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# *Pinus ponderosa* Does not Always Support Dendrochronology

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**Abstract:** A mature open-grown *Pinus ponderosa* tree was felled in winter 2009, Sidi Arhoma Farm, Al-Marg-Libya. A Disc at 0.5 m above ground of its trunk was removed, and transferred to the laboratory. Time series of ring widths over four radii, 90° to one another, from pith outwards were plotted. Tree-ring data from this study do not support three key assumptions made by dendrochronology: 1) Standardization of master chronologies, 2) The assumption that any single radius is highly representative of the trunk as a whole, and 3) Cross-dating done on the basis of what dendrochronologists have perceived to be "sensitive" rings.

***Keywords:*** *Pinus ponderosa*, dendrochronology, tree- ring, annual ring.

## INTRODUCTION

Principles and practices of dendrochronology are considered here in relation to tree physiology, and with reference to statistical approaches used for cross-dating. Xylochronological technology purportedly yields an accuracy of exactly one year; however, assignment of a calendar year to a particular layer of xylem is based primarily on alignment of its ring characteristics with those of a reference chronology, itself produced in the same way. Rather than acknowledging and accepting *G* x *E* interactions among phenotypes, researchers have required that anomalous rings be present based upon the assumption that the anomalies were due to abrupt and widespread environmental change more or less uniformly affecting trees throughout a geographic region. This bias for "sensitive" rings involves invalid and scientifically unsupported ideas about cambial physiology, and it greatly increases the uncertainty attending year assignment.

Dendrochronological dating is unlikely to be exact because trees of temperate zones do not necessarily add a new layer of xylem to pre-existing wood each year, and the uncertainty is exacerbated by false, partial and supernumerary rings. Deciding if a ring is annual, missing or surplus is largely subjective when investigating living trees, and is even more equivocal with dead wood of uncertain origin. Thus, the current practice of using dendro years as references for $^{14}$C dating is flawed, and a more valid approach would be to assign unknown woods their radiocarbon ages followed by attempts at cross-dating. However, implementation of that change would require reassessment of radiocarbon dating technology, as supposedly infallible tree-ring ages regularly have been used to calibrate radiocarbon data and adjust atmospheric $^{14}CO_2$ content. Moreover, total carbon contents in woods vary, and there are additional uncertainties attending $^{14}$C measurements in wood.

Dendrochronological aging and event prediction are likely to be in error, but the ligno-cellulosic framework of trees nevertheless develops sequentially if not with regular periodicity. Thus, the possibility remains that more exact dating technology based on the biochemistry of wood formation and wood chemistry will yet emerge.

Dendrochronology is defined as "the science that uses tree rings dated to their exact year of formation to analyze temporal and spatial patterns of processes in the physical and cultural sciences" (Grissino-Mayer, 2002). It is debatable whether dendrochronology truly is a science or merely a technology, but within the preceding broad definition the effort has grown from that of only a few individuals a century ago to a well supported activity involving hundreds of investigators. Dendrochronologists are concerned with two quite distinct activities: 1) Analysis of tree rings in specimens of wood to assign each its historical year of formation, and 2) Use of tree rings having assigned years of formation to analyze temporal and spatial patterns of historical processes (or, "events") not necessarily linked directly with trees. Various sub-disciplines of dendrochronology serve the second, for example, dendro-archaeology, -chemistry, -climatology, -ecology, -geomorphology, -glaciology, -hydrology, and -pyrochronology. All have annual-ring year assignments as their starting point.

Inferences about historical events made through analysis of dated tree rings were initially regarded as non-scientific (Glock *et al.*, 1937; Sampson 1940; Sampson and Glock 1942), but *a priori* existence of "annual" rings prevailed over such scepticism. There of course is no question that a layer of xylem, when it is formed, is produced during the growing season of the tree, nor that determining the age of wood by counting rings in living trees of known planting year can be accurate, plus or minus a few years. Thus, when examining wood from trees of known background, statistically valid investigations can correlate tree-ring characteristics with recorded events that occurred concomitantly with the growing season, such as changes in rainfall or air temperature. On the other hand, developmental plasticity within trees includes ability not to produce xylem or to produce false, partial and supernumerary 'annual' rings. When investigating wood for which there is no certain knowledge of when, where and under what circumstances the source tree grew, how likely is it that past growing conditions can be correctly deduced through analysis of annual rings? As considered below, when the assumptions underlying cross-dating and event prediction are placed within the context of tree physiology, dubious year assignments and associated uncertainties appear as high likely outcomes.

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Approximately 80 000 tree species are on earth, and another 20 000 may have become extinct during the last century (Pimm and Raven, 2000). Thus, excluding the many species which disappeared in previous geological eras, about 100 000 remain of potential relevance to dendrochronology. In addition, perennial woody shrubs have been suggested worthy of investigation (Schweingruber, 1996). Although quite a number of 'softwoods' and 'hardwoods' (Coniferophyta and Magnoliophyta, respectively) have been or are being investigated, the primary emphasis has come to be on *Pinus* and *Quercus* species.

The term 'wood' is merely a lay person's catchall for many different kinds of similar materials, but notions evidently abound that 'wood is wood, cambium is cambium, trees are trees, and cambial growth and wood formation occur in the same way in all.' In fact, each wood manifests occurrence of specific developmental processes, and the features enabling different species to be distinguished are due to underlying genetic differences (Panshin and de Zeeuw 1980 and Savidge 2000). The existence of genetic hence biochemical differences between species may seem obvious but, as considered below, the implications evidently remain to be given serious consideration within both dendrochronology and the related activity of radiocarbon dating.

