Summary and Discussion of Procedures at The Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology, Cornell Tree-Ring Laboratory[*]

The basic data source of dendrochronology[1] is straightforward: trees growing in temperate, boreal, and some tropical areas put on a (visible) new growth ring, or tree-ring, every year, right under the bark. We study these rings and their history. A tree ring is "a layer [band] of cells produced in one year in the xylem or phloem".[2] The nature of the cells produced by the tree (or shrub) is a product of the different forces, conditions, and/or constraints operating on the individual specimen; the overall set of tree rings thus reflects all the complexities of the plant's lifespan. Dendrochronology is the study of the history contained in the tree-rings; it comprises many sub-fields, and the full 'reading' of the wood is a complicated process. Often people think dendrochronology is fairly simple, and merely involves measuring and comparing tree-ring measurements (and so it is just some statistical exercise involving time series of measurements). However, although measurement and comparison of tree-ring series is central, it is not the first step, nor often the most important step, in the study of samples. Indeed, the founder of dendrochronology (A.E. Douglass) built his chronologies via a technique called skeleton plotting, which involves no actual measurement – and the Laboratory of Tree Ring Research at Arizona, and many other workers, continue to use this technique today (see e.g. http://www.ltrr.arizona.edu/dendrochronology.html).[3] The tree-ring boundary is in fact just one of many features in the wood which are the subject of study. Dendrochronology involves reading the historic record of the wood and its anatomical features: this applies to wood, carbonized wood, and charcoal – all tree-ring growth contains a complex history. Dendrochronologists look to the features in a sample, and then to whether these may occur in other samples from the site or area, in order to find linkages – ideally sets of such events or specific growth features that can combine to form signatures that allow a unique visual association.[4] Ring-widths can be one of the features compared (and even at the level of ring-width it is in fact a complicated, visual-analysis-process, looking not only at ring width, but to the thickness and density of earlywood and latewood, abnormalities, groupings of rings (trends) over decades, etc.). Ring width measurements, and then the use of statistics on these, are thus very much secondary to the close preparation and visual analysis of the samples. Sometimes we also get jig-saw cases: where with study (aided in some cases by photographs/drawings and records from excavators) we are able to make physical joins between various pieces of charcoal to build up a larger original sample (again this is not statistics – but painstaking visual analysis and the getting to know and love every sample).

The rate of growth (width of the tree-rings) varies depending on many factors. For a given species of tree (different species can grow very differently) in a similar geographic area, the main variables for any set of such trees are (i) the age of the tree (young trees starting life typically grow wider rings, and mature trees grow narrower rings); (ii) the climate in any given year (in our climate area, a wider ring is produced in a favorable

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[*] This statement applies for work at the Laboratory since Sturt Manning became Director (July 2006), and slightly revises past practice. These procedures apply explicitly to all statements, reports and publications appearing from the Laboratory from 2007 onwards with Manning as author or co-author. Manning wishes to thank Peter Ian Kuniholm, Director Emeritus of the Laboratory, for generously sharing his experience and advice.

[1] An excellent general introduction to dendrochronology is Schweingruber, F.H. 1987. *Tree rings: basics and applications of dendrochronology*. Dordrecht: D. Reidel Publishing Company. See also Baillie, M.G.L. 1982. *Tree-ring dating and archaeology*. Chicago: University of Chicago Press (reprinted 1990 by Croon Helm, London). For more detailed discussion of dendrochronology, dendroecology and climate, see the classic study of Fritts, H. C. 1976. *Tree Rings and Climate*. London: Academic Press. For details and discussions on methods in dendrochronology (including more sophisticated statistical analyses), see in Cook, E.R. & Kairiukstis, L.A. (Eds.). 1990. *Methods of Dendrochronology: Applications in the Environmental Sciences*. International Institute for Applied Systems Analysis. Dordrecht: Kluwer Academic Publishers.

