: Histogram of time spans.
- Part 3: Master series with sample depth and absent rings.
- Part 4: Bar plot of master dating series.
- Part 5: Correlation of each series with master.
- Part 6: Potential problems: low correlation, divergent year-to-year changes, absent rings, outliers.
- Part 7: Descriptive statistics.
- Part 8: Undated series adjustments for highest correlations.

The user can delay this choice until the end of the run by responding with an "S." Each part of the COFECHA output is discussed in a later section.

### **Option 9: Omitting Absent Rings from Subsequent Analyses**

Locating an absent ring (a year when the tree put on no wood along the radius under study) in a measurement series is subjective, even though the person conducting the crossdating has a high degree of confidence in its placement based on the same rings for that year for all other series so far dated. When assessing crossdating accuracy, omitting absent rings from calculation of the master dating series is desirable because it allows an assessment based only on observed narrow rings for a given year, rather than subjectively placed missing rings. Missing rings, however, will still be checked to verify that they occur where rings are usually narrow. To help assess those years in which missing rings occur, COFECHA conveniently lists absent rings on the first page by series identification. By default, the program will not include absent rings in computing the master series. If, however, the placement of missing rings is certain, the user can select to include missing rings in the calculation of the master dating series and therefore during the correlation analyses when testing individual segments.

### **Option F: Transforming Series using First Differences**

Tree-ring series are sometimes non-stationary, containing longer-term trends in variability (*i.e.* extended periods of low variance and periods of high variance) that may mask the high-frequency year-to-year variation desirable for crossdating. First differencing is a transformation technique that subtracts the year's previous value from the year's current value. The advantage of this technique is that the transformed series is more stationary, *i.e.* the transformed series has effects of low-frequency trends in variability minimized. A minor disadvantage of this technique is that a spurious amount of autocorrelation may be added to the series after transformation because first-differencing of a value uses the year's previous value.

## **WHAT COFECHA DOES**

Once all options have been selected, the user can press the return key to begin the COFECHA run. Each series is transformed via spline fitting, autoregressive modeling, and log transformations (all by default unless turned off), and by first differencing (if selected). Each resulting series therefore has all or most low-frequency trends removed. The values in this transformed series are added to an accumulating series, and a counter series (number of series for any given year) is incremented for the time interval. After all series have been transformed, the accumulated series is divided by the counter series to give an arithmetic mean value function based on all transformed dated series.

Each transformed series is then tested against the master dating series using correlation analyses performed over the selected segment length and overlap. The master series is first adjusted, however, by removing that part of the master chronology contributed by the series being tested to avoid comparing the tested series against itself. For each segment, a correlation coefficient is calculated using the values in the series being tested versus the adjusted master dating series. The correlation is verified to be positive and significant at the chosen confidence level. The correlation is also checked to see if a higher correlation occurs when matched at alternative positions shifted year-by-year up to

ten years earlier (-10) or ten years later (+10) from the dating. This ten-year lag on either side of the dated position is adequate to locate most crossdating errors, and will also catch errors made by inadvertent skipping or repeating a decade while measuring.

Successive segments are lagged by the number of years selected in Option 2, with the default value being half the segment length. To test to the ends of the series, the first segment to be tested will always begin with the first year of the series, while the last segment to be tested always ends with the last year of the series. All segments tested, no matter when they begin, are of the same length selected in Option 2. Intermediate segments being tested will always begin on years evenly divisible by the lag value. The overlap of the first two and the last two segments is therefore usually greater than the lag.

If most series that make up the master series are incorrectly dated in any given time interval, the master series itself may not contain the correct dating pattern, and most or all of the series will show low correlations for that interval. Test runs have shown, however, that COFECHA is still effective at locating problem segments when more than half of the series being tested were incorrectly dated in a given time interval, if the sample depth is sufficient. This occurs because the series that are crossdated correctly will dominate the signal in that segment of the master dating series, despite the high number of misdated series. As long as the misdated series are not systematically misdated, COFECHA will still correctly identify those series containing errors while not flagging the correct series. The inclusion among the dated series of some with severe errors, though not preferred, generally does not destroy the dating pattern.

## OUTPUT PRODUCED BY COFECHA

### Part 1: Title Page, Options Selected, Summary, Absent Rings

The first page of the output consists of a title page that lists (1) the name of the file containing the dated series being checked; (2) the COFECHA Main Menu with the options selected by the user; (3) summary information that includes the number

of series and number of rings analyzed, the average series intercorrelation, the average mean sensitivity, the number of problem segments, and the average series length; (4) series that have absent rings not showing as being narrow rings in the chronology; and, (5) all absent rings listed by series. This listing of absent rings is especially important as these rings should be checked to ensure they are indeed correctly located absent rings. These rings are listed in Part 6 as well.

### Part 2: Histogram of Time Spans

This part of the output provides (1) histograms showing the length of each series relative to all other series, and (2) the series identification (IDENT), the sequence number (SEQ) based on the numerical position within the ring measurement file, the beginning and ending years for each series, and the range of years covered by all series. The sequence numbers and series identifications appear in all later portions of the output.

