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Future of dendrochronology with respect to archaeology

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Summary

The future of dendrochronology with respect to the field of archaeology is forced to address several issues including legacies from the past involving the curation of data and physical specimens. Practical considerations involve the optimization of chronological coverage in both geographical and temporal dimensions to maximize future archaeological dating potential. One over-riding consideration is the integration of tree-ring derived information, both chronological and environmental, with other well dated information from other proxies to provide archaeologists with the best possible background picture for their studies. The corresponding duty of archaeologists is to concentrate resources on sites that can be well dated so that information on human activities can be integrated with the environmental story underpinned by dendrochronology.

Keywords: Dendrochronology, archaeology, radiocarbon, multi-disciplinary, future.

Introduction

When you agree to present such a paper you often don't realize just what a poisoned chalice it is going to turn out to be. What is the future of dendrochronology from an archaeological perspective – what are the needs of research? Tricky questions! I was going to start by discussing the issue at least partly from an island perspective; using the Irish experience as a model. However, that decision rapidly foundered because Ireland is not typical. In the same way, the future of archaeological dendrochronology cannot really be separated from the wider applications of dendrochronology, particularly those relating to environment. For the future, the attitudes of archaeologists are probably as important as those of dendrochronologists. What follows should be seen as a basis for discussion rather than any fully developed argument. The very act of trying to write such a document forced me to consider, essentially for the first time, where dendrochronology might be going in the 21st century.

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The apparent fragility of the discipline

Let me start by saying that there was a point in time, just a few years ago, when, in the British Isles, it began to look as if there wouldn't be a future for dendrochronology. Maybe it is better put as follows: one began to envisage a situation where someone looking back from 2010 would be saying something like "dendrochronology was a technique that was used back in the 20th century but no-one does it any more". The episode which triggered that thought was the departure of two expert dendrochronologists from Sheffield – Gretel Boswijk and Jennifer Hillam. Their departure made it very obvious just how fragile the dendrochronological presence in the British Isles actually was. It would only have taken a few deaths, retirements or career changes and to all intents and purposes dendrochronology, as a working discipline, might have disappeared from the area.

Of course, the basic tree-ring data and the master chronologies for oak would have survived along with the literature, but what else? We don't have to look back very far in the history of British dendrochronology to see what happened to the operation carried out by Alan Heyworth (1978) at Aberystwyth. Back in the 1970s Alan collected and worked on coastal oaks from Wales and SW England. He published on them in the 1978 British Archaeological Report volume edited by John Fletcher, but thereafter he left the field. Within a short time the physical tree-ring samples had been disposed of by the university and eventually all that remained was the ring width data in a single copy of his Ph. D. thesis which could be consulted in the university library. John Fletcher's archive of tree-ring measurements on panel-painting boards fared somewhat better after his death in the late-1980s. The basic measurement data was preserved by David Haddon-Reece and was eventually re-processed and verified by the Sheffield team (Hillam, Tyers 1995). Of course, the original panels are back with their owners and can no longer be checked or re-examined without an extremely tedious amount of work – in fact it is unlikely that permission would ever be obtained for re-examination in many individual cases. Those examples show that the raw data may survive, but the physical samples, which might form the basis for future research, may not. Let me mention the related situation in the Belfast tree-ring laboratory. The Belfast operation was originally set up to build a chronology which would allow the supply of precisely-dated wood samples for radiocarbon calibration. The work was successful and blossomed into chronology building in Scotland and England, commercial archaeological dating, and excursions into archaeological and environmental issues. Virtually all the original ring width measurement data is checked and archived, and is thus safeguarded. However, what is the medium to long-term future of the circa 10,000 oak and pine samples currently in storage at Queen's University? The simple answer is that no-one knows and there is no specific plan to deal with the issue. The University as an institution has no opinion on the matter, apart from the opinion that storage space is not a valueless commodity. The individuals who were originally responsible for the collection of most of the samples (Pilcher and Baillie) are not personally responsible for their future. This raises the open-ended question – who is? A very similar situation was exposed by the death of Bernd Becker in the early 1990s. Although the initial crisis has now passed, there was a real danger during the 1990s that the entire tree-ring operation at Hohenheim, and the wood collections housed there, could have been lost. So, the future of dendrochronology is not just about what will be done in research terms in the field of dendrochronology in the years to come, it must also address the legacy of previous work.

Having said that, let us imagine that all the dendrochronologists in the British Isles did die, retire or leave the field. Imagine we had a situation where at some point in time there is no-one actually practicing dendrochronology in this area. What would the loss be? All the basic data could be retrieved by any interested individual, just as Heyworth's or Fletcher's data has been. So any dedicated researcher who wanted to incorporate British Isles tree-rings into some wider study could still do so – with effort. On the practical side, archaeologists, building historians and palaeoecologists would find they could not get dendrochronological dates. However, if there was enough pressure for dates, that situation could be rectified by finding funding to train or import one or more expert dendrochronologists.

Perhaps the message from the discussion so far is that one should not think on too small a regional scale. Because chronologies have tended to be built and used for dating on a local basis, this has conditioned dendrochronologists to think small. Now that many oak chronologies exist, and are to some extent available within the peer group, local thinking need no longer apply. This is well exemplified by the routine dating of imported Baltic and Scandinavian timbers in England and Scotland. So, at a European scale we can assume that dendrochronology, as a dating tool, has a guaranteed future. Whether the same applies to studies which might involve re-measurement or examination of the original timbers is a different matter. Personal experience with re-examination of actual wood samples spanning some of the 'narrowest ring' events in the Irish chronology (Baillie, Munro 1988) implies that it is vitally important that the original samples remain available for study. This point relates not just to the ring patterns but to everything from the cellular structure to the elements/isotopes deposited within the structure of the rings.

Pioneer work

Back in 1983 in a general article on dendrochronology I pointed out the existence of pioneer and optimization phases (Baillie 1983). Looking back, I said: *"Once completed it is desirable to optimize the chronologies from a dating point of view. If we assume that there is a tree-ring signal, i. e. a controlling influence which causes the individual trees to produce patterns of wide and narrow rings sufficiently similar for dendrochronology to be possible, then to optimize dating and chronology we should have that signal saturated… In addition to optimizing individual chronologies this phase should include attempts to saturate both geographical and temporal coverage."*

With another two decades of hindsight little has changed. In the pioneer phase there is always rapid progress. Building an initial chronology sees the filling up of time, with effort put into the solution of specific problems e. g. bridging gaps in the chronology, acquiring replication etc. During this phase the common sentiment is that someone will come along later to tidy up any loose ends, the only factor of over-riding importance is that the absolute nature of the discipline be maintained – the chronology must have calendrical integrity.