[2] Kaennel, M. & Schweingruber, F.H. (Compilers) 1995, *Multilingual Glossary of Dendrochronology. Terms and Definitions in English, German, French, Italian, Portuguese and Russian.* Birmensdorf/Berne: Swiss Federal Institute for Forest, Snow and Landscape Research/Paul Haupt Publishers, Berne, p.369. This resource is also available online: http://www01.wsl.ch/glossary/.

[3] An introduction to the Arizona approach and to skeleton plotting can be found in the (otherwise somewhat dated) introductory book of: Stokes, M.A. & Smiley, T.L. 1968. *An introduction to tree-ring dating*. Chicago: University of Chicago Press (and republished in 1996 by the University of Arizona Press).

[4] See e.g. Schweingruber, F.H., Eckstein D., Serre-Bachet F. & Bräker O.U. 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. *Dendrochronologia* 8: 9-38.

year and a narrower ring occurs in an unfavorable year); endogenous disturbances; (iv) exogenous disturbances; and finally (v) other unexplained factor "*x*" issues.[5] Dendrochronology works on the principle that over a long period of time (especially 100 years or more) there is a pattern of tree-rings of wider and narrower rings which respectively reflect years favourable for the tree (which, in the Mediterranean zone, for example, means especially high precipitation) versus bad years (which in the Mediterranean particularly refers to those years with poor precipitation, even drought),[6] and that the period during which any tree lived will be uniquely represented in its tree-ring pattern (considering all features, including ring-widths). This unique pattern can be detected in other geographically-similar tree-ring chronologies of the same species, and more than one species can contain the same pattern, depending on whether the species' limiting-growth factors (precipitation, temperature, moisture, etc.) are similar. This relative pattern is irrespective of the age of the individual tree; however, to combine ring-width data together statistically, standardizing techniques are used to remove (de-trend) the normal age-related growth trend and, in particular, to scale down – typically with a negative exponential function – the very wide rings of a young tree. The aim is to turn the "normal" growth into a straight line over the lifetime of the tree.

An immediate caveat, however: not all trees work! (For a list of many of those that have been employed in dendrochronology, see e.g. http://web.utk.edu/~grissino/species.htm). Why? Some trees do not grow visible or regularly detectable annual rings, or may in effect form multiple apparent rings, etc. Olive (*Olea europaea*) is such a tree. Some tree species live for only about 50 years and grow very wide rings which never offer a sample suitable for matching. Older trees that have grown in very favorable circumstances or that were cultivated can have very complacent ring growth which is often problematic (for example Poplar). And, in reverse, slower grown trees with distorted ring sequences because of pollarding, coppicing (both regularly seen cultural practices in the Mediterranean), cambial damage, or other damage/distortion, are not usually datable (and we deliberately avoid sampling such trees, but do sometimes detect the likely effects of such practices and effects in wood/charcoal studied). In some individuals "unexplained factor" can be dominant, and such trees must simply be discarded from further analysis – for example, even in a group of trees generally suitable for dendrochronology, it is quite possible to have some 10-30% of individuals which produce problematic information which cannot be employed in further or wider analysis. But, overall, dendrochronology with most trees (and indeed some shrubs) can work – given time, decent ring sequences, and patience.