### Part 3: Master Series with Sample Depth and Absent Rings

The master dating series used by COFECHA for the correlation analyses is listed in this part of the output. The series reflects a residual time series that has been standardized to a mean of zero and standard deviation of 1.0. Narrow rings are indicated by negative values, while wide rings are indicated by positive values. Because values of -2.0 and +2.0 indicate departures from the mean by two standard deviations or greater, values of this magnitude are rare in the series and indicate very narrow and very wide rings (marker rings) useful for crossdating. To the right of each value is the number of series (sample depth) for that year ("No"), and the number of absent rings for that year ("Ab"). If an absent ring is not narrow for that year based on the information from all other series, it is flagged ("<<"). These are the same problematic absent rings first listed in Part 1.

This master dating series can be used to create a master skeleton plot if no such master plot already exists. Skeleton plots generally focus on the narrow rings (*i.e.* rings with negative values in the

output), with narrower rings receiving greater weight, resulting in longer lines drawn on the plots. The lengths of these lines can range between 1 and 10 on the graph paper. As a guide, plot lengths of “1–2” can be assigned to master series values  $> -0.4$ , “3–4” to master series values from  $-0.5$  to  $-0.9$ , “5–6” to master series values from  $-1.0$  to  $-1.6$ , “7–8” to master series values from  $-1.7$  to  $-2.2$ , and “9–10” to values  $< -2.2$ .

#### Part 4: Bar Plot of the Master Dating Series

The same master dating series in the form of a bar plot serves as a visual aid in crossdating. The bar plot simulates a line plot of the master dating series, and should not be confused with a skeleton plot. Wide rings in the master dating series are indicated by longer lines, while narrow rings are indicated by shorter lines. Alphabetic codes are also given to each year. Upper case letters indicate rings that are wider than the mean, while lower case letters indicate rings that are narrower than the mean. The “@” symbol indicates a value very close to the mean. The higher the letter in the alphabet, the wider or narrower the ring. Each letter progressing through the alphabet indicates an additional 0.25 standard deviation departure from the mean.

#### Part 5: Correlation of Each Series with Master

A correlation matrix is next printed that shows the correlation coefficients between each segment being tested and that same segment from the master dating series (once the series being tested has been removed from the master series). If the segments of the test series are crossdated precisely, positive and statistically significant correlation coefficients will occur. If the pattern of rings in the segment being tested does not correlate with the master chronology, low and/or statistically insignificant coefficients will occur. COFECHA then seeks an alternate placement by shifting the segment  $-10$  and  $+10$  years on either side of the current placement one year at a time, and flags the problematic segment in the output. Flags take two forms. An “A” flag indicates the calculated cor-

relation coefficient for that segment fell below the coefficient associated with the 99% confidence level, but COFECHA could not find a better match anywhere in its  $-10$  to  $+10$  shifts. A “B” flag indicates COFECHA found a higher correlation (and therefore a potentially correct dating position) somewhere within its  $-10$  to  $+10$  shift from the dated position. The average of all correlation coefficients for any given segment is also printed at the bottom of the matrix.

#### Part 6: Potential Problems

This portion of the COFECHA output provides critically important information for diagnosing segments with potential dating problems, as well as individual rings with possible measurement problems. Part 6[A] shows correlations with the master dating series of flagged segments of series being tested at every point from ten years earlier ( $-10$ ) to ten years later ( $+10$ ) than the dated position. The segment time span is listed in the left-most column, followed by a number (under the “High” Column) that represents the shift required for the position with a higher correlation. For example, a  $+1$  in the “High” column for a segment spanning 1700–1749 indicates that a higher correlation coefficient was found if the segment is shifted one year later (*i.e.* 1701–1750).

Part 6[B] shows the effect of data values during certain years that most lower or raise the correlation with the master dating series. COFECHA will first print “Entire series, effect on correlation (.RRR) is:” and then list individual years that have data values that lower and raise the correlation coefficient. “RRR” is the correlation calculated between that series and the master dating series. The four years that most reduce the correlation are then listed, along with the value that shows how much they reduce the correlation. For example, “1857  $-0.015$ ” indicates that inclusion of the value for the year 1857 lowers the correlation by 0.015 below the same segment without that value. The four years that most raise the correlation are also listed.

If a segment is flagged in Part 5, COFECHA also lists years during that segment that lower and raise the correlation. For example, COFECHA may print the following lines in Part 6[B]:



“1675 to 1724 segment:

Lower	1715	-.069	1677	-.039
	1706	-.039	1724	-.034”

Inspection of Part 5 shows that the correlation of this segment with the master dating series was only 0.32 and received an “A” flag. The year 1715 alone has lowered this correlation by 0.069, *i.e.* without the 1715 ring, the correlation of this segment would be 0.39. If a series is misdated midway in the segment, the rings in the errant part of the segment will be listed in the “Lower” section. The rings that occupy the correctly dated portion of the tested segment will be listed in the “Higher” section. In this way, the output in Part 6[B] can help isolate the portion of the segment that appears to be misdated.