Designation of a species epithet to an unknown wood can be problematic. When a specimen has been matched to a taxonomic family, genera and species remain to be distinguished by observing anatomical and chemical details. The possibility of a faulty assignment cannot be excluded. Considering pines and oaks, for example, each individual tree contains several kinds of wood differing in both their anatomy and chemistry, and taxonomic confusion therefore can arise even when comparing samples of wood all from the same species (Panshin and de Zeeuw 1980; Savidge 1996; Savidge 2000 and Savidge 2003). Many distinct species of pine and oak exist, and a number within each genus exhibit quite similar woods, even among trees that have grown continents apart. Within Pinaceae, woods from *Abies*, *Larix*, *Picea*, and *Pseudotsuga* are sufficiently similar that, if examined only superficially, any might be mistaken for *Pinus*.

When dendrochronology reports are vague about the species investigated and fail to provide supporting wood anatomical details, it is implicit in such omissions that species do not represent variables in terms of the nature of their cambial growth, their perceived responses to environment, or their ability to be cross-dated. This of course is contrary to forest ecology and xylem systematics (Carlquist 2001), and from the beginning of dendrochronology it was acknowledged that variation between species exists (Douglas, 1919).

The three dimensional extrinsic realm of a tree extends well beyond its physical margins and comprises innumerable physical, chemical and biological phenomena that change diurnally and seasonally, and that are able to modify one another independently of the tree. Not all of the components are yet fully defined. The tendency in dendrochronology has been to see the extrinsic realm as the independent variable, but ample research has shown that both physical and chemical phenomena in proximity to trees are influenced by the intrinsic realm (Savidge 1996, Savidge 2000 and Savidge 2001a). For example, compared to an open stand, beneath a closed forest canopy it is invariably darker, cooler with higher humidity during the growing season (Savidge, 2001a). Tree roots alter below ground physical and chemical conditions in a variety of ways, and trees also change their extrinsic atmosphere by emanating volatile organic compounds, some of which like ethylene are potent regulators of growth and development (Savidge 1996, Savidge 2000, Savidge 2001a and b). The extrinsic realm undoubtedly changes in volume and form as a tree progresses from seedling to mature tree.

Trees of the temperate zones exhibit annual cycles of growth and dormancy in parallel with the changing seasons. Thus, they are the ones most likely to produce true annual layers, or "rings," of xylem. Again, however, the underlying biochemistry and associated gene expression for dormancy vis-à-vis growth remains poorly investigated (Savidge and Főrster, 1998). Extrinsic phenomena arising temporally out of phase with cambial growth appear to be equally or more important as in-phase phenomena in determining the characteristics of the annual ring.

Rings are sometimes produced in trees growing in tropical/sub-tropical locations, but in those environments the onset of cambial dormancy evidently is in response to abscission and other defoliation events, themselves usually but not necessarily linked to the occurrence of dry periods. However, relatively little physiology research has been done with such species, and it cannot yet be confidently stated that dormancy in tropical species involves rest or if it is merely quiescence, or 'exodormancy' (Savidge, 1993). Resumption of growth following a period of dormancy in tropical species evidently does not hinge on fulfilment of a chilling requirement.

When a dendrochronologist attempts to cross-date an unknown specimen of wood, little or nothing is known about the growing history of the source tree, its chilling requirement, or the photoperiod to which that tree's ancestors had acquired genetic fitness. Movement of tree seed and establishment of plantations in new latitudes, even opposite hemispheres, have long histories (Evelyn 1664 and Morgenstern 1996), and the location to where a provenance may have been transplanted could influence not only the rate of secondary growth but also the anatomy and chemistry of the wood (Zobel and van Buijtenen 1989 and Morgenstern 1996).

Radially narrow xylem layers interspersed between wider rings have been interpreted by dendrochronologists as evidence for unusually severe drought, whereas exceptionally wide rings have been viewed as evidence for abundant rainfall (Douglas 1919; Chapman 1940; Fritts 1976 and Fritts 1991). This reasoning evidently derives from agricultural considerations, as water unquestionably can be limiting for crop production, and data from weather stations commonly find practical application in helping to predict production of annual crops. However, there are obvious substantive differences between annual agricultural crop plants and trees, and the fact that extrinsic factors such as rainfall and air temperature influence growth of monocultures under intensive management does not allow projection of such relationships to growth of forest trees in the wild.

A temporal tie between precipitation and water uptake is probable for shallow rooted tree species (Paul 1963 and Kozlowski 1971), but the species favoured for investigation in the early years of dendrochronology were conifers growing in arid regions, particularly the Southwestern USA.

From his physiological perspective in 1940, Sampson and Sampson and Glock (1942) challenged the thinking that rainfall controlled ring width: "The possibility of the influence of factors other than precipitation on tree-ring widths is not to be lightly cast aside. Plant physiologists are well aware that many chemical reactions within the plant affect the rate of respiration and influence the pre-eminent hormone and enzymatic systems, and thus regulate the amount of cellulose laid down. These reactions in turn are influenced greatly by temperature, wind, soil-water relations and nutrients, and by many biotic factors…it is unfortunate and on the whole fallacious to attempt to interpret so complicated a function as deposition of cellulose in relation to precipitation cycles…" (Sampson, 1940). Chapman (1940) dismissed Sampson's concerns with the assertion that "Water is a limiting factor, scarcity of which is capable of reducing the average width of these rings to a greater extent probably than any other of the elements of the environment…On no other hypothesis than the variation in rainfall can the coincidence of broad and narrow rings in these trees be explained."