On consideration, in retrospect, most dendrochronology can be divided down into two broad areas. First, there is the never-ending quest for new problems and new areas into which pioneer excursions can be made. This questing comes from two constraints, namely that it is mostly the pioneer questions which can obtain funding, while individual dendrochronologists are stimulated by fresh applications of the technique; this pioneering work includes of course all of dendroclimatology and dendroecology. The second broad area is application of the method to dating questions; the primary interface with archaeology. So, this simple excursion into the history of dendrochronology reveals that everything reduces to either pioneer work or dating application. It is probably fair to say that it is those involved in dating on a regular basis who will eventually provide the optimization of chronological replication and coverage.

The unfinished business

Now, let us go back and look at some of the unfinished business left behind by the pioneers. In this instance, because it is a small island entity, I am going to use Ireland as a vehicle for discussion. What should the dendrochronological situation be in Ireland, in an ideal world, and what would be necessary to meet that goal? The same thinking can be applied to any area.

First, is there such a thing as a single Irish oak chronology? If not, how many chronologies should there be? What should their length be, and their level of replication? Second, how should they be made? Are index chronologies really the best representation? Have mean chronologies been adequately explored? An excursion into widest and narrowest rings in every year produced the surprising finding that the entire envelope of growth accurately tracks the existing chronologies, in other words, there may be entirely different ways of presenting data which have no-where been adequately explored. The concept of presenting an 'envelope of growth' could be a way to allow other workers to develop a feel for what tree-growth is actually telling us. It may be every bit as informative to archaeologists as figures for cereal crop production, and has the advantage of being precisely dated.

The bottom line, from a dating point of view, is that there should be sufficient regional chronologies to maximize the chances of dating individual oak samples from archaeological contexts throughout the island (or any other area). However, this maximization also requires that thin portions of the pioneer chronologies be gradually enhanced to maximize the chronology signal – the optimization referred to above.

Fine, and as long as fresh samples are gradually accumulated from all parts of the area, and processed in a single laboratory (or in laboratories which work cooperatively) to a uniform standard, one can imagine a future time when optimum area and time-depth coverage would be achieved. However, here is an interesting twist in a tree-ring area as small as Ireland. The simple fact is that there is not enough archaeological (and building) dating work to sustain even one dendrochronologist full time. Thus archaeological dating application on its own, in Ireland, can never achieve the optimum. In fact, the only way that dendrochronology as a discipline can survive in Ireland is if enough pioneer research activity is undertaken, over and above commercial dating, to sustain income and employ dendrochronologists. This tells us that the best situation, in the absence of philanthropy from some government, institution or individual, is where a dendrochronological research presence is supplemented by a commercial operation which gradually fills in the gaps and optimizes the chronologies in the broadest sense (note that this is exactly what Tucson has managed to do with some success for about eight decades). It is, however, at this point that the Irish model can be seen to break down. Exceptionally in Europe, Ireland is the one country without a large supply of timber-yielding medieval buildings. In most other countries large numbers of such buildings serve to keep dendrochronologists employed; employment which forms the basis for a dendrochronological presence.

This is as good a point as any other to address an outstanding deficiency in dendrochronology, just about everywhere. How, even in a near ideal, combined, research and commercial operation are modern chronologies to be upgraded? The relentless ageing of chronologies means that we now have some 'modern' chronologies which end in the 1960s. In Ireland there is only one well-replicated site chronology for oak which runs up to the year 2000, indeed a whole block of site chronologies end in 1979, with others finishing in 1985, 1992, 1994 etc. The funding necessary, and the time involved, in bringing a suite of Irish site chronologies up to date virtually guarantees that this will never happen. It would probably be impossible to convince a research council that such an effort is worth funding; so who is ever going to undertake the exercise? If it is impossible to bring modern chronological coverage up to date in a place as small as Ireland, how much worse is the situation with trans-Eurasian or trans-American chronology suites such as those pioneered by Fritz Schweingruber? Thankfully, this is not an archaeological problem!

I suppose that the factors covered above sound rather negative. However, it is important to remember that they are underpinned by exposure to most aspects of dendrochronology over several decades. The single most important aspect of the problem is that in democracies, governments, with the possible exception of France, take essentially no part in setting up tree-ring institutions. For three decades in western Europe it has been obvious that no-one in authority planned dendrochronological research. Instead, individuals, attracted to the research potential of pioneer dendrochronological work, went out and set up their own operations which could be either research based or commercial, or occasionally both. Essentially none of the best known individuals – for example, Becker, Bonde, Baillie or Kuniholm – were employed as dendrochronologists. Rather they were employed as archaeologists, biologists, classicists, palaeoecologists, museum curators and used their positions as a base on which to build dendrochronology. The main problem with this *ad hoc* arrangement is that it required, and requires, individuals with a personal commitment to the subject. There is never any guarantee that a dead or retiring dendrochronologist, who was not employed as a dendrochronologist, will be replaced by a dendrochronologist. It is issues such as this which are inevitably going to dictate the shape of dendrochronology in the future. It is possible to envisage situations where only commercial dating operations – where funding is implicit in the activity – will survive in some areas. Without a continuous supply of pioneering initiatives research funding and academic researchers drop from the picture. In this respect the Irish experience is a model. While chronologies were under construction – the pioneering work – it was easy to acquire research support. Once the chronologies were completed, the pioneer had to devise defensible questions to attract further support. To some extent this is what happened in the world-leading Tucson laboratory around the 1960s. As the pioneering possibilities dried up at home dendrochronologists were forced to look further and further afield. Stockton effectively moved to Morocco while LaMarche toured the Southern Hemisphere. In Switzerland the limitations set Fritz Schweingruber off on his peregrinations; Cook took up where LaMarche had left off.

So, we can conclude this general introduction by making a short list of key words/phrases relevant to any discussion of the future of dendrochronology and archaeology:

commercial dating	pioneer research
funding	training
curation of data	curation of wood samples
optimization of sample depth	education of archaeologists
optimization of chronological coverage.	

The future of dendrochronology in the field of archaeology

The second millennium AD

There are of course notable differences in the length and quality of historical records in different parts of the world, however, for simplicity we can think of three broad chronological divisions within archaeology which can be loosely defined as the last millennium (or the period of widespread detailed records), the period of just over a millennium that spans the first millennium AD and the end of the first millennium BC (the period of limited record keeping but where at least the dating of the historical record is fairly secure) and prehistory (the period before the first few centuries BC wherein history varies from altogether absent, to poorly dated, to highly localized). The interactions between archaeology and dendrochronology are rather different in each of these periods. For the last millennium dendrochronological coverage is so vast that high levels of dating success are now possible, be it in the broad transect from Ireland to Poland, the Eastern Mediterranean or North America. In this period, outside America, historical documentation is normally at chronological resolution, with the result that dendrochronology acts to refine chronology and is unlikely to uncover major lapses in historical/archaeological chronology. However, opportunities do exist to add considerably to the environmental background within which human populations operated. This enhanced environmental knowledge can come from studies of the tree-ring chronologies themselves both at a local level and at a hemispheric and inter-hemispheric scale. Thus we can imagine interrogating chronologies to identify phase changes between regions. As an example, take oak chronologies in Ireland and England. It is possible to identify short periods where the normal common response of trees in the two neighboring regions suddenly alters – tree populations which have been responding similarly suddenly show opposite growth response. It can be shown that such changes, for example one in the late ninth century, are not due to changes in replication but appear to mark real divergences in behavior. Figure 1 shows identically prepared index chronologies for Irish and English oaks across the period AD 865–920. The chronologies are behaving in a very coherent manner until the late 870s when we see completely opposite growth response from AD 884–890, thereafter coherence returns. This implies that whatever conditions prevailed up to the 870s changed in such a way that the oaks in Ireland and England which had shared a more or less common regime found themselves growing in different