Part 6[C] shows consecutive year changes that diverge by 4.0 standard deviations or more from the mean change in all other series. Part 6[C] is usually printed if a segment is perhaps misdated. If a false ring was inadvertently inserted, or a missing ring was inadvertently passed over during crossdating, then a major change will occur in that location of the tested segment that is not apparent in the average from all other series. For example, a particular segment may have a missing ring that was inadvertently passed over during crossdating, located between two very wide rings. All other dated series had the missing ring showing as a narrow ring. The tested segment will show consecutive wide rings, whereas the average of all other segments shows a wide ring followed by the very narrow ring. These two rings in that tested segment will therefore be flagged by COFECHA in Part 6[C], thus indicating the possible precise location that has caused the misdated segment.

Part 6[D] lists absent rings (“0” measurement values) if any are present in the series being tested. The year of the absent ring is listed, along with the index value for the master dating series, the number of series (sample depth) for that year, as well as the total number of absent rings from all series for that year. This information helps ensure that a missing ring has been placed correctly during crossdating. Furthermore, COFECHA will print “ring is not normally narrow” if a missing ring is not suggested in the average of all other

series for that year. “Missing” rings can also occur due to measurement error. These rings should always be reinspected to ensure (1) the proper placement of a likely missing ring, and (2) that the “0” measurement value is indeed a valid “measurement” for that ring. If only a few other series cover the year of the absent ring, they are identified to assist the re-inspection.

Part 6[E] lists measurements that are statistical outliers when compared to the mean from all other series for that particular year. A ring is considered an outlier if its measurement is greater than 3.0 standard deviations above or 4.5 standard deviations below the mean of the other series for that year. These measurements could represent (1) rings that were measured incorrectly, or (2) the possible location when a segment has been misdated. If the segment was not flagged, then these rings should be reinspected for possible measurement problems. If the segment was flagged as a potentially misdated segment, then this ring could help pinpoint the location of the dating error. In this case, the ring will reflect the same ring first flagged in Part 6[C].

## Part 7: Descriptive Statistics

Statistics for the individual series are presented in a table in Part 7. Each series is listed with its Sequence Number (“Seq Num”), range of years (“Interval”), total number of years (“No. Years”), number of segments tested (“No. Segmt”), number of segments flagged (“No. Flags”), and the correlation of the series with the master dating series (“Corr with Master”), adjusted by removing the series being tested. This last column helps screen individual series for possible removal. Series with very low correlations with the master, especially those with flagged segments, should be considered for removal from further analyses if all possible efforts have been expended to accurately date those individual series.

The next five statistics are calculated on the original (“unfiltered”) ring measurements. The average of all ring measurements is presented in the next column (“Mean msmt”), followed by the maximum ring measurement (“Max msmt”). The standard deviation (“Std dev”), series autocorre-

lation (“Auto corr”), and mean sensitivity (“Mean sens”) are printed in the next three columns. In general, high values are desirable for both standard deviation and mean sensitivity, while a low value is desirable for autocorrelation. Low values for mean sensitivity would range between 0.10–0.19, intermediate values between 0.20–0.29, while sensitive measurement series would be represented by values above 0.30. Autocorrelation is an inherent property in tree-ring data, primarily because climate (and therefore biological inertia) tends to be persistent from one year to the next. Low values are desirable. The standard deviation of unfiltered series can not be compared between series because this value is dependent on the mean. A high mean value is usually accompanied by a high standard deviation.

The last four columns represent statistics calculated on the detrended series. “Max value” represents the largest index value in the detrended series. The standard deviation is now a much more useful statistic for comparing the variability about the mean because the means for all series have been standardized to 0.0. Hence, high values of standard deviation indicate series that have indices that are highly variable, indicating higher sensitivity to environmental changes. Values for autocorrelation will now be near zero because all persistence within each series has largely been removed by the detrending procedures (spline fitting, autoregressive modeling, and first differencing, of selected). The last column (“AR (-)”) represents the order of the autoregressive model used in the detrending. Most AR coefficients will range between 1 and 4, with higher values indicating a series with persistence over several years.

Total or mean values are listed at the bottom of the table. The percentage of flagged segments can be calculated using the values listed for total segments tested and total flagged segments. The average correlation with master is a valuable statistic for gauging the strength of crossdating for a site. In general, values above 0.50 are desirable for the average interseries correlation, but this value will depend on the species examined, the geographic location, and the regional climate. For example, an interseries correlation value of 0.5 would be very high for pine species growing in the Southeastern

US, but would be only moderately high for Douglas-fir trees growing in the Southwestern US.