To measure tree-rings we need a cross section of timber, ideally from the bark (thus last year of life or cutting date) to the pith (physiological axis of the tree). Samples are taken in the form of cores (from living trees or drilled from timbers), cross-sections, or the best available sample (in the case of charcoal and wet wood from archaeological or palaeoenvironmental sites). Samples are prepared so that the rings and their structure can be examined and then measured under a microscope. This usually means sanding to a high polish for timber, but can also involve carefully razor-blading a surface area, or other tactics for wet, damaged wood, or for fragile charcoal. Sample preparation is critical to the success of measuring. The samples are then studied and recorded under a binocular microscope using a traveling stage which allows measurement of the tree-rings with a precision of 0.01mm (or to 0.001mm for some small or very narrow ring samples). Wood-anatomical features and anomalies in particular are noted. The optimal path(s) of the measurements taken is marked on the sample. Each ring or year is thus represented by a measurement in a time series, with the innermost ring being placed at the beginning of the series, and the outermost ring concluding the data set. At Cornell, each sample is independently measured by two people, and then reconciled by comparing the two sets of measurements: ring-widths that are different by over 3% and sequences when there is a difference in the year-to-year change in widths (they should both increase or decrease) are re-measured. For all sections, two radii are measured unless there is little variability in the ring widths across the section. In the case of cores, the replication comes from taking usually two cores per tree, or multiple cores from timbers from standing structures or other preserved wood.

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[5] See Cook, E. 1990. A conceptual linear aggregate model for tree-rings. In Cook & Kairiukstis, L.A. (Eds.), pp.98-104.

[6] See for example and more details Touchan, R., Xoplaki, E., Funkhouser, G., Luterbacher, J., Hughes, M.K., Erkan, N., Akkemik, U. & Stephan, J. 2005. Reconstructions of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. *Climate Dynamics* 25: 75-98.

Some potential samples, for example certain museum objects, require non-destructive techniques. The Cornell Laboratory works with and develops non-destructive techniques, ranging from use of a portable measuring station through digital scanning of samples.

The next steps are to compare the observations as well as time series of measurements from any given sample with the data and time series for the same species from the same site, to build a chronology, and to be able to date new samples against this multi-sample chronology. It is from any collection of such chronologies that we deem contemporary that we then work to develop a master chronology (for a site, and later a region) – and only then do we try to date new samples against this. Here things become more complicated and involved. The process of study and analysis in Dendrochronology is not an exact science (though when a robust unique match is found the date obtained is exact and therefore has great value in fields like archaeology where secure exact dates create tight frameworks for analysis and interpretation[7]). One is searching to find similar to very similar patterns to fit two or more samples and their histories including the ring-width time series together. However, individual trees or regions can have idiosyncratic variations for many reasons (competition, geomorphological events, insect or microbiological activity, microclimatic or genetic factors, etc.). Sometimes growth patterns can be very placid and thus also hard to match. The patterns in species growing close to the margin of their range (e.g., some oaks in the east Mediterranean) can be difficult to match due to temporal variations in the parameters that control the range boundary. Thus many factors have to be considered in matching patterns in tree rings. For example, we look to see if there are "signature years" in a chronology – years where most or all trees show very marked low or high growth, generally due to an extreme in some parameter that has a similar influence on the included trees' ring growth.[8] Patterns of such events can sometimes enable a chronology to be built and matched up (and this is the basis of the "skeleton plotting" method created by Douglass and used as the standard technique still at Arizona). The key step is getting to know each sample – this is how one may start to see possible features and cross-dates, or suspect (and then look for) problems like an absent ring(s) in particular samples. Such issues and problems – for example absent rings – in turn then provide important information.

At Cornell after a consideration of any distinguishing or potentially diagnostic features, we then compare the samples' de-trended measurement series against each other and against chronologies we have built up. This is done by cross-dating, both visually and statistically, using our own CORINA software: http://corina.sourceforge.net/api/overview-summary.html. Along with the visual comparison, we use three basic indicators following the general "European" model: (i) the (modified) Student's t-value cross-correlation from Baillie and Pilcher;[9] (ii) the Pearson correlation coefficient (the Student's t is a modified version of this); and (iii) The "Gleichläufigkeit," from Eckstein and Bauch,[10] which is a measure of the year-to-year agreement between the interval trends of two chronologies, based upon the sign of agreement. The last statistic is usually expressed as a percentage of cases of agreement. (The D test[11] is not now used at the Cornell Laboratory; however, several prominent laboratories use the D-test or Cross Date Index (CDI) implemented in the TSAP-Win software.)