Ironically, although dendrochronologists of 1940 and earlier had acknowledged that a direct link between rainfall and ring width was but a hypothesis, and a controversial one at that, prosecution of that hypothesis within the scientific method remains to come to the forefront of dendrochronology research. Thus, still today, there is no convincing evidence that precipitation and drought events explain wide and narrow growth rings, respectively, in arid-region trees. Telewski and Lynch (1991) moved the speculation one step further by suggesting that trees of dry environments were overstressed and, therefore, that it could not be assumed that a growth ring had been produced during severe conditions. Major treatises in dendroclimatology have been published on the premise that the science is solid (Cook *et al.*, 1999), but the research needed to substantiate such ideas remains to be done.

When woods from differently aged trees of the same species growing on the same site are examined at the same height in their trunks, a crude pattern of cambial growth in relation to tree development may sometimes be found, beginning with large radial increments in the small diameter shoots followed by an exponential decline in ring width as the circumference increases. However, this is not always the case.

In wild *Acer saccharum* growing as dominant canopy trees in a natural (i.e., untended) uneven-aged unevenly spaced stand under the same site conditions in New Brunswick, Canada, our previous research (Lamlom and Savidge, 2006) has shown that the pattern of ring widths over radii varies fundamentally from one direction to the next at any particular height in the tree. In addition, the pattern of ring widths across the stem base differs substantially from that at locations higher in the trunk. Moreover, when xylem layers of the same year are compared, there are obvious differences between-tree in the patterns of ring widths. Thus, it would be a serious error to assume that any single radius from a bole is highly representative of the trunk as a whole, although such assumptions are routinely made within dendrochronology. Data from Lamlom and Savidge (2006) also make it evident that those singular wide or narrow annual rings which are considered in dendrochronology to be environmentally sensitive indicators of abrupt environmental change, and therefore useful for cross-dating purposes, cannot be relied on to be present among trees even when the trees have grown in close proximity. As discussed above, the factors influencing such variation are numerous, although many probably remain to be identified (Paul 1963; Kramer and Kozlowski 1979; Zobel and van Buijtenen 1989).

Exponential decline is superficially evident in the two older of the three *S. giganteum* trees (Lamlom and Savidge, 2006), but this interpretation does not stand up to close scrutiny. All three giant sequoia trees were tall, evidently healthy specimens. Trees 1 and 2 were felled in 1995 following a fire, and tree 3 snapped in a 1980 winter storm. A radius from each was sampled near 1.5 m above ground level. Tree 1 grew beneath a canopy of larger giant sequoias, such as trees 2 and 3. In contrast to trees 2 and 3, the diameter growth of tree 1 was flat over its first 60 years, but began to increase exponentially after 1950. Shaded trees such as tree 1 usually begin their growth slowly and later accelerate, and such trees are common in wild stands (Lamlom and Savidge, 2006). Thus, the idea in dendrochronology that master chronologies need to be "standardized" by applying a smoothing curve to the overall growth trend is not well supported by the natural variation as shown in Lamlom and Savidge (2006). Genetic variability is equally or more important than environmental variability in determining the intrinsic environment and a tree's competency to grow (Savidge 2001a); thus, it could be argued that such standardization is really only useful when considering clonal stock. Standardization of variation in a number of wild-type specimens may serve to provide an indication of an "average" tree, but it undoubtedly also imposes substantial uncertainty upon the variation which is natural to populations of trees.

## MATERIALS AND METHODS

### Tree species and sample preparation:

A mature open-grown *Pinus ponderosa tree* growing wild was felled in winter 2009, Sidi Arhoma Farm, Al-Marg-Libya. A Disc at 0.5 m above ground of its trunk was removed, and transferred to the laboratory. The disc was air-dried for about two months in a reduced light environment, then stored at 0 °C in darkness.

**Tree-ring analysis:**

An electric planer was used to create clean surfaces for four cardinal radii of the stem disc. In some cases where it was difficult to distinguish growth rings, a power-disc hand sander with 110- followed by 220-grit sand paper was also used.

Radial widths of the annual rings were measured at the Natural Resources and Environmental Sciences, Wood Technology Laboratory, in Al-Baida-Libya. Beginning beside the pith, the width of every annual ring was determined across each of the four radii. Pictures were taken for the stem disc by using a digital camera (Kodak C–7070) and then were entered into the computer system, and by using image analysis software (Digimizer), annual ring widths were measured in the four radii.

**Statistical analysis:**

LOWESS (Locally-Weighed Scatterplot Smoother), otherwise known as locally weighed polynomial regression was used to analyze the data.

## RESULTS AND DISCUSSION

The data from the time series of ring widths over 4 radii at 0.5 m above ground of its trunk revealed wide variation in the annual tree-ring widths across any one radius and also between the four radii (Figures 1 and 2). This is demonstrating an absence of correspondence between radii in the annual rate of cambial growth.