## INTERPRETING FLAGGED SEGMENTS

An “A” flag can occur for several reasons. First, the series of rings being tested may have widths influenced by some disturbance to the tree itself that is not represented by all trees within the stand. For example, a tree falling and injuring a neighboring tree may cause damage reflected in subsequent years’ growth. Second, the rings were perhaps obscured by excessive resin or some other discoloration that made measurement accuracy especially difficult. Third, rings representing juvenile growth often cause “A” flags because these rings responded more to physiological aging processes than to environmental processes. Finally, ring measurements on the very outer portions of the sample may be inaccurate because growth may have been extremely slow, causing very narrow rings that do not reflect the signal found in rings from all other trees during that period. “A” flags are occasionally observed for the outermost (most recent) segment.

In general, segments with “A” flags nonetheless represent noise as these rings do not share the common environmental signal found in the majority of samples for that period. Therefore, the flagged segments should first be evaluated under the microscope, then those rings causing the majority of noise should be discarded from the series. Determining which rings to discard is aided by COFECHA, which also prints output explaining which individual rings in that flagged segment are causing the correlation coefficient to be lowered. For example, the innermost 50-year segment (1715–1764) of a sample was flagged with an “A” flag, and COFECHA indicated that four years in particular—1715, 1716, 1719, and 1723 (in Part 6[B])—significantly decreased the correlation of that segment with the master for that period. The rings from 1715–1723 most likely represent juvenile growth rings, and should therefore be discarded. A similar technique is applied to rings on the very outer portion of the sample. Discarding rings should occur only if the rings are indeed causing a significant decrease in the correlation co-

efficient for that segment. The exclusion of rings from inner and outer portions of the series must be justified.

Ring exclusion is more difficult, however, if an "A" flag occurs for a segment in the middle of a series, with non-problematic segments on either side. If the segment represents a period for which numerous samples exist in the entire data set, then the flagged segment likely can be retained with minimal negative influence. However, if few samples exist for that period, the flagged segment may adversely affect the signal derived from other samples. The problematic rings in the flagged segment can be identified as before. One possible solution is to create two separate individual series from the series being tested, one series representing the inner portion of the original series, and the other representing the outer portion. The problematic rings should be excluded from these two newer series. If the original series is short, division of the series may not be desirable or feasible, and the entire series should be considered for deletion from the data set.

Segments with "B" flags may have more serious problems. These flags indicate a potential crossdating error because COFECHA has found a higher correlation at an alternate dating position within the  $-10$  to  $+10$  range. The correlation coefficient for the alternate position, however, must be much higher than the coefficient at the dated (or "zero-shift") position. For example, a coefficient of 0.54 at the alternate position is not necessarily a significant improvement if the coefficient at the zero-shift position is 0.52. Such high coefficients for alternate positions are rare but can occur occasionally simply by chance. Further support that this flag represents a suggested alternate position that occurred by chance can be found in the segments to either side of the flagged segment. If no alternate dating position is indicated for the segments on either side, then the flagged segment occurred simply by chance. In general, if the coefficient for the alternate position is twice as high as the coefficient for the zero-shift position, then a potential dating error may be indicated.

"B" flags become more serious when two or more adjacent segments are flagged at alternate dating positions that are much stronger than the

zero-shift position. Such dating errors are called "systematic errors" and are a strong indication that crossdating is inaccurate. For example, three consecutive segments may have correlation coefficients at an alternate placement of  $+1$  that are at least twice as high as the coefficients at the zero-shift placement. This  $+1$  shift is reasonable, and strengthened by the fact that all three coefficients are significantly higher at the alternate placements. This  $+1$  shift likely represents a missing ring (if dated from the pith to the bark) that was not noticed during the visual or graphical crossdating procedure. The sample should be reinspected to locate the precise location of the ring, the measurement series should then be corrected, and the analysis performed over.

### USING SHORTER SEGMENT LENGTHS TO ISOLATE DATING ERRORS

Option 2 in the Main Menu ("Segment length to examine") is also a diagnostic tool for helping isolate the location of potential missing or false rings. Subsequent runs of COFECHA using shorter segment lengths can help pinpoint the location of problematic rings. For example, a measurement series may span from 1700–1875. A run of COFECHA using 50-year segment lengths indicates accurate crossdating for these 50-year segments: 1700–1749 ( $r = 0.67$ ), 1725–1774 ( $r = 0.71$ ), 1750–1799 ( $r = 0.66$ ), and 1775–1824 ( $r = 0.63$ ). The correlation coefficient for the 1800–1849 is also significant, but lower than all previous values ( $r = 0.41$ ). COFECHA then flags an obvious crossdating error in the 50-year segment 1825–1874 which has an  $r$ -value of  $-0.13$ , followed by the final segment of 1850–1899 (actually 1850–1875) with another low  $r$ -value of  $-0.10$ . Neither of these  $r$ -values is statistically significant. COFECHA suggests an alternative dating placement of  $+1$  year for these last two segments. Because this series was crossdated from the pith to the bark, a missing ring must be located within the 1825–1874 segment. The outer ring for the series must instead be 1876.