None of the statistical approaches is perfect, due both to the nature of tree-ring growth discussed above and the statistics themselves. They do not produce real "confidence intervals" in the standard statistical sense due to the varying values of overlap between two time series. Cases of problems are well known in the dendro community and the literature – nonetheless, in practical everyday terms, these simple methods usually work satisfactorily (and are used by many labs around the world) subject to applying a suitably cautious approach and looking for sets of correlating indicators.

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[7] For a good discussion on the role of independent dating in archaeology, see J.S. Dean. 1978. Independent dating in archaeological analysis. In *Advances in Archaeological Method and Theory* 1: 223-255.

[8] Schweingruber *et al*. 1990. *Dendrochronologia* 8: 9-38.

[9] Baillie, M.G.L. & Pilcher, J.R. 1973. A simple cross-dating program for tree-ring research. *Tree-Ring Bulletin* 33: 7-14. Further development of this program aimed at investigating the significance of the best match identified can be found in Munro, M.A.R. 1984. An improved algorithm for cross-dating tree-ring series. *Tree-Ring Bulletin* 44: 17-27.

[10] Eckstein, D. & Bauch, J. 1969. Beitrag zu Rationalisierung eines dendrochronologischen Verfahrens und zu Analyse seiner Aussagesicherheit. *Forstwissenschaftliches Centralblatt* 88: 230-250.

[11] Introduced by Schmidt, B., 1987: Dendrochronologie und Ur- und Frühgeschichte, unpublished manuscript, p. 13.

But the over-riding and primary issue is the visual analysis of the samples. And statistical approaches are only relevant when appropriate. For example, when dealing with trees/samples where there are major problems of missing/absent rings in samples, the critical thing is to identify these and to build up overall sequences – here skeleton plotting and signature based analysis is the only approach (with the Bristlecone pine chronology being a classic case – but this is also very relevant to e.g. Juniper and Cedar in the east Mediterranean). Only subsequently are statistical analyses potentially useful. In contrast, in some situations missing/absent rings are very uncommon to unheard of (e.g. German oaks) – here the statistical tests have proved useful in many cases (though nonetheless with some occasional issues).

One issue affecting dendrochronology is what is referred to as "autocorrelation," which can lead to bias in the statistical indices. A problem is that the t-test assumes each value is independent, whereas for trees the previous year's growth is relevant to the following year – via especially buds, hormones, stored substances like sugars, etc. General patterns of growth for a given species in a given area can also be (unsurprisingly) quite similar when comparing segments which are decades, centuries, or even millennia apart (the cultural re-use of wood can further promote such possible complications). For short sample series this is the main problem due to multiple possible fits. This problem is usually resolved for long samples (100 to 200+ rings) by the values of the other statistical tests plus a visual inspection. Other criteria such as the origin of the sample, signature years, and the statistics of correlations with other samples in the indicated period can help – but not always. High t-scores merely indicate (do not "prove") the most possible matches, thus dates. A close visual inspection plus the other statistics and other criteria (in situ location of the sample, signature years, etc.), and possible further analysis then come into play. With t-scores, it is quite easy to find multiple possible matches with values greater than 3.5 (a significant value), but it is generally possible to determine whether or not they are the correct placement by looking at such associated analyses. The values are incorrectly high mainly when there are short sequences within the total overlap period in which the series are very similar, and in some cases nearly exactly the same, even though the two series do not particularly match over the rest of their overlap. It takes a visual inspection of the two series over the whole length of their overlap, plus a look at the other statistics (particularly the correlation coefficient over the full length) for a judgment call in such cases. For shorter overlaps, particularly those less than 100 years, the other criteria are generally more critical. On the other hand, in some cases there will only be one plausible fit, at statistically significant but lower scores, and again, the determination of the secureness of the fit will come from other criteria such as matching signature-years, other fits to other chronologies, etc. Most dendrochronologists thus prefer to see t-value ranges of >5 and ideally higher, and for any match suggested to be supported by several data and by matches with other independent local and regional chronologies, but experience and the nature of the samples is critical.[12] A package of multiple good fits, and inspection of the visual matches between graphs, creates confidence that a robust chronology or date has been found. The key criterion is to be cautious.

