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DENDROCHRONOLOGY: A REVIEW WITH EMPHASIS ON NEW ZEALAND APPLICATIONS

Summary: The distinction is drawn in this paper between true dendrochronological studies (using crossdating) and studies using tree-ring counts to age trees or date events. The advantages of the former approach are emphasized. We summarize the main methods used in dendrochronology, concentrating on new approaches and techniques important in the New Zealand context, present a review of recent dendrochronological research in New Zealand, and finally discuss applications of dendrochronology relevant to New Zealand.

Keywords: Dendrochronology; tree-rings; palaeoclimate reconstruction; forest history; New Zealand.

Introduction

The study of sequences of annual growth rings in trees is called dendrochronology. Although many aspects of dendrochronology have been dealt with in various texts, notably Fritts (1976), no overview in a New Zealand context is available. We attempt to remedy this deficiency here.

In discussing studies using annual tree growth-rings it is necessary to distinguish between those studies that use strict dendrochronological techniques such as crossdating, and those that simply use ring counts to age trees or date events. Strict dendrochronological techniques offer much to ecologists, as they provide an absolute chronological basis for tree-ring dates. In this review we have concentrated on studies that have used the strict dendrochronological approach, but we also discuss other applications of tree-ring measurements, as we believe that they can benefit from a more precise dendrochronological approach.

Methodology of Dendrochronology

The basic methodology of dendrochronology has been reviewed by Stokes and Smiley (1968), Fritts (1976) and Schweingruber (1983), and in the various papers in Hughes *et a1*. (1982). A brief overview of the methodology is presented, emphasizing those aspects we feel are important in the New Zealand context or where new developments warrant more detail. Computer programs are available from the authors for some of the statistical analyses described.

Three methodological steps are common to most dendrochronological studies: collection and preparation of samples; crossdating and measurement; and chronology building. Two important applications of dendrochronology are in growth-climate relations and forest history. The methodology involved in these is also briefly discussed.

Sample collection and preparation

Tree growth, and hence ring-width, is dependent on a range of environmental and biological factors (e.g. climate, soils, competition, browsing). Careful site and tree selection is necessary to ensure that specific influences can be studied. The failure to achieve convincing crossdating, leading to a lack of success in early New Zealand dendrochronological studies, was probably due to inappropriate site selection (e.g. Bell and Bell, 1958; Cameron, 1960; Scott, 1964, 1972). However, a site that is suitable for studying one factor may not be suitable for a second. For example, if the purpose of the study is to examine the relationships between ring-width and temperature, trees growing at sites near the alpine timberline are sampled. However, subalpine sites are unlikely to be suitable for investigating relationships between seed production and growth, as temperature effects are likely to mask any seed effects.

In North America, long tree-ring records suitable for reconstructing past climate have been developed from trees growing at the limits of their distribution. Such trees (e.g. *Pinus aristata)* are often very old and gnarled. In New Zealand, however, tall, straight boled, dominant canopy trees have proved the most suitable for chronology construction (Norton, 1983b, c; Ahmed and Ogden, 1985), although in some cases (e.g. to study avalanche events) damaged trees, often of poor form, are likely to yield the most information.

Field sampling is undertaken either by extracting increment cores or by felling the tree. Coring procedures are described in detail by Stokes and Smiley (1968) and Burrows and Burrows (1976). The number of trees sampled depends on the nature of the study; we have found 15 to 20 trees adequate for studying growth-climate relations. It is important that the sampled trees come from an homogenous site.

In most dendrochronological applications, absolute measures of ring-widths are not needed (c.r. mensuration of living trees) and samples are dried before further analysis. Cores are best air-dried rather than oven-dried, then glued into grooved wooden mounts with the transverse surface of the core upwards. Correct core orientation is essential if the growth rings are to be clearly seen. Although several North American authors recommend that cores be surfaced using a razor blade (e.g. Stokes and Smiley, 1968), we have found that with the narrow rings typical of many New Zealand trees, this makes ring identification difficult. In our experience, the best surface for counting and measuring the growth rings is obtained by sanding the cores and discs with successively finer grades of sand paper using an orbital sander. Staining of wood has not been found necessary with the species we have examined but procedures for this are outlined in Burrows and Burrows (1976).