Although the first flagged segment is the 1825–1874 segment, the lower  $r$ -value for the 1800–1849 segment indicates the errant ring is located

at some midpoint in this segment. COFECHA should be run again, this time with a segment length of 30 years and an overlap of 15 years. We find that all 30-year segments have statistically significant coefficients up to the 1800–1829 segment, which has an *r*-value of 0.59. The *r*-value for the 1815–1844 segment, however, is lower at 0.36. We can conclude that the rings are accurate up to 1829. Reinspection of the sample reveals a missing ring at 1831. Although COFECHA did not pinpoint the exact location of the missing ring, it did pinpoint an area of the sample which should be reinspected.

### USING COFECHA TO DATE UNDATED SERIES

Occasionally, crossdating of ring patterns using memorization, graphical, or list techniques may be unsuccessful or uncertain. Such series should never be assigned any calendrical dates to avoid confusion. Calendrical dates should only be assigned when the crossdating is 100% certain and has been verified using COFECHA. Instead, the beginning year of each series should be assigned the year "1" and all rings for the undated series should be measured. These undated series can then be input, either individually or as a group, as an undated file into a run of COFECHA. The program will then search for possible dating placements for each undated series. This technique, however, should never be relied upon as the sole means for dating tree-ring series.

Two possibilities exist when dating undated series. First, one may have a set of tree-ring samples for which no nearby dated samples exist or for which no nearby reference chronology is available. This situation is common for archaeological sites. In this case, one wishes to establish *internal* dating among the various samples. COFECHA can be run by entering the file name containing these undated series when prompted during the initial start-up of the program, but without entering a file containing crossdated series. COFECHA will then attempt to date all series in the file against each other and suggest possible overlaps (if any exist) for the undated series. The second situation occurs when a nearby reference chronology exists or some of the

samples for the site were successfully crossdated. The file containing the reference chronology or the dated series can be input when prompted during program start-up (under "Crossdated tree-ring series"), and COFECHA will attempt to date the undated series against the crossdated series or chronology.

If a file containing undated series is entered in COFECHA during program start-up, an additional part will be printed in the output titled "Part 8: Undated series adjustments for highest correlations." The appearance and information presented in the output will depend on which of the two situations is being analyzed. If no file containing crossdated series or a reference chronology is entered, the output will contain only the possible overlaps of each series against every other series. For example, if a file contains four undated series (series 1, 2, 3, and 4), the first part of this output will contain the five best matching positions of the first series with the other three series (1 versus 2, 1 versus 3, and 1 versus 4). The second part of the output will contain the five best matching positions of the second series with the third and fourth series (2 versus 3, and 2 versus 4), since series 2 has already been tested against series 1. The final part of this output will contain the only possible remaining match, series 3 versus series 4. Therefore, the number of possible dating attempts printed in this output is  $\sum n$  for  $n = 1$  to  $(n - 1)$ , where  $n$  is the total number of undated series in the file. This is important because a file containing 20 undated series will therefore have 190 series matches, representing 950 best matching positions. An analysis conducted on a smaller subset of undated series (*e.g.* 6–10 series) is more easily interpretable.

The output will first list the ID's of the two series being tested, with the second series being the subsequent remaining series in the file (*i.e.* not necessarily the actual second series in the data file). The rest of the line represents the five best matching positions. Each of these five possible matches first lists the last ring of the two series where the five best matches were found by COFECHA. This placement helps when aligning the skeleton plots of the series being tested. The next portion lists the number of rings represented in the

**Table 3.** Example of Part 5 in the COFECHA output, indicating no problem segments. The six series are part of a much larger data set containing 57 series, and are listed here for illustrative purposes only.

Seq	Series	Time Span	1675	1700	1725	1750	1775	1800	1825	1850
			1724	1749	1774	1799	1824	1849	1974	1899
1	LLC001A	1700 1876	0.67	0.71	0.66	0.63	0.60	0.64	0.65	
2	LLC001B	1705 1858		0.66	0.72	0.75	0.77	0.68	0.53	
3	LLC002A	1696 1857	0.78	0.79	0.76	0.74	0.75	0.68	0.68	
4	LLC002B	1699 1869	0.69	0.71	0.70	0.74	0.74	0.64	0.81	
5	LLC003A	1695 1874	0.79	0.80	0.73	0.75	0.76	0.64	0.64	
6	LLC003B	1695 1889	0.74	0.73	0.70	0.70	0.78	0.61	0.53	0.57

overlap of the two series. This overlap should be carefully inspected to ensure an adequate number of rings is contained in the overlap to suggest a strong match. The next portion lists the correlation coefficient, followed by its associated t-value. In general, a very high correlation coefficient is desirable along with a very high t-value. A possible match is suggested when the t-value is above 3.5, but much higher values are desirable for a conclusive match (e.g.  $t > 6.0$ ). If the t-value is 3.5 or higher, an asterisk is placed between the ID's of the two series in the first portion of the line to aid rapid identification of possible matches. Furthermore, a match between two series will show a large gap between the correlation for the first best match and the correlation for the second best match, because only one match can be found between two series, if the two series do indeed cross-date against each other.