Figures 1 and 2 showed that by looking at the four radii of our studied species, it can be concluded that there is a variation in the annual ring width between the four radii contradicting Glock *et al.* (1937) whoes stated that in trees of established uniformity throughout the trunk, such as the ponderosa pine, a single radius gives a record highly representative of the tree as a whole”. Upon careful examination of Figures (1 and 2) it can be seen that although similar, both the raw data and LOWESS models of variation are not in perfect agreement. LOWESS is a modeling method combining much of the simplicity of linear least squares regression with the flexibility of non-linear regression (Cleveland 1979, Cleveland 1981 and 1985). Useful visual information concerning ring width ($y_i$, i = 1,... , n) as a function of year ($x_i$, i = 1, . . ., n) produced can be obtained by computing and plotting LOWESS-smoothed points. The value at $x_k$ is the value of a polynomial fit to the data using weighed least squares, where the weight for ($x_i$,$y_i$) is large if $x_i$ is close to $x_k$ and smaller if it is not. In other words, LOWESS gives more weight to points near the one being estimated and less weight to points further away, in essence fitting a series of simple models to localized data subsets. Thus, in the absence of a researcher making assumptions or specifying a global function of any form to transform his data, LOWESS objectively describes the deterministic part of variation in the data. The fitting procedure generally is effective in preventing outliers from distorting the smoothed points.

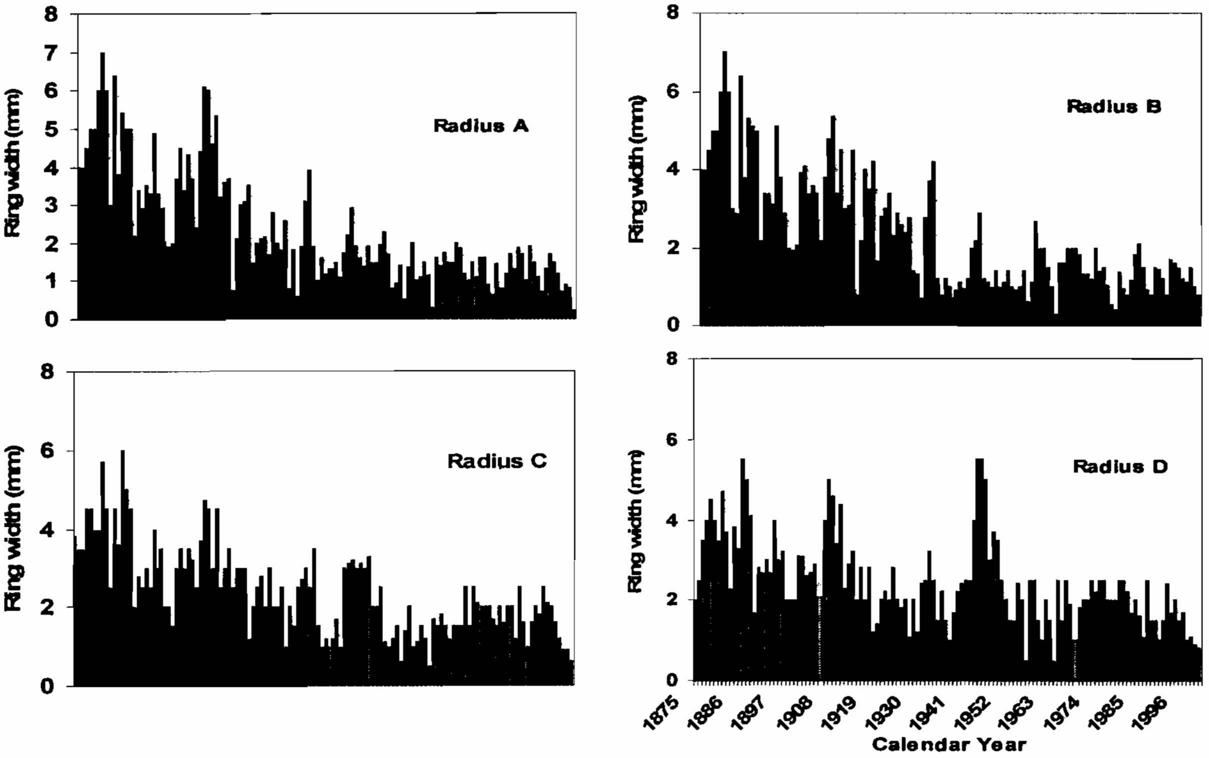

**Figure (1)**: Profiles of *Pinus ponderosa* ring widths as function of year when each ring was produced at 0.5 m above ground of the trunk of a mature open-grown *Pinus ponderosa* over four radii.