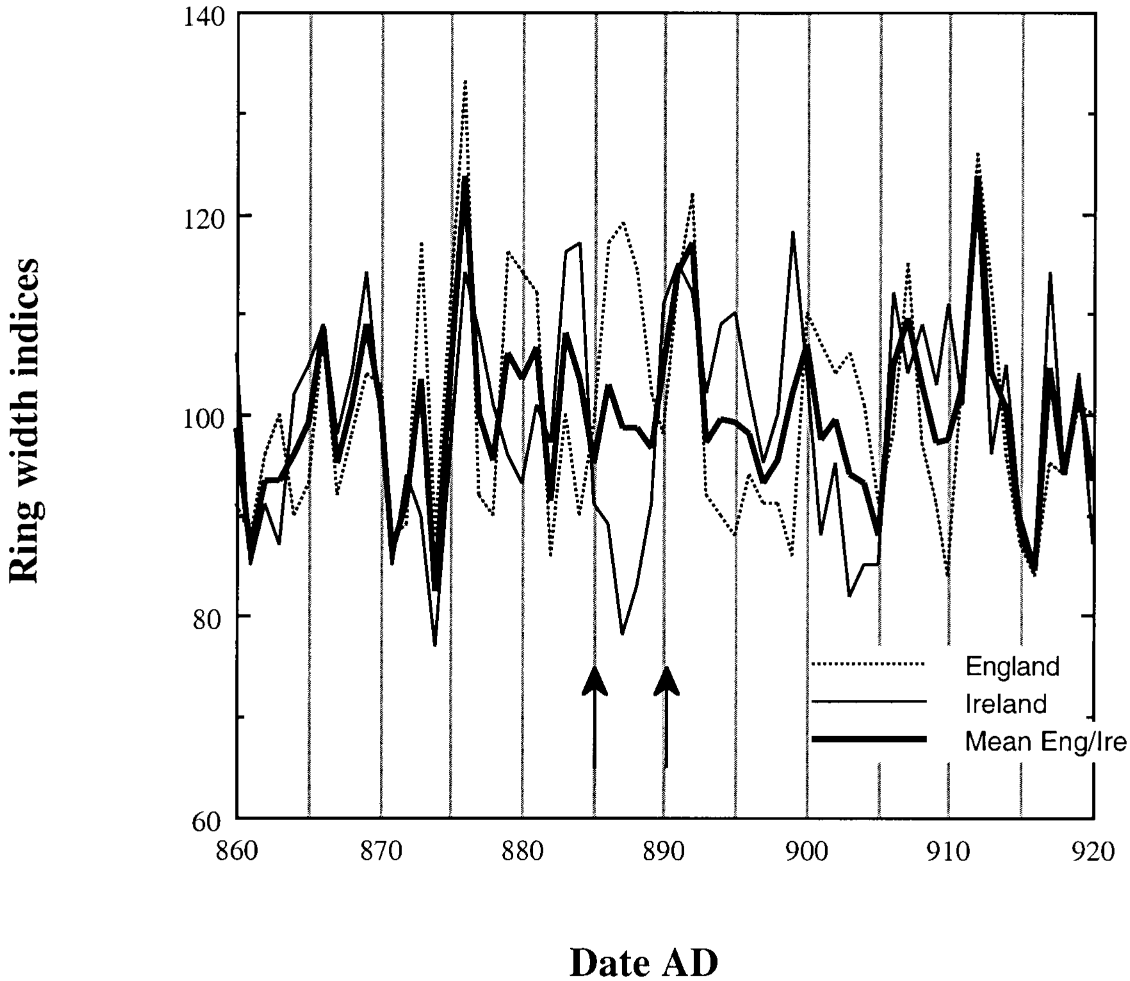
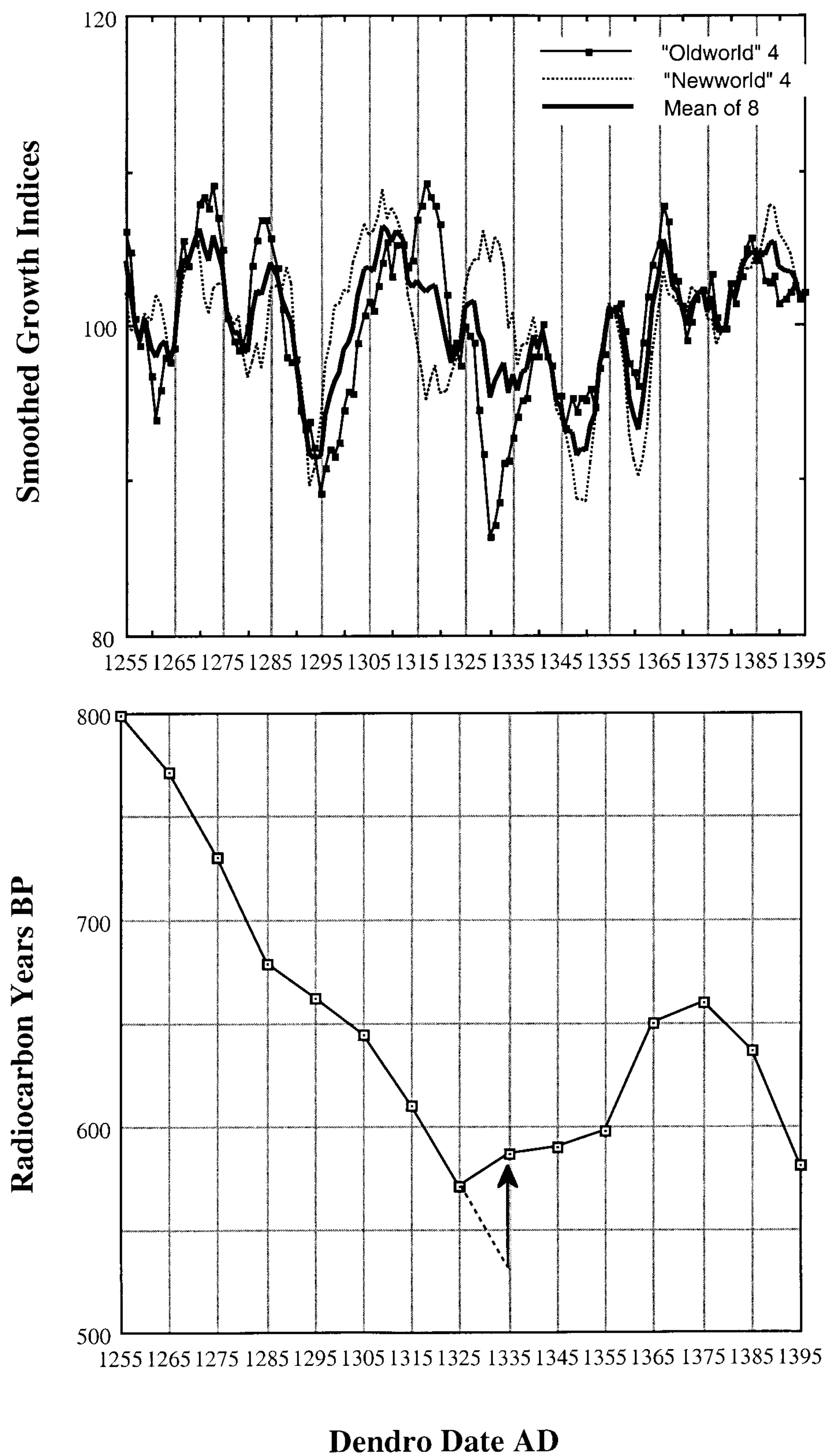