Crossdating and measurement

"Crossdating is the most important principle of dendrochronology" (Fritts, 1976). Crossdating involves matching of similar ring-width patterns between different trees and is possible because the same or similar factors are limiting growth of several trees at a site in a similar way. As this limiting factor varies from year to year, so too does ring-width.

In some years growth rings may be absent or more than one ring formed (see below). Such anomalous rings place tree-ring sequences out of chronological order. These anomalous rings can, however, be identified by crossdating, as on one side of the anomaly the ring-width pattern will match with other trees while on the other side they will not. When these anomalous rings are recognized and taken into account, the ring-width series from several trees will match for their entire length (Fig. 1) thus providing an absolute time base for all tree-ring sequences.

A number of approaches to crossdating, both subjective and objective, have been described (Stokes and Smiley, 1968; Eckstein and Bauch, 1969; Huber and Giertz, 1970; Baillie and Pilcher, 1973; Wendland, 1975; Cropper, 1979; Munro, 1984). Although ring-width series can be crossdated objectively, using computer techniques, all matches must be inspected visually before accepting them as true. Furthermore these objective methods are only appropriate when the number of anomalous rings is small. Because of the large number of absent rings in many New Zealand tree-ring series and because of the need for visual

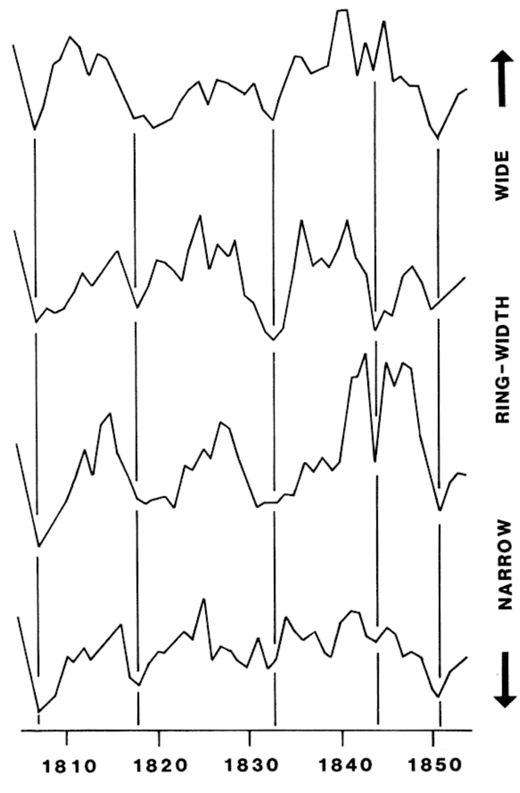

Figure 1: *Crossdating between four* Libocedrus bidwillii *trees from 1805-1855 AD. Distinctive narrow rings occurred in 1807-1809, 1818, 1833, 1844 and 1851 (Norton, unpubl.).*

checking, we have found that crossdating is best undertaken visually. The statistical degree of similarity is assessed later.

Microcomputer-based measuring systems (Robinson and Evans, 1980) are widely used for measuring ring-width; measurement is from the latewood-earlywood boundary and is undertaken after crossdating. Ring-width is not the only growth ring variable that can be measured. The size and number of different cell types and the elemental concentrations in the wood of different growth rings have been used (e.g. Hill, 1982; Eckstein and Frisse, 1982; Stuiver, Burk and Quay, 1984; Berish and Ragsdale, 1985). However';'the most commonly measured attribute of growth rings after width is density, especially latewood density (Polge, 1970; Schweingruber, 1982). Latewood density has been shown to be better related to growing season climate than ring-width (Schweingruber *et al.,* 1978). The only New Zealand use of ring density that we are aware of has been with *Pinus radiata* (e.g. Cown and Kibblewhite, 1980).