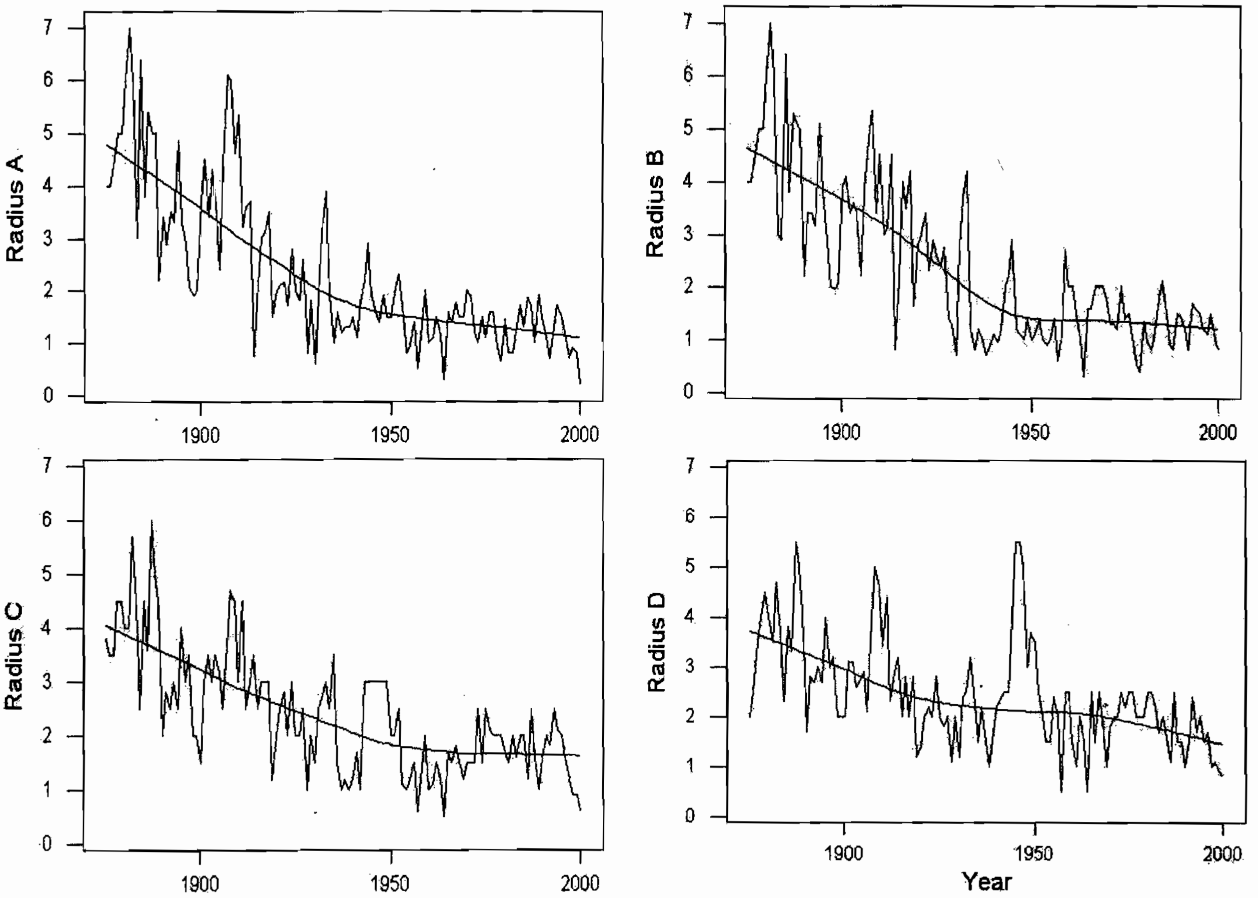

**Figure (2):** Time series of ring widths (mm, Y axes) over four radii, 90° to one another, from pith outwards, at 0.5 m above ground in the trunk of a mature open-grown *Pinus ponderosa*. The raw data compare well, but not perfectly, between radii. The roughly parallel LOWESS polynomials fit to the raw data are an indication of similar but not identical intrinsic environments at the four points.

If conventional standardization approaches of dendrochronology accurately reflect similarity in genetic competence between trees, one would expect LOWESS curves as applied to raw ring width data of individual trees to parallel one another closely. However, our observations indicate that each tree tends to generate an unique LOWESS model (Lamlom and Savidge, 2006), and a similar finding has been made in our current study for radii sampled at the same height within a singular tree (Figures 1 and 2).

It became apparent in our research that dendrochronology purports to be an exact science, with at least some dendrochronologists stating that it is absolutely free of uncertainty. However, our observations imply that the uncertainty in estimating the year of formation of an annual ring by dendrochronological methods could be very great. The uncertainty associated with estimation of the year of formation of an annual ring in sugar maple and giant sequoia trees was at least ± 5 rings. We suggest that wood should be radiocarbon dated firstly, prior to any effort being made to cross-date it on the basis of sensitive rings (Lamlom and Savidge, 2006).

Glock *et al.* (1937) stated that, *viz.*: ring does not maintain a constant thickness in its course around a section or lengthwise of the trunk. However, among the species used intensively for tree-ring work, rings do maintain a constant thickness in relation to adjacent rings, to such a degree that any radius from the trunk is highly representative of the trunk as a whole. In other words, if a graph of ring width as a function of year produced is prepared by measuring successive ring widths along radii at either varied trunk heights or randomly selected circumferential positions, the undulations should parallel one another. An example supporting this concept is shown in the data of Sequoia trees in our previous work (Lamlom and Savidge, 2006). For convenience, we refer to the concept as 'parallel representation.' Parallel representation has been one of the key assumptions of dendrochronology from its outset (Douglass, 1941).

From first principles, parallel representation is theoretically possible in any tree, regardless of species, but in nature it is improbable except under special circumstances of growth involving persistently uniform conditions, and even under ideal circumstances there may be complicating factors. Evidence for parallel representation around the circumference is apparent in our studied *Pinus ponderosa* tree (Figures 1 and 2), one of the favoured species in dendrochronology (Glock *et al.*, 1937 and Douglass 1941). Wild ponderosa pines such as that generating the data in Figures 1 and 2 grow distantly spaced. They can be expected to have deep root systems, and trees growing on arid lands rarely experience canopy closure. However, upon careful examination of Figures 1 and 2 it can be seen that although similar, both the raw data and LOWESS models of variation are not in a perfect agreement.