As a chronology is built we also calculate the correlation coefficient among the elements; this is another measure of the covariance between series (i.e., how successfully they match each other), but since it is a totally linear analysis prior detrending is critical. A value of 1 means a perfect match, and 0 means no match at all. In dendrochronology, researchers look for correlation coefficients well above the 95% probability level, but rarely see anything above 0.75. However, assigning a threshold value of correlations for our lab is difficult since the correlation values depend a lot on species, length of overlap, and variations in the climate and environment over the region involved. A lower threshold, still well over the 95% probability level, should be established for each species and the size of the included region with the necessary testing of the forest samples to find a level that is realistic and functional. The autocorrelation issue again may be relevant where present in tree-ring records unless one removes it via use of software like ARSTAN or SAS. In the end, however, visual verification by an experienced dendrochronologist is key.

Secure cross-dating relies on correlating longer tree-ring sequences. Sample (or sequence) numbers are of equal importance. Dating a site chronology (= multiple samples) improves cross-dating dramatically since the

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[12] Typical is the statement that "Experience suggests that [t] values greater than 4.0 may be significant and values greater than 6.0 are very likely to be significant": Pilcher, J.R., Baillie, M.G.L., Brown, D.M., McCormac, F.G., Macsweeney, P.B. & McLawrence, A.S. 1995. Dendrochronology of Subfossil Pine in the North of Ireland. *The Journal of Ecology* 83: 665-671, at p.667.

averaging of several samples reduces the variability unique to each tree and thus it cross-dates better with other chronologies. There can be some complications in building a site chronology from wood found only at that site. In any building, there may have been more than one building phase, or relatively continual building and replacement such as in wetland areas. Only the samples that cross-date very well, both visually and statistically, should be included in a site chronology. Then shorter and more irregular sequences may be able to be securely dated to that chronology, but should not be included in it. Timbers in buildings or at archaeological sites may have been imported from outside the local region, or from a specific and perhaps unusual area, where conditions do not match the local trees, and so on. This can make dating a challenge – but it also creates the possibility of the field of dendro-provenancing, where such "exotic" timbers can be sourced by looking for areas where they would much prefer to belong (and dendrochemical methods can then be further applied to test such hypotheses[13]).

Sometimes the approaches described above are all that are needed. However, when building a chronology for dendroclimate purposes, or when dealing with cases where cross-dating is not clear, the next or ancillary step is to use other established software programs that allow one to easily use more complex statistical methods. Here the Cornell Lab employs a mixture of software, including the TSAP-Win (http://www.rinntech.com/Products/Tsap.htm), PAST, Minitab, SAS, and especially the application of linear time series approaches via the COFECHA and ARSTAN programs available from the Dendrochronology Program Library and written by Richard L. Holmes and Edward R. Cook (http://www.ltrr.arizona.edu/pub/dpl/). COFECHA provides a quality control assessment of a chronology (especially written to look for missing rings) and ARSTAN provides tools for chronology development and analysis (such as de-trending and analyses to remove and/or quantify autocorrelation issues).

But it should be stressed that the Cornell Laboratory primarily works from the physical samples: the wood we have is the reality. Thus we only add missing rings when we find physical evidence for these – we do not add or subtract solely on the basis of a statistical analysis (e.g. COFECHA). For basic chronology building – which is the core function of the Cornell Laboratory – with its primary mission to build long-term chronologies for the Aegean, east Mediterranean and Near East – the wood is the key evidence.

The Cornell Laboratory is presently working (2007-) toward the analysis, re-analysis and up-dating for publication of several of its forest and historic building chronologies, and some other major robust chronologies (the Gordion area chronology through to 2006). This work will illustrate and detail our current procedures in practice as of now.