If a file containing dated series or a reference chronology was entered during the initial start-up of COFECHA, the user will be asked whether to list the best matches for the undated series in order of either the (R) highest correlation or (D) date adjustment. The default is to list the best matches

by the highest correlations. Each undated series is matched against the master dating chronology using segment lengths and segment overlap lengths as entered in the Main Menu. The first part of the output lists the series ID, followed by the segment being tested. The best 11 matches are listed next, each containing (1) the number of years to add or subtract, and (2) the correlation coefficient associated with that date adjustment. If a match is found, the date adjustment listed in the first match should be similar for all segments being tested (e.g. +1760). In general, the coefficient associated with the best match should be much higher than that associated with the second best match. For example, a match for a segment is suggested if the coefficient is 0.72, while the coefficient for the second best match is only 0.39. Furthermore, the coefficients for the remaining nine matches will be close to each other and decline steadily in value (e.g. 0.38, 0.37, 0.33, 0.32, 0.30, 0.29, etc.).

The correct dating position, however, may not be present as the best match in all tested segments. In general, the majority of tested segments should indicate the same date adjustment. Occasionally, ring patterns for a particular segment may be

**Table 4.** This portion of Part 5 in the COFECHA output indicates a misdating problem beginning with the 1750–1799 segment, which has a much lower correlation coefficient of 0.37.

Seq	Series	Time Span	1675	1700	1725	1750	1775	1800	1825	1850
			1724	1749	1774	1799	1824	1849	1874	1899
1	LLC001A	1700 1876	0.67	0.71	0.66	0.63	0.60	0.65	0.66	
2	LLC001B	1705 1858		0.66	0.72	0.75	0.77	0.67	0.53	
3	LLC002A	1696 1857	0.78	0.79	0.76	0.74	0.75	0.69	0.68	
4	LLC002B	1699 1869	0.69	0.71	0.70	0.74	0.74	0.64	0.81	
5	LLC003A	1695 1874	0.79	0.80	0.73	0.74	0.75	0.61	0.61	
6	LLC003B	1695 1888	0.74	0.73	0.70	0.37	0.07B	0.17B	0.11B	0.15B

**Table 5.** Part 6[A] in the COFECHA output for the series shown in the previous table, clearly indicating a missing ring for this series by the systematic dating adjustments.

[A] Segment		LLC0038B 1695 to 1888 (194 years)											
High		-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	+0	
1775	1824	1	-0.10	0.18	-0.10	0.03	-0.05	-0.03	-0.02	0.00	0.03	0.01	0.07
1800	1849	1	0.31	0.13	-0.09	0.22	0.00	-0.02	-0.12	-0.16	0.11	0.06	0.17
1825	1874	1	0.22	0.10	-0.02	0.20	-0.05	0.19	-0.15	-0.12	0.09	-0.05	0.11
1839	1888	1	0.12	0.21	0.04	0.00	0.03	0.26	-0.10	-0.12	-0.01	-0.15	0.15

anomalous due to a local disturbance that affected the tree for a period lasting several years or decades. The date adjustment for the rings in this segment therefore may not be the same date adjustment as seen for the other segments. Therefore, the systematic date adjustment may not necessarily occupy the first best match listed for all segments. Instead, the systematic date adjustment may occupy the first best match in a few segments, but can be found in other best matches (positions 2–11) for other segments. Therefore, the user should carefully scan all best matches for a systematic date adjustment, which is aided by the summary line below the output for each series.

If an undated series does not date anywhere against the master dating series, no systematic date adjustment will be seen for the tested segments. Instead, the date adjustments will be random, with the correlation coefficient for the first best match listed not significantly different from the coefficients for the remaining 10 best matches. A correctly dated series will have a systematic date adjustment listed for all tested segments.

If the undated series being tested contains one or more missing rings, these will also be apparent in the date adjustments, provided enough years ex-

ist in the undated series. For example, the first three 50-year segments tested may show a systematic date adjustment of +1760. The fourth segment, however, shows a date adjustment of +1801, with the +1760 date adjustment listed as the fifth best match. The remaining segments tested then indicate a date adjustment of +1761. This situation clearly shows a possible missing ring midway through the fourth tested segment. The series should be adjusted for the correct date adjustment (+1760), and the missing ring located using graphical or visual crossdating techniques. If two missing rings occur in close proximity, the date adjustments may reflect a difference of two years for consecutive segments.

Once all segments and their date adjustments have been listed, a final summary line is provided that lists the best matches, which includes (1) the number of years needed for the date adjustment ("Add"), (2) the number of segments found with a similar systematic date adjustment ("No"), and (3) the average correlation coefficient ("R<sub>av</sub>"). The summary line will be printed only if three or more segments with similar systematic date adjustments are found. Occasionally two or more possible date adjustments are found represented

**Table 6.** In this case, crossdating proceeded from the outer ring to the pith and passed over a missing ring for 1780. Note that the outer segments are correctly dated in this case, with initial misdating indicated again for the 1750–1799 segment.