Parallel representation is plausible from a physiological perspective when considering trunks of open-growing conifers having 100% live crown and still making yearly gains in height growth. Parallel representation possibly also applies to trees in uniformly spaced even-aged plantations, under the circumstance where live-crown reduction proceeds upward at a uniform rate. This is the case for most softwood plantations. However, should it be possible to find evidence for parallel representation under either of those circumstances, this would not permit the conclusion that the same species is likely to exhibit parallel representation under all conditions. Excepting clonal stock, where variation in theory arises only as a result of environmental differences, the width and other characteristics of annual rings may be expected to vary between individuals of the same species growing on the same site.

Missing rings evidently are normal in trunks of both suppressed and highly aged trees (Bormann 1965; Kozlowski 1971 and Telewski and Lynch 1991). Trees forming circumferentially complete annual rings in the upper stem do not necessarily form a layer of new xylem each year in the lower stem (Bormann 1965 and Kozlowski 1971). In the trunks of trees having only a small percentage of live crown, and in older but still living branches, the layer of new xylem may extend downward below the basal position of the foliated region only partially, tapering to dormant cambium below. Where the cambium does not grow at all, the result is a 'missing ring.' In the region between the position where no diameter growth occurs and the crown base, cross sectional analysis reveals arcs rather than full circles of wood. These arcs are otherwise known as 'partial' or 'discontinuous' rings.

The ability of trees to omit annual rings from their structure clearly is a dilemma for dendrochronology. It is conceivable that cambium could remain dormant for one, two or more successive or intermittent years before resuming xylem production, but there is no indication of where in the wood the lapses occurred. Partial or discontinuous rings that are present but that do not completely envelop the circumference at any particular height in the tree may also be overlooked, especially when ring analysis is done using a single radius.

In addition to the problem of missing rings, supernumerary rings commonly form in trunk and branches, particularly during the younger years of a tree's life, and they may continue to be produced in the developing juvenile corewood within the upper crown as the tree ages (Kozlowski, 1971). These extra rings normally arise in response to intrinsic physiological activity, such as after a second burst of shoot growth in the one growing season. In addition, once cambial growth has commenced, rings within annual rings can be induced by various environmental factors, such as a sharp frost, prolonged drought, severe heat, flooding, insect feeding, damage to buds and young twigs by birds or squirrels, wounding, displacement of the organ in relation to its existing gravitational equilibrium, and application of chemicals (Peace 1962 and Kozlowski 1971).

It is also possible to misinterpret a true annual ring as a false ring. For example, frost damage in conifers typically results in formation of abnormal wood (deformed tracheary elements, excessive and enlarged parenchyma), and should such damage occur two or more years in succession during early spring time cambial reactivation, a true annual ring is likely to appear as a false one. Frost rings are of common occurrence, and "spring and autumn frosts of damaging intensity are likely to occur wherever local topographical conditions lead to the pooling of cold air" (Peace 1962). Thus, the interpretation that frost rings can serve as indicators of immediately preceding volcanic activity is no better supported than the notion that wide rings are induced by rainfall (LaMarche and Hirschboeck, 1984).

The false ring can be quite similar to the expected annual ring in displaying distinctive earlywood and latewood bands. False rings can, but do not necessarily, envelop the full circumference. Partial rings, or arcs, are particularly common in association with growth under light-suppressed conditions and during reaction wood formation.

Partial rings, often quite eccentric as seen in cross sections of branches and roots, are common (Kozlowski, 1971), and when wood cores, only, are investigated partial rings can be misinterpreted. Again, a partial ring can be either a false ring or a true annual ring. In general, decisions about false, supernumerary and true annual rings during analysis of radii tend to be highly subjective interpretations.

Cross-dating is simply correlative investigation, usually on the basis of distances measured between what are rather subjectively perceived to be successive latewood boundaries. Douglass (1941) defined cross-dating to be recognition of the same pattern of ring characteristics (as observed in the transverse section) in different trees from a localized area of forest. In other words, cross-dating is essentially the same concept as that of parallel representation described and shown above, except that correlations are sought between trees. The approach taken by Douglass (1941) was raw data correlation in its least massaged form, attempting to match ring-width series without attempting to standardize or otherwise transform data.

The implicit hypothesis within Douglass's definition of cross-dating was that, if sequential ring patterns as measured over two specimens of wood matched, then the actual years of formation within the compared woods corresponded. The dendrochronology community remains to demonstrate scientific rigour by doing everything possible to disprove this hypothesis, but Baillie (1982) quite correctly warned that "simply because two pieces look alike does not necessarily mean that they fit together." Douglass (1941) noted from the outset that cross-dating of species distantly separated geographically was not successful. However, Fritts (1963 and 1976) considered that "some series may exhibit significant correlations where distances are as great as 1100 miles."

Whether raw or transformed ring data are considered, cross-dating requires correlative assignment of an unknown's sequence with that of a pre-dated, or "master" series. Cross-dating is also used to extend master chronologies deeper into the past.

A major shortcoming of cross-dating is that master chronologies have not been produced by processing raw ring data from a random sampling of nature, rather by subjectively deciding that wood specimens do, or do not, contain the desired "sensitive" years, followed by attempting to force matches between specimens perceived to contain the same sensitive years. Data from samples not exhibiting sensitive years have not been permitted to contribute to the master chronology even when they have been derived from similar trees growing on the same site.