The Cornell Laboratory is also actively developing research in the area of dendroclimatology. Here a variety of additional statistical techniques are employed. See for example a paper in press for June 2007 in *International Journal of Climatology* by C.B. Griggs, A.T. DeGaetano, P.I. Kuniholm, and M.W. Newton, "A regional high-frequency reconstruction of the north Aegean from oak tree-rings, AD 1089-1989." DOI: 10.1002/joc.1459

Dendrochronology can provide us with the felling date of a tree if bark or waney edge[14] is present on the sample; a narrow range of possible felling dates if sapwood is present (sapwood estimates apply to oak only); or a broader "felled after" date if only heartwood rings are included (a *terminus post quem* date). In the prehistoric through pre-modern Mediterranean we believe on the basis of wood-technological observation, historical sources, and ethnography that timber was usually employed "green," or unseasoned. Construction employing tree timber thus probably occurred in the year of felling or fairly soon thereafter (a year or two). Therefore, if a group of timbers from a given structure are found to have all been felled within the same year, then this (or the following year) is likely the year of construction. Study of sets of timbers from structures can also allow investigation of repairs, replacements, and re-used timbers in structures.

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[13] For an example, see English, N.B., Betancourt, J.L., Dean, J.S. & Quade, J. 2001. Strontium isotopes reveal distant sources of architectural timber in Chaco Canyon, New Mexico. *Proceedings of the National Academy of Sciences* 98: 11891-11896.

[14] "The curved cambial surface exposed by removing the bark, i.e. the last-formed tree ring before felling, sampling or death of the cambium": Kaennel & Schweingruber, p.380.

The Cornell Laboratory is seeking to build robust long chronologies by species and by region. The aim in the long-term is to build chronologies reaching from the present back through to the prehistoric period for the Aegean, east Mediterranean, and near eastern regions in the overall Mediterranean zone. We are also building chronologies in the greater Cornell region of NE North America.

As of now (AD 2007) the Cornell Laboratory will only state as a firm dendro-date or correlation a result that passes a rigorous process of examination and verification and our best judgment (and we will explain why we think this in the publication or statement – there will be no “ex cathedra” pronouncements): that means we are pretty confident that the date or correlation (to a set of significant chronologies) will not change in the future. This should therefore be a final date (whether in absolute calendar terms for the absolutely dated dendrochronologies, or in terms of relative years and/or near-absolute placement for floating chronologies such as the Bronze-Iron chronology set[15]). In contrast, any dates that we think likely or plausible but are not so certain of will be labeled as “tentative.” These dates may need to be revised in light of additional data, further analysis, and so on. Hence they are tentative. We will very happily inform and update submitters of progress on their samples, and of what we are currently thinking (and why) – but this is entirely non-final and subject to change as we analyze, add in samples, check, and so on. Some samples, despite having 100+ rings and being from suitable trees, still do not match against our chronologies. This can be for many reasons; even for optimal looking sample material, experience indicates that only some 70-90% of samples are datable. We will periodically re-examine such un-dated samples to see if they can subsequently be matched as we build and improve and extend our chronologies.

With your samples (please send – thank you!), support, and interest, The Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology, Cornell Tree Ring Laboratory is actively working to create robust, high-quality, dendrochronologies to provide fundamental data and evidence for a number of fields and topics, from basic dating frameworks for historic and prehistoric contexts in the Mediterranean and Near East, to archives from which to investigate past and present climate.

Sturt W. Manning

Carol Griggs

Maryanne Newton

Tomasz Wazny

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[15] For the last see e.g. Manning, S.W., Kromer, B, Kuniholm, P.I. & Newton, M.W. 2001. Anatolian tree-rings and a new chronology for the east Mediterranean Bronze-Iron Ages. *Science* 294: 2532-2535.