Figure 1. Index chronologies for Irish oak (thin line) and English oak (dotted line). Showing an episode of opposite growth trend in the AD 880s. The thick line is the mean of the Irish and English chronologies that serves to highlight the differences between the regional curves.

regimes. Moreover, the disagreement is not just with England but with a wider European chronology. So marked are the differences that it must be surmised that some environmental zone boundary has shifted between the two areas. Such observations should allow further interrogation of existing historical records and other tree-ring records in search of related evidence. It is worth noting that, even though we

▶

Figure 2. a) 5-point smoothed "Old-World" (thin solid line) and "New-World" chronologies (dotted) with overall "Global" chronology in bold. The former comprising data from the Polar Urals; Fennoscandia; European Oak and an Aegean average chronology; the latter comprising chronologies from North and South American, New Zealand and Tasmania(see acknowledgements). There is clear evidence for opposite response between AD 1313 and 1335 with surprisingly good agreement for the following 60 years.
b) A simplified version of the well replicated radiocarbon calibration curve across the same period showing the switch from radiocarbon enrichment to dilution following AD 1325 (the dotted line is to indicate what might have happened had the enrichment continued and to highlight the change to dilution). These two figures suggest an ocean-related component to the observed variations in both tree-rings and radiocarbon.


120
100
80
Smoothed Growth Indices
"Oldworld" 4
"Newworld" 4
Mean of 8
1255 1265 1275 1285 1295 1305 1315 1325 1335 1345 1355 1365 1375 1385 1395
800
700
600
500
Radiocarbon Years BP
1255 1265 1275 1285 1295 1305 1315 1325 1335 1345 1355 1365 1375 1385 1395
Dendro Date AD

cannot be sure of the actual 'instrumental' conditions we can describe the observed differences in word pictures – something which should be useful to archaeological colleagues.

On a larger scale it is now possible to produce large scale mean master chronologies for regions or even hemispheres. I say this as an avowed 'lumper' – my attitude is not to ask questions of small areas or individual trees, but rather to lump together as many records as possible to search for hints of larger 'pictures'. With the generosity of a wide range of colleagues who have provided data for comparison, I have been able to look at what seem to be hints of global patterning. Figure 2 a illustrates the mean of four smoothed chronologies from the Old World, (the four are a chronology from the Polar Urals, one for Fennoscandia, one representing the mean of all European oak, and a mean of three Aegean chronologies; see acknowledgments). For comparison a "New World" smoothed mean chronology has also been produced for four areas outside the Old World. This New World chronology is biased towards the Southern Hemisphere (the four chronologies are one for the mean of nine bristlecone pine chronologies; one for the mean of two South American chronologies, one from New Zealand and one from Tasmania).

What is surprising about this figure is that it shows broadly similar global tree-ring response from AD 1250 until the start of the second decade of the fourteenth century, then, the two curves diverge very noticeably, showing opposite responses until around AD 1340; thereafter, until AD 1400 they behave in an extraordinarily coherent manner. This sort of behavior is not what most dendrochronologists would have anticipated – why should tree-growth be in any way similar between the hemispheres? The answer must be that when it comes to macro-growth patterns (where our eight chronologies are a proxy for all the temperate trees in the world) the trees are responding to global forcing (it seems that there is a good deal of common growth signal between the two hemispheres provided that smoothed chronologies are used, i. e. it may be a mistake to try to understand tree growth at annual resolution!). It is this 'common-response' concept which makes the observation of the *opposite* response between roughly 1310–1340 so interesting. What else was going on? This is where a multi-proxy approach serves to lend some colour to the story. If we turn to some of the work reported in the American Southwest, we find that Arroyo Hondo was established about 1300. Rose et al. (1981) report that rainfall remained above the long term average for the first 35 years of the fourteenth century, with the consequence that:

"*... the pueblo grew to nearly a hundred times its original size in the first three decades of the 1300s ... (however) ... about AD 1335 the pattern of precipitation shifted towards high annual variability with severe droughts separated by brief wet intervals ... soon after 1335 the town's population began to decline ... by about 1345 the pueblo was virtually abandoned ...*".

So we know that this was an interesting period from a climate point of view, something borne out by the horrendous wet episode in Northern Europe in the teens of the fourteenth century. However, there are other proxies that can be interrogated. For example, there are replicated radiocarbon calibrations being carried out simultaneously on northern hemisphere (English and Irish oak) and southern hemisphere (New Zealand cedar) wood of identical age, making it possible to see changing inter-hemispheric radiocarbon offsets through time (McCormac et al. 1998). This work builds upon and refines the original Pearson and Stuiver high-precision calibration work. In Figure 2 b, for simplicity, I have plotted a replicated oak calibration across the period 1250–1400 to parallel the global chronologies in Figure 2 a. What we see is that after a long period of radiocarbon enrichment (where the radiocarbon age is decreasing faster than calendar age – in the 70 years from AD 1255–1325 radiocarbon age decreases from 800 BP to 570 BP), the trend suddenly reverses (I have highlighted this by dotting in what the calibration curve might have been expected to do between 1325 and 1335 compared with what actually happened). So, at a time when sites are being abandoned in the American Southwest because of drought, in the run-up to the Black Death of the 1340s in Europe, when we see notable opposite response in provisional global tree-ring records, we also see a highly defined change in the amount of radioactive carbon in the atmosphere. These changes simply must relate in some way to changes in ocean circulation, and all such information must ultimately have archaeological/historical implications. This ability to pull together precisely-dated records from tree-ring chronologies, from tree-ring dating for archaeologists and from dendro-based radiocarbon calibration must be one of the directions for dendrochronology and archaeology in the future.

Such information is, of course, in addition to the instrumental style environmental reconstructions being undertaken across whole transects of the northern hemisphere; the very work which has been underpinned by the activities of Fritz Schweingruber and has led to a well-defined picture of such things as the effects of volcanoes on high altitude/high latitude conifers in recent centuries (Briffa et al. 1998). Thus, the opportunities for dendrochronology, in its widest sense, to add to the picture of human history in the last millennium seem considerable.