Dendrochronology presently uses a large number of interactive computer programs, known as the 'dendrochronology program library' (Grissino-Mayer, 2002), to cross-date and predict past events. This mathematic sophistication embodies major assumptions about trees, none of which have been substantiated through physiological investigation. Consequently, the raw data (which are rarely published) are attended by inestimable uncertainties. Again, as a 'science,' dendrochronology could make a greater effort to disprove, rather than prove, the existence of temporal correspondence between time series.

It is instructive to recall some of the concerns early in the history of dendrochronology. Glock *et al.* (1937) wrote: "even in the sampling of individual trees a very small portion of the entire organism is chosen. Usually one radius is selected, this being the best or the longest. Further drastic reductions are commonly made of the samples in the laboratory where a mere fraction of the field collection is selected for measurement and study. The 'best' specimens are chosen, these apparently being those, which match each other most closely. Thus, rather than being representative and random, the samplings are greatly restricted and highly selective."

Sampson (1940) expressed a similar concern: "One of the most outstanding weaknesses in tree-ring theory is the fact that radial specimens must be selected on the basis of sensitivity, or response of an occasional tree to variation in rainfall. This close selectivity itself initiates statistical unsoundness into the whole theory."

If the uncertainty attending dendro dating is to be fully accounted, cross-dating must include probability analysis in relation to the employed master chronology, whether or not the unknown specimen exhibits what are believed to be the corresponding "sensitive" rings. To consider a hypothetical case, if 50 of 100 trees are sufficiently "sensitive" to qualify for inclusion in a data set used to produce a master chronology, then the probability of an unknown's time series being correctly cross-dated by means of that master chronology can be no greater than 50%. This 50% probability applies even if the ring characteristics of the unknown agree perfectly with those of the master chronology.

In practice, it is difficult to obtain good correlations between raw data when a "floating" (i.e., un-aged) time series spanning many years is compared with a master chronology. Fritts (1963) converted raw ring widths to logarithmic values and used a least squares program to do linear regression of those as a function of time. More complex standardization approaches are now in routine use, with the purpose of removing "undesirable" long-term variation. Undesired information is curtailed by dividing actual measurements by those predicted from a statistically derived equation that relates tree growth over time to tree age. As explained by Grissino-Mayer (2002), standardization "tries to remove the growth trends due to normal physiological aging processes and changes in the surrounding forest community." In other words, standardization rejects the natural phenotype in favour of an imagined average one. It may be asked why any analysis should desire to introduce greater uncertainty into already uncertain interpretations of nature, and how smoothing or averaging of natural variability inherent to woods can be accomplished in a way that begins to do justice to either the physiology or the chronology of individual tree growth and development?

Standardization is assumptive and serves to destroy the physiological individuality that is entirely reasonable for a genetically diverse population.

The characteristics of radial files of xylem provide an indication of the cambium's physiological state as it was when the elements in the radial files were produced, regardless of where in the tree they were produced. Objective analysis of raw data could provide insight into the cambium's changing physiology over an unknown's entire span of years, without the need to make unsupportable assumptions about whole tree physiology. We suggest, therefore, that standardization should be abandoned in favour of retaining and comparing raw data sets. Further, cross-dating should be considered invalid whenever it cannot be demonstrated that there was a high probability that the cambium producing the wood had similar physiological circumstances (i.e., *G* x *E* interactions) to that of the reference chronology.

Given objective, physiologically based treatment of the variation in a time series of raw ring-width data, within dendrochronology's current practice the first requirement to be satisfied, before cross-dating were attempted, would be the demonstration that the entire time series of an unknown shared parallel variation with the corresponding time span in a master chronology. LOWESS, introduced above, has already found use in relation to dendrochronology (Goelz and Burk 1998, Goelz *et al.*, 1999), and LOWESS models could be used for assessing parallel variation hence cross-dating potential. Such an objective approach would respect raw data and would reduce the subjectivity presently attending master chronology development. However, the variability normal to wood makes it unlikely that the requirement of parallel variation could be satisfied but rarely. Should highly correlated polynomial functions between unknown and reference be found, this could be interpreted as evidence that their cambia experienced similar physiological conditions. However, there would remain concern that the two series have no actual chronological relationship.

LOWESS modeling of variation in tree rings encounters the same limitation that affects all of dendrochronology, namely that the investigation is actually post-mortem analysis, whereas the deductive aim of the research is often to know how cambial growth itself was influenced as the layer of xylem was forming. LOWESS gives more weight to ring widths near the year being estimated for the mathematical model and less to annual rings more distantly removed. This could be considered to be physiologically reasonable, as storage reserves in sapwood can be mobilized outward through the ray system in support of cambial metabolism, and the nearer the reserves are to cambium, presumably the greater is the likelihood that they are allocated to it. On the other hand, LOWESS as it has been used considers ring width data on both sides of the ring under consideration. Giving equal smoothing weight to future and earlier produced rings is problematic simply because the future ring years were not in existence when the rings of interest were being produced.

## CONCLUDING REMARKS

'Dendrology' (Greek *dendron* = tree) refers to studies of whole living trees (Hardin *et al*., 2001). Thus, the term 'dendrochronology' (Latin *chronologia* = study of time) may impart the idea of a disclipine having keen scientific insight into how trees make wood over time. However, in reality dendrochronologists have opted almost exclusively for making post-mortem inferences about tree growth and development based on examinations of dead xylem (Greek *xulon* = wood). *Dendro*chronology really should be *xylo*chronology, just as study of wood in general has been referred to as xylology (Corona 2000).