Seq	Series	Time Span	1975	1700	1725	1750	1775	1800	1825	1850
			1724	1749	1774	1799	1824	1849	1874	1899
1	LLC001A	1700 1876	0.66	0.71	0.65	0.63	0.60	0.64	0.65	
2	LLC001B	1705 1858		0.65	0.72	0.74	0.77	0.68	0.53	
3	LLC002A	1696 1857	0.77	0.79	0.77	0.75	0.76	0.68	0.68	
4	LLC002B	1699 1869	0.69	0.70	0.71	0.74	0.74	0.64	0.81	
5	LLC003A	1695 1874	0.78	0.79	0.73	0.75	0.76	0.64	0.64	
6	LLC003B	1696 1889	-0.25B	-0.30B	-0.17B	0.21B	0.57	0.61	0.53	0.57

**Table 5.** Extended.

+1	+2	+3	+4	+5	+6	+7	+8	+9	Series 6 +10
0.57*	-0.22	0.07	-0.09	-0.18	0.03	-0.20	0.22	-0.20	0.26
0.61*	-0.35	-0.01	-0.11	-0.23	-0.25	-0.26	0.15	0.01	0.04
0.52*	-0.25	-0.14	-0.23	-0.22	0.02	-0.02	-0.08	-0.15	0.00
0.57*	-0.18	-0.27	-0.11	-0.22	-0.11	0.14	-0.13	-0.29	0.16

\*Statistically significant.

by three or more segments with high correlation coefficients. An additional line will then be printed with the date adjustments in chronological order.

As a final check, the skeleton plots or graphs should be assigned their correct calendrical years as suggested by COFECHA and crossdated visually against the wood, if necessary. In addition, the measurement file containing the undated series should be corrected using the dating positions suggested by COFECHA. Another run of COFECHA using the adjusted dates should indicate alternate dating positions of "0" for all tested segments. Furthermore, the suggested match should be apparent and obvious, both statistically and graphically. If the alternate position suggested by COFECHA is not apparent, the crossdating must be considered inconclusive, and the series removed from further analyses. Only when a series is crossdated with 100% confidence should it be included in the master site chronology and in further analyses.

Occasionally, a number of series in a data file

may not display obvious crossdating, according to COFECHA. This situation can occur whether the series were entered either as being dated or undated series. As long as a few series date against each other, COFECHA often can identify these series, despite the noise introduced by the misdated or undated series. The crossdated series can be found by inspection of the interseries correlations associated with each series. To help date the undated or potentially misdated series, the user may wish to pull out the series that clearly date against each other (*i.e.* have the highest interseries correlations) and construct a temporary data file containing the well-dated series. In addition, each undated series can be placed in its own individual data file. The program EDRM (for "Edit Ring Measurements"), also written by Richard Holmes, can easily create such files from one larger data file. During subsequent runs of COFECHA, the user can enter the temporary file containing the well-dated series along with the file containing the individual undated series. In this way, the user can systematically attempt to

**Table 7.** Example of COFECHA output, indicating potential misdating for the sixth series LLC003B. In this example, the years 1780 and 1831 are missing. Crossdating proceeded from the pith to the outer ring. Note that the output provides no indication that two missing rings exist.

Seq	Series	Time Span	1675	1700	1725	1750	1775	1800	1825	1850
			1724	1749	1774	1799	1824	1849	1874	1899
1	LLC001A	1700 1876	0.66	0.71	0.66	0.63	0.60	0.66	0.67	
2	LLC001B	1705 1858		0.65	0.72	0.75	0.77	0.67	0.53	
3	LLC002A	1696 1857	0.77	0.79	0.76	0.74	0.75	0.68	0.67	
4	LLC002B	1699 1869	0.69	0.70	0.70	0.74	0.74	0.64	0.81	
5	LLC003A	1695 1874	0.79	0.80	0.73	0.74	0.75	0.62	0.61	
6	LLC003B	1695 1887	0.79	0.78	0.77	0.41	0.07B	0.06B	-0.05B	-0.18B

**Table 8.** Part 6[A] of the COFECHA output, however, clearly indicates the presence of two missing rings. Date adjustments of +1 are shown for segments 1775–1824 and 1800–1849, while date adjustments of +2 are shown for segments 1825–1874 and 1838–1887. The second missing ring, 1831, is more difficult to isolate. Using shorter segment lengths and use of the other diagnostics, however, would help locate this ring.