Is there a global tree-ring signal?

Before leaving this idea of hemispheric or global chronologies, let us consider the question 'is there a global tree-ring signal?'. To attempt to answer this question I took the eight smoothed world chronologies listed above and produced an overall mean 'world' chronology. I then took the turning points in the resultant chronology and plotted them in Figure 3. I did this using different approaches to equalizing the base chronologies and the two plots in Figure 3 represent the two attempts; as can be seen they are almost identical, implying a relatively stable signal of some sort. According to Figure 3 the answer

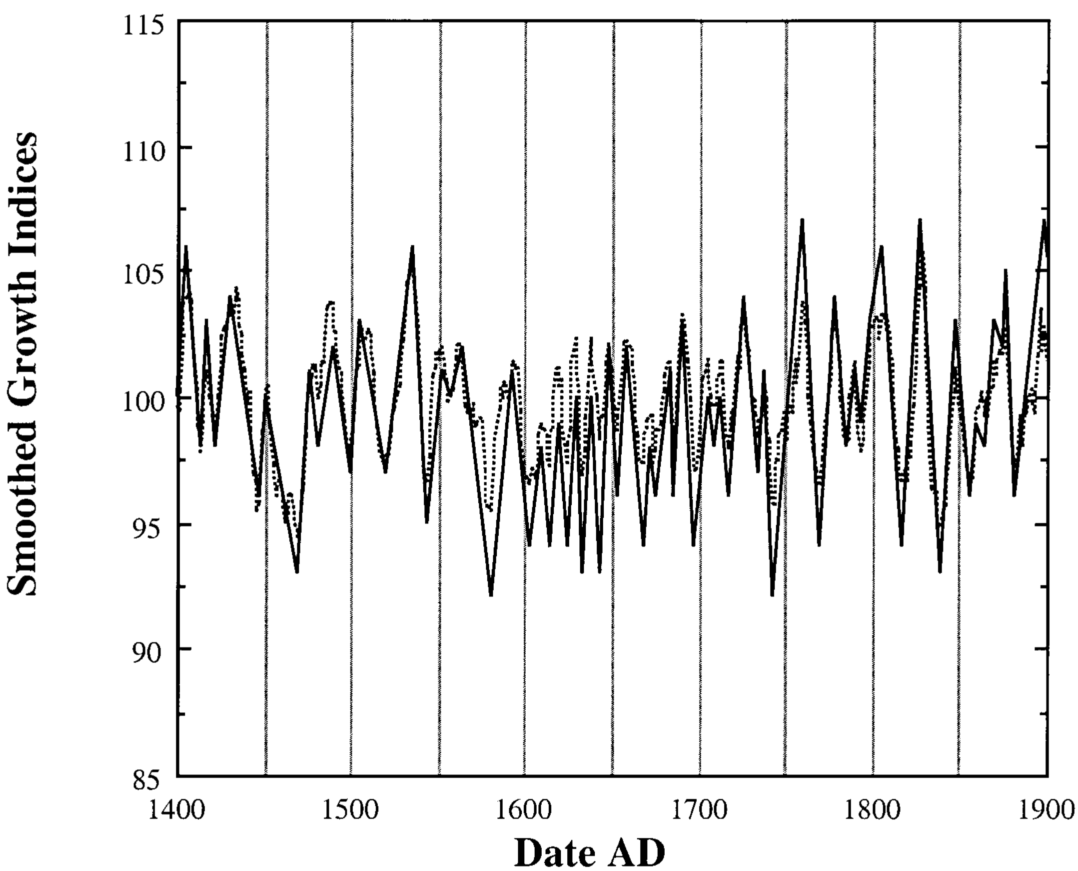


Figure 3. The "Global" chronology from Fig. 2 a for the period AD 1400–1900 reduced to its simplest turning points showing clear "cyclic" character (dotted curve shows an earlier attempt at producing the same figure; all the main elements are preserved). The character of the curve shows a notable change at AD 1600 with a higher frequency apparent for over a century afterwards.

to our question is 'yes, there is a global signal' and it changes through time in interesting ways. The most notable feature is that the large scale 'cycling' up to AD 1600, with some eleven peaks and troughs in 200 years, is replaced abruptly with a cycle closer to eleven peaks and troughs in 120 years. Thereafter, a longer period cycling re-establishes itself.

Of course, the year AD 1600 is not an arbitrary date, and the fact that a global tree-ring signal changes in character just at that time is probably no coincidence. Numerous writers have pointed out the dust-veil event of 1600/1601 and its consequences in tree-ring chronologies (Briffa et al. 1992, 1998). In the case of the Fennoscandian temperature reconstruction, Briffa et al. (1998) recognized 1601 as the coldest growth season in some 1500 years. The volcano at least partially responsible was Huaynaputina in Peru, though others may have been involved. What seems clear is that the event appears to have triggered a change in global tree-ring signal, something not suspected before Figure 3 was plotted. So, it looks as though large scale lumping of tree-ring data can produce some interesting hints of macro climate changes. What the implications of the circa 1600 changes are for the stability of climate reconstructions from tree-rings remain to be seen. If, for example, there are 'system shifts' in global climate then some long term reconstructions may be called into question as the assumptions underpinning the calibration process may be unreliable.

The first millennium AD and the later first millennium BC

Turning further back in time, the problems are somewhat different. Obviously dendrochronology can provide an enhanced dating environment wherever it is applied. It can also provide further environmental evidence, not least in terms of global events as exemplified by the common response of chronologies to the happenings around AD 540 (Baillie 1995, 1999a). However, the poorer chronological record provided by history/archaeology in earlier time periods opens up different opportunities. I consulted Ian Tyers and Cathy Groves on this issue and they felt, based on experience in Sheffield and London, that there were three broad areas of interplay between dendrochronology and archaeology as we move back through the first millennium.

i) There are situations where the results of dendrochronological analysis can confirm history/archaeology; when, for example, an established felling date coincides exactly with conventional or accepted wisdom. If an early Roman site known to have been constructed in AD 60 yields timbers felled in AD 60, Occham's razor suggests that the one date confirms the other (more complex solutions are possible but basically perverse).

ii) There are situations where definitive felling dates make it clear that the prior information which has come down to us is flawed in some way; for example, when the dendro dates for timbers from Roman Carlisle are found to be consistently earlier than the 'traditional' date of the fort (Hillam 1992). Similarly, Anne Crone has demonstrated that at the Buiston crannog in Scotland the real (i. e. dendro) dates for building activity in the late sixth and early seventh centuries are later and more compressed than previous radiocarbon analysis had suggested (Crone 2000). In this case the poor performance of radiocarbon dating was mostly due to the unfortunate shape of the radiocarbon calibration curve across the period in question, but, according to the author, may also be due to other factors which are still to be reported upon.

iii) The most common situation is where prior historical or archaeological information is either vague or non existent; here dendrochronology can provide completely new, and sometimes unexpected, dates. A classic Irish example is the AD 148 BC date for the Corlea bog roadway; a roadway which had initially been loosely assigned to the 'Bronze Age' by archaeologists (Baillie 1995). This huge construction, involving contiguous split oak trunks lying across longitudinal rails, extends for kilometers. The importance of dendrochronology is the recognition that almost identical roadways were being constructed in Germany within just a few years (Raftery 1996). Such observations have serious implications for understanding social conditions and contacts in early prehistory.