Following a century of tree-ring counting, measurement, statistical transformation and sequence comparison, from a tree physiology perspective there is yet no persuasive justification for accepting dates assigned to any master chronology, or any other age estimate that has been made through dendrochronological cross-dating. Admittedly, where there is due circumspection in relation to a species, its geographical placement and site conditions, it is probable that the majority of trees living today in the temperate zones can be relied upon to produce an annual layer of xylem over the entire trunk each year. Roots and branches are unquestionably less reliable. It is clearly not vital for survival of temperate-zone conifer species that they produce a new layer of xylem every year, and the physiological basis for how and when cambium does not grow is even less well understood than that of cambial growth. Thus, although annual ring counts of wood in extent trees of known planting year are very likely to yield accurate ages, xylochronologists have not been justified in projecting their empiricism to woods for which there is no knowledge of the trees' past.

Not only have dendrochronologists avoided doing the research needed to support their assumptions, which in the final analysis concern the intrinsic physiology of wood formation, but when samples have yielded information other than what preconception demanded, the practice has been to exclude data. The magnitude of uncertainty attending discovery of the past by 'reading' what is recorded in wood specimens of unknown history is heightened by requiring those samples to exhibit so-called ring sensitivity, seen most commonly as anomalously wide and/or narrow rings within a background of less variable ring widths. Sensitive rings have been interpreted as indicators of fluctuating climatic extremes, with specimens lacking sensitive rings representing trees that somehow were exempted from the environmental effect. Within this same flawed logic, sensitive rings could be interpreted as evidence for a tree being unsuitable for analysis because it, and not its neighbours, was somehow predisposed to produce anomalous rings. In the same vein, a specimen lacking sensitive rings might be considered less likely to generate error during aging.

The thinking that there is a common response of trees throughout a region to changing climatic conditions during particular years is at the heart of dendrochronological cross-dating. This gross simplification of microclimatic variability, combined with unjustified projection of the extrinsic environment into the intrinsic realm and the assumption of parallel variation of xylem layers within trees, underlies all that dendrochronology does. In actual fact, morphogenesis through $G$ x $E$ interactions, genetic diversity within as well as between species, and genetic competence within each plant for producing variable phenotypes enable immense versatility in secondary growth. Expression of that versatility in the form of variable woods is very well documented and makes it highly unlikely that dendrochronology has treated nature, or its own efforts, at all objectively.

In relation to wood and chronology, of one thing can science be certain. The ligno-cellulosic framework in perennial woody species is produced sequentially, if not with regular periodicity, as the earth circles the sun. Because of the variable and uncertain periodicity operating within trees, radiocarbon measurement would appear to be the only currently available method for estimating at all accurately when wood was produced. However, because the history of radiocarbon dating from its outset became interwoven with that of dendrochronology, there is need for a complete reanalysis of past radiocarbon findings and interpretations as they have been influenced by investigations into woods.

The cambiology research effort pales alongside that of dendrochronology, although both began about a century ago. The lack of progress undoubtedly relates to the small number of research personnel in cambiology (Savidge 1996; Chaffey 1999; Savidge 2000 and Savidge 2001a). As an applied technology, dendrochonology has received cross-disciplinary support from anthropology, archaeology, the radiocarbon community, more recently the climate change community and others. In contrast, cambiology until recently has been compelled to admit that its research has no immediate relevance other than to new biological knowledge, and areas such as silviculture and wood science that could also benefit from cambiology research have shown little other than academic interest in it (Savidge 2000 and Savidge 2001a).

Another reason for the delayed growth of cambiology undoubtedly has to do with the exceptional degree of difficulty attending such research. With modern technology it may be somewhat costly to prepare specimens for tree ring analysis or to acquire precise measurements, but otherwise it is not particularly difficult; thus, the emphasis has been on data generation and statistical analyses. In contrast, in cambiology, exceptional effort and financial commitment is needed. The processes of wood formation are multifaceted and none is lacking in complexity. Investigations to elucidate those processes require multi-disciplinary expertise in biochemistry, biophysics, cell biology and whole tree physiology as well as plant anatomy, chemistry, and physics (Savidge 1996, 2000, 2001a and 2003). It cannot be overstated that each tree species deserves in depth treatment as a genetically unique organism.

Areas of physiology research that could aid dendrochronology in becoming a more exact science include characterization of the sub-cellular intrinsic environment and variable gene expression of cells in the cambial region, elucidation of the mechanism of phloem unloading and how it is regulated in support of secondary growth, experimental manipulation of vascular development (particularly through *in vitro* research under completely defined environmental conditions); and controlled investigation into secondary growth over extended periods within whole trees to determine their responses to defined extrinsic factors at varied levels.

The first three approaches can provide the biologically more fundamental and definitively absolute information about direct responses of cambium to changing environment, as well as information on the signals transmitted between shoot and root systems, how they are affected extrinsically and work to modify the nature of the intrinsic environment, hence annual ring formation. The last approach recognizes that cambial growth varies with position and age of cambium in the tree. Concerted research efforts operating in all four domains are needed to make the more important progress.

With continuing research into molecular wood properties, genotypic variation, within-tree variation in the cambial region's physico-chemical environment, and intrinsic mechanisms of regulating cambial growth and dormancy, the possibility remains that reliable, and perhaps entirely novel, dating technology based on analysis of woods will yet emerge.

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