LLC003B 1695 to 1887 (193 years)													
[A] Segment	High	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	+0	
1775 1824	1	-0.14	0.21	-0.05	0.04	-0.07	0.00	0.00	0.02	-0.10	-0.04	0.07	
1800 1849	1	0.09	0.35	-0.11	0.05	0.22	-0.05	-0.06	-0.04	-0.23	0.04	0.06	
1825 1874	2	0.03	0.23	-0.07	0.02	0.11	0.11	0.17	-0.08	-0.18	-0.03	-0.05	
1838 1887	2	0.00	0.12	0.18	-0.02	-0.04	0.07	0.33	-0.03	-0.13	-0.13	-0.18	

crossdate one series at a time against the well-dated series. When an undated series becomes crossdated, it can then be added to the file containing the series already dated.

### LOCATING DATING ERRORS: AN EXAMPLE

I obtained cross sections from stumps found near Lake Louise in southern Georgia, sanded them, then crossdated their outer portions with the inner portion of a chronology developed for a nearby site. I entered their measurement series (two radii per sample) into COFECHA. The output in Part 5 clearly shows that all sections have been dated correctly against each other (Table 3). All correlation coefficients in this table are very high and statistically significant ( $p < 0.001$ ). Furthermore, no flags were assigned by COFECHA to any segment that might have indicated a possible dating error.

To illustrate a misdated series, let's assume the year 1780 in the sixth series, LLC003B, contained a missing ring that was inadvertently passed over during the initial crossdating attempt. In this example, let's assume crossdating proceeded from inner ring to outer ring. Part 5 of the COFECHA output (Table 4) now clearly shows four segments containing "B" flags beginning with the 1775–1824 segment. We also notice that the coefficient for the 1750–1799 segment (0.37) was much lower than the previous coefficients, therefore indicating the problem ring may well occur in this segment rather than the first flagged segment. Inspection of Part 6[A] in the COFECHA output (Table 5) confirms that a missing ring must be inserted in this series, perhaps at some point in the

1750–1799. Note the systematic alternative dating position ("High" = +1) and associated higher correlations (0.52–0.61) at these positions, indicated by asterisks. All segments following the initial problem segment of 1750–1799 have to be adjusted by +1, indicating a missing ring. Part 6[B] lists the following:

1775 to 1824 segment:

Lower	1787	-0.059	1803	-0.054
	1818	-0.028	1802	-0.023

Because the 1787 ring and following rings in 1802 and 1803 significantly lower the correlation coefficient for that segment, we can conclude that the errant ring may occur prior to 1787. Using the master dating series in Part 3 and the bar plot in Part 4, and comparing them to our plot and measurements for the series, we eventually isolate the missing ring in this series for the year 1780.

Occasionally, dendrochronologists find it easier to crossdate samples from the outer ring to the inner ring. In this case, missing rings will cause misdated segments in the earlier portions of the series, rather than the later portions. Using the previous example with 1780 being a missing ring that was passed over during crossdating, Part 5 in the COFECHA output will show the outer segments are correctly dated in this case, with initial misdating indicated again for the 1750–1799 segment (Table 6). All prior segments are therefore misdated as well.

In rare cases, two missing rings may occur in a ring measurement series. Using the same data set shown in Table 3, let's assume two missing rings, one in 1780 and another in 1831, were inadvertently passed over during the initial crossdating,



Table 8. Extended.

+1	+2	+3	+4	+5	+6	+7	+8	+9	Series 6 +10
0.60*	-0.22	0.07	-0.04	-0.17	0.03	-0.25	0.15	-0.17	0.30
0.59*	-0.04	-0.02	-0.01	-0.11	-0.33	-0.23	-0.10	0.07	0.13
0.16	0.50*	-0.18	-0.18	-0.20	-0.19	-0.01	0.04	-0.07	-0.18
0.20	0.61*	-0.17	-0.30	-0.10	-0.19	-0.06	0.15	-0.16	-0.29

\*Statistically significant.

which proceeded from inner ring to outer ring. Part 5 of the COFECHA output again clearly indicates misdated segments (Table 7), similar to the pattern shown for only one missing ring (Table 4). However, inspection of Part 6[A] of the COFECHA output (Table 8) indicates systematic date adjustments of +1 for the 1775–1824 and 1800–1849 segments, and +2 for the 1825–1874 and 1738–1887 segments. All four correlation coefficients are very high, being orders of magnitude greater than the coefficient at the zero-shift position. Part 6[B] of the output again illustrates that the first dating error occurs prior to the 1787 ring. Note, however, that the diagnostics for later segments are not reliable until the first missing ring is isolated and corrected.

### SUMMARY

Crossdating is the most important principle and technique in dendrochronology. In most cases, crossdating begins using visual and graphical techniques, and is then confirmed using the rigorous statistical assessments provided by computer programs, such as COFECHA. This program is highly versatile, concise in its analyses, and provides numerous options that can be user-adjusted to accommodate different tree species of different ages, growing in a wide variety of environmental settings. COFECHA can be used to help identify potential dates for undated series, and provides diagnostics for evaluating measurement accuracy as well. With familiarity and careful use, COFECHA

can significantly increase the quality of any study involving the use of tree-ring measurements.

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