Prehistory

It is in prehistory that dendrochronology is set to make some of the most dramatic headway. Whereas twenty years ago there were almost no precise prehistoric dates, the completion of the oak chronologies means that, for Europe, we can expect a continuous stream of dates to be injected into archaeology. Already there are fifty prehistoric tree-ring dates for Ireland and others in England to complement the large numbers of dates becoming available in Europe. It is easy to see that we will soon be able to paint broad geographical pictures of human building activity in tight time control. Even preliminary examination of the available data implies a strong hint of environmental control on building activity (see below). It is to be hoped that the work in the Eastern Mediterranean can soon convert the currently floating chronologies into absolutely dated chronologies to allow further real time comparisons (Kuniholm et al. 1996, Manning et al. 2001).

One problem is that archaeologists are largely unaware of just how profound some of the developing examples are destined to be. This is partly due to the fact that relevant information has only recently been accumulating in the hands of dendrochronologists; much is not yet in print. Here are some observations on what is about to happen. Whole clusters of dates are becoming available, but, more importantly, dendrochronologists have the opportunity to make comparisons between the straightforward archaeological dates and information from the tree-ring chronologies themselves. I have previously pointed out the close juxtaposition between environmental indications of an event at 2911 BC in Ireland and a building pause in central Europe to within a year (Baillie 1999b). Alternatively we could take the case of the developing story around 1627 BC, the date first pointed out by LaMarche, Hirschboeck (1984) as a severe frost ring in bristlecone pine. To that can now be added the Irish 'narrowest ring event' (Baillie, Munro 1988), the possible Anatolian growth anomaly (Kuniholm et al. 1996) [though see below], the Fennoscandian growth downturn now identified around the same date (Grudd et al. 2000); we probably shouldn't rule out the rather strange coincidence that the longest Fitzroya chronology just happens to start around 1630 BC (Lara, Villalba 1993). The important point about this event is that it is becoming apparent in different records – indeed, I called it a 'marker date' back in 1991. I'll quote the main point because it is relevant to this current discussion:

"Certain dates, derived ultimately from tree-ring studies, by their very nature seem likely to occur and recur in the archaeological record. These can be entitled 'marker dates': dates which archaeologists should note carefully, since they may well have an existence in the evidence of archaeology" (Baillie 1991).

The question is, did the archaeological world take any notice? Precious little.

From an archaeological viewpoint, whether archaeologists are ready for it or not, the occurrence of this package of information, fixed in time (however we define it) around 1627 BC, means that all relevant archaeology will inevitably have to fit itself around this date. Put bluntly, well-dated sites can be discussed in relation to this event, poorly dated sites cannot. Archaeologists will have to decide if they want their sites to be part of the bigger picture represented here or to merely add period colour. Such decisions have implications for which sites are excavated, how sites are excavated, what is dated, and the proportion of resource devoted to chronology as opposed, say, to artifact conservation.

Overall, the logic of this situation should be the development of pressure on the archaeological community to concentrate their resources on sites which offer the potential for refined dating; to select sites and apply resources to finding out the true age of human activity. The contribution of dendrochronologists should be to provide a much clearer chronological and environmental framework, which is actually useful to archaeologists.

Why this obsession with dating archaeological sites? The simple answer is that we need some measure of human response to the environmental changes as observed in the tree-ring, and other proxy environmental, records. The much publicized environmental downturn (catastrophe?) around AD 540 serves as an excellent example. The event was observed first in Irish trees and then in chronologies from Siberia to Chile. Once it had been ascertained from the tree-ring chronologies that we were looking at the symptoms of a global event, it was noted that detailed dating of archaeological sites in Europe and in the American Southwest both showed a dramatic increase in the number of dated sites immediately after the environmental event (Baillie 1995, fig 6.6, page 100). Thus the environmental event seems to have been a trigger for an observed wide-scale change in the archaeological record – it produced, for whatever reason, a human building response (or an increase in the survival of datable timbers). This is an existing example of what will eventually be possible on a wider scale.

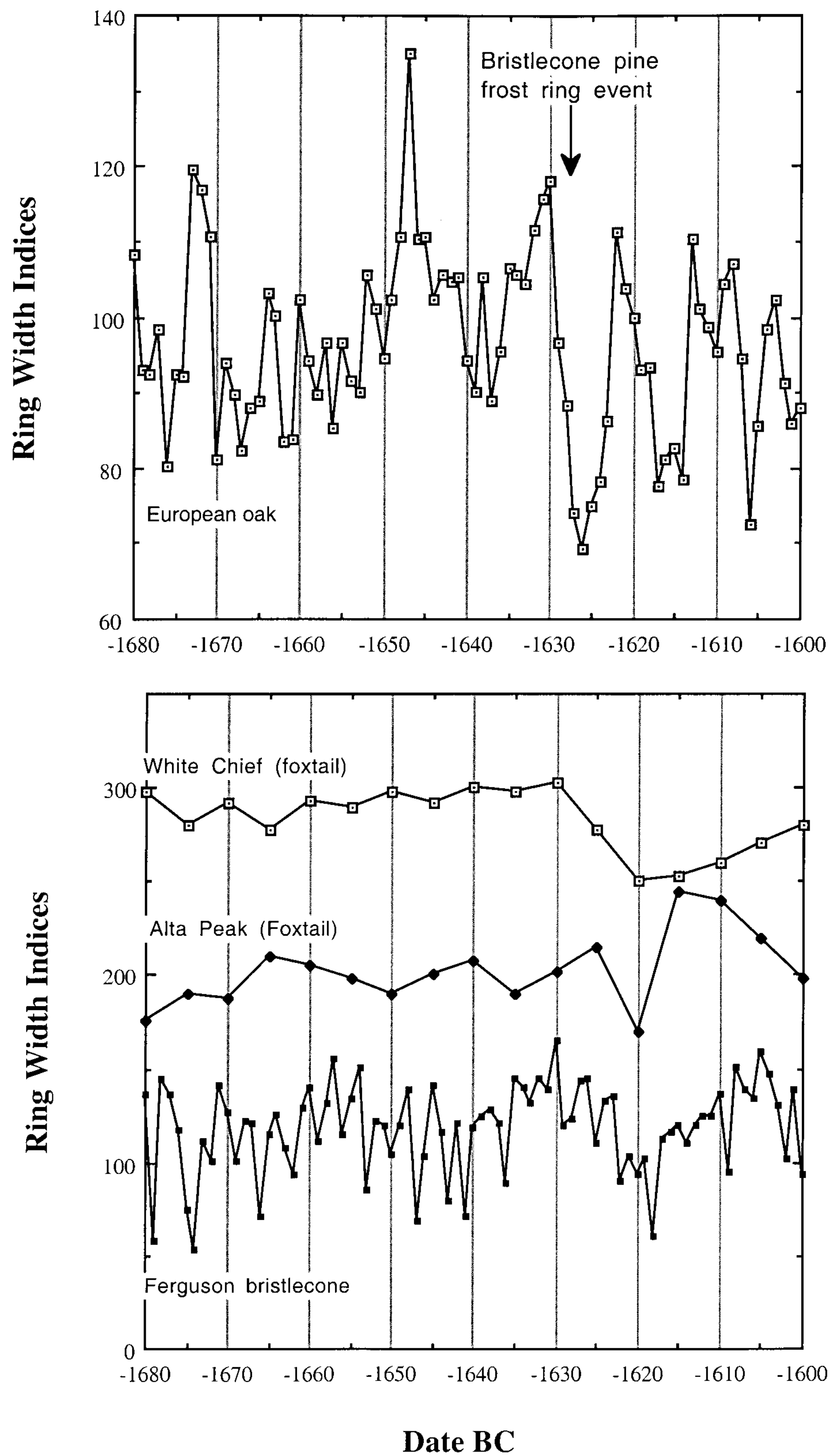
Here it is necessary to return to the 1628/1627 BC environmental event. In the first draft of this paper I noted the anomaly in the Anatolian chronology which had been suggested as coinciding with the 1628/1627 BC events in the oak and bristlecone pine chronologies. It now transpires that in a revision of the dating of the Anatolian floating chronology (Manning et al. 2001) this anomaly has been moved to the 1640s and, as the trees were growing downwind of the Santorini eruption, it has been proposed that the date of the eruption be moved from the previously suggested 1628 BC date to a date in the 1640s. Now, this is an extremely interesting issue for the following reasons.

If we imagine that Manning et al. (2001) are, in fact, correct and that the eruption no longer has anything to do with the 1628/1627 environmental event (it must be environmental because it affected tree growth in Europe and America, and it has not moved) then we can deduce several things and speculate on several others. First, now that Claus Hammer (2000) claims to have found Santorini tephra in the GRIP core at a date of 1645 (as deduced from the Dye3 record (Hammer et al. 1987)) it appears that the unreplicated Dye3 ice core is being claimed to have been essentially calendrically exact back as far as 3600 years ago – an astounding, and unprecedented, feat. Second, if Santorini really did erupt in the 1640s, as now claimed, it leaves the environmental effects in the 1620s without an obvious cause. This is interesting because moving the Santorini eruption does not move the environmental event which stays in the 1620s. Figure 4 a shows a mean European oak chronology (mean of eight separate chronologies) across the century. The event in the 1620s is profound. This is backed up in Figure 4 b wherein American foxtail (Caprio, Baisan 1992) and bristlecone pine (Ferguson 1969) chronologies are plotted on the same time scale. From this combined figure it is clear that Santorini (if it erupted in the 1640s) had no discernable environmental effect in these widely dispersed chronologies. This of course leaves us with an interesting proposition. If the biggest (the event at 1645 BC in Dye3 and at 1636 BC in GRIP is by far the largest acid signal in the century), and presumably the most environmentally effective, eruption around this time had no significant environmental effect, then what does this tell us about volcanic hazards?

If this truly were the case, then humans would no longer have to worry about anything other than the rare and massive super-volcanoes. Large explosive eruptions in the 30 to 50 cubic kilometer range, such as Santorini or Tambora (1815) could be relegated to largely local hazards. Again, if this truly were the case we would be left wondering about the actual causes of the events such as those at AD 540 and 1628 BC. This is the most interesting twist of all. Elsewhere (Baillie 1999a, 2001), I have argued that all the main tree-ring downturns originally identified by Baillie, Munro (1988), namely 2345 BC, 1628 BC, 1159 BC, 207 BC and AD 540, seemed to have some comet associations. Of the list the one

▶

Figure 4. a) Mean of eight European oak chronologies showing the notable decline in growth after 1630 BC; the original bristlecone pine frost ring of 1627 BC is indicated by an arrow. b) Two foxtail pine chronologies and one bristlecone pine chronology from the western United States all showing a decline in growth by 1620 BC. If Santorini did not erupt in or around 1628 BC, as has now been suggested by Manning et al. (2001), then the widespread environmental effects in the period after 1630 BC require an explanation.


140
120
100
80
60
Ring Width Indices
Bristlecone pine
frost ring event
European oak
-1680
-1670
-1660
-1650
-1640
-1630
-1620
-1610
-1600
White Chief (foxtail)
Alta Peak (Foxtail)
Ferguson bristlecone
300
200
100
0
Ring Width Indices
-1680
-1670
-1660
-1650
-1640
-1630
-1620
-1610
-1600
Date BC

event which *seemed* definitely to be volcano-related was the 1628 BC Santorini event. Now with the suggestion that Santorini actually erupted in the 1640s, with little effect, the 1620s BC event is freed up to have been caused by an extraterrestrial vector, like the others (or by some hitherto unsuspected type of environmentally effective volcano).

I think it is fair to say that this issue is of the most profound importance. If a volcano such as Santorini can either cause a global environmental event (if we imagine it erupting in 1628 BC) or have little effect (if we imagine it erupting in the 1640s BC), we need to know which is correct. We need to know not just in order to be able to gauge the effects of sizeable volcanic eruptions, but so that we can be sure whether or not we are correctly assessing extraterrestrial hazards. The obvious importance of precise chronology in such circumstances is self evident – we know dendrochronology can provide such a chronology, the ice cores are still not convincingly replicated or absolutely dated, and the ice-core workers still have to prove themselves on this issue.

Conclusion

I don't think this is the place to discuss improvement in dendrochronological technique. By and large we're getting there with the existing techniques. The need for research into improved dating – other species, short ring patterns, whatever – is not a high priority in comparison with some of the bigger issues mentioned above (such as safeguarding world class archives of environmental samples or understanding volcanological and extraterrestrial hazards). Neither is it the place to discuss whether we need single year radiocarbon calibration curves, nor whether trace element or stable isotope records should be derived for every area. What we need, archaeologically, for the foreseeable future, is an integration of dendrochronology with history and archaeology, and indeed with proxies of all kinds – a truly interdisciplinary approach. Let us go back, once more, to the event around 1627 BC, discussed above. One of the few relevant pieces of discussion came from Buckland et al. (1997) where it was suggested that such events were no more than 'myths' – basically artificial creations. While that certainly is a defensible point of view, what was not acceptable was the authors' misrepresentation of LaMarche, Hirschboeck's frost ring record with respect to volcanic activity (see Baillie 1998 for a detailed reply). What this skirmish suggested was just how little integration there is of the archaeological and dendrochronological worlds. Why might this be?

Well, I suspect that it goes back to a fundamental issue which affects the fields of history and archaeology. These disciplines have firmly rejected the concept of environmental determinism – the idea that the environment can drive human affairs. Environmental scientists, including dendrochronologists, are probably much more open minded on this issue. After all, we know how difficult it is to work out what actually happened in the past. We also know that the trees record (or give us information about) extreme events, be they droughts (Stahle et al. 1998) or tsunami (Yamaguchi et al. 1997), frost events (LaMarche, Hirschboeck 1984) or postulated global catastrophes (Baillie 1999a). It seems to me that it is up to us to convince the archaeological world that what we have is worth knowing about, and relevant. The way to do this is to bring together a lot more of the information we have available to us and confidently provide global pictures. When something shows up at AD 540 in Irish oaks it can be disregarded as 'local', just as LaMarche, Hirschboeck's 1627 BC frost event was dismissed by Warren (1984) and contested by Buckland et al. (1997). But we now know that AD 540 was a global event present in records everywhere – a classic 'marker date' – and it can no longer be ignored. The dendrochronological community will start to make real inroads when they show that, as I indicated above, the droughts that affected the Anasazi in the American Southwest were part of global environmental alterations which also affected populations in Europe and China.

To give one final example, the next Irish oak "narrowest ring" event back in time before 2345 BC was at 3195 BC, where more than one third of all available trees showed their narrowest rings in the range 3197–3190 – obviously a very bad set of conditions for Irish oaks by any standard. Figure 5

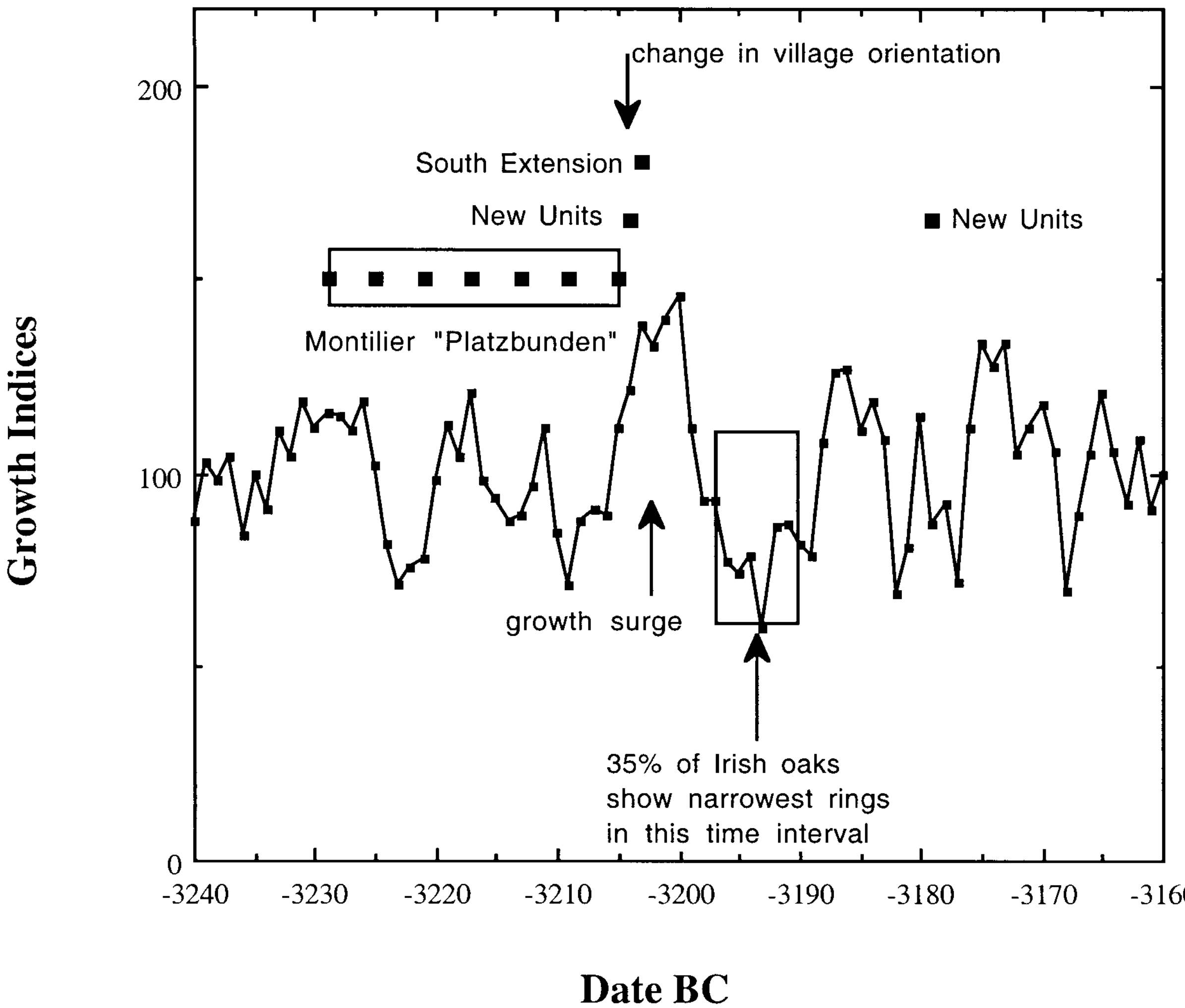


Figure 5. Accumulating information on the events around 3200 BC include a 'narrowest ring event' in Irish oak with a precursory growth surge and a pause in building at Montilier, Switzerland, associated with a change in village orientation which could indicate a change in prevailing wind direction. When combined with other hints of ocean-related change around the same time (see text) this would appear to be a large-scale event of potential interest to archaeologists.

shows the Irish chronology together with evidence for a building pause in a Swiss lake-side settlement. Tercier et al. (1996) reported a change in village orientation at Montilier "Platzbunden" in the years just before a building pause from 3202–3187 BC. What is interesting here is that archaeological opinion suggests that a change of orientation is most likely associated with a change in prevailing wind direction. That in turn suggests a possible change in atmospheric circulation which in turn could be associated with something happening with ocean circulation. Interestingly hints of changes in sea level had already been deduced from the strange coincidence of oak chronologies starting just around 3200 BC in the low-lying areas of both eastern and western England (Baillie 1995). That suggestion is reflected in the observation of high sulphate in the Greenland GISP2 ice core between 3200–3100 BC, which Zielinski et al. (1994) interpreted as probably due to deposition of biogenic sulphate from open water in the permanent sea ice off the Greenland coast. Once again we see that the accumulation of evidence from different proxies spells out potentially important environmental stories of direct relevance to archaeologists, not least in this case because of a transition in the archaeological record in the British Isles around 3200 BC.

In fact, when we, the dendrochronologists, provide decade by decade, century by century pictures of what trees thought of their growth conditions, over as large a geographical range as possible, in conjunction with information from other proxies, back to about 4000 BC, we will have sorted out the future research needs of dendrochronology as it relates to archaeology.

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