Because the growing season in the Southern Hemisphere spans two calendar years, the convention used is to date a growth ring by the year in which growth started. Thus, a growth ring that was laid down over the 1986-87 season is referred to as the 1986 growth ring.

Anomalous growth rings

In some years, environmental or biological conditions are such that tree growth is severely reduced, with radial growth localized to certain radii, or not occurring at all. These rings are said to be 'partial', 'locally absent' or 'missing' (Fritts, 1976). Missing rings appear to occur for two reasons (Norton, Palmer and Ogden, 1987). Firstly, during years in which photosynthesis is severely reduced, most radial growth is confined to the upper part of the bole with little growth in the lower bole (Farrar, 1961). For example, in *Nothofagus solandri* the percentage of missing rings is greatest closest to the ground (Norton, 1986). Secondly, missing rings occur because of ring wedging, where a single ring or a group of rings are absent around a portion of the circumference (e.g. Dunwiddie, 1979). This is thought to be a result of the development and death of major branches and consequent variations in food and growth regulator supplies (Fritts *et al.,* 1965).

Missing rings have been identified in a number of New Zealand tree species (Norton, Palmer and Ogden, 1987) and on single radii can be as high as 10% of the total number of rings present. Missing rings are potentially a serious problem in tree-ring studies but can be detected by crossdating.

A second type of anomalous growth ring occurs as a result of changes in cell structure during the course of the growing season causing the formation of a band of narrow cells resembling latewood and referred to as a 'false ring'. False rings occur when growing season conditions become temporarily severe (e.g. soil moisture deficits or low temperatures). When more favourable conditions resume, the subsequently formed cells are larger and have thinner walls. False rings are usually easily identified as there is a gradual transition in cell size on both margins of the band in contrast to the normal ring boundary, where there is a pronounced change in cell size. False rings have been observed in a number of New Zealand tree species. In Switzerland the occurrence of false rings in several conifer species has been related to the number of cold days during the growing season (Schweingruber, 1980).

A third type of anomalous growth ring occurs as a result of frost damage and can be common in subalpine trees (LaMarche, 1970). In affected rings, severe distortion of cells occurs. Frost rings have been identified in *Nothofagus solandri* (Norton, 1985), and are probably uncommon away from temperature caused timberlines. Frost rings, if sufficiently widespread in occurrence, can offer a useful crossdating parameter independent of ring width (Ogden, 1978).

Chronology development

Ring-widths often decrease with increasing tree age. This biological growth trend is usually independent of other factors influencing tree growth (e.g. climate) and it is often helpful to remove it by a curve-fitting procedure prior to further analysis (Fritts, 1976). In this 'standardization' procedure, the measured ring-widths are converted to ring-width indices by dividing each width by the expected growth derived from the fitted curve. Traditionally negative exponential and polynomial curves have been used for standardization (Fritts, 1976). However, several difficulties occur with these, including (a) the need to subjectively select a curve fitting procedure for each ring-width sequence, (b) curve distortion due to eccentric data points and (c) the tendency to 'overfit' curves to short ring-width series (Warren, 1980; Cook and Peters, 1981; Briffa, 1984). The most promising alternative involves the use of digital filters (Mitchell *et al.* 1966; Briffa, 1984). Filters have two advantages over exponential and polynomial curves for standardization. Firstly, the spectral properties of the filter can be precisely defined and secondly, their functioning is independent of the length of the time series.

The approach used by Briffa (1984) involves setting the weights in the filter proportional to the ordinates of a Gaussian probability curve. Because of the nature of the Gaussian distribution, it is possible to precisely define the variations removed by the filter, and by altering the number of weights in the filter, to change the amplitude of the variation retained after filtering. For example, a 30 year filter will pass 50% or less of the variance at wave lengths of 30 years or greater. By using this filtering technique it is possible to objectively standardize ring-width time-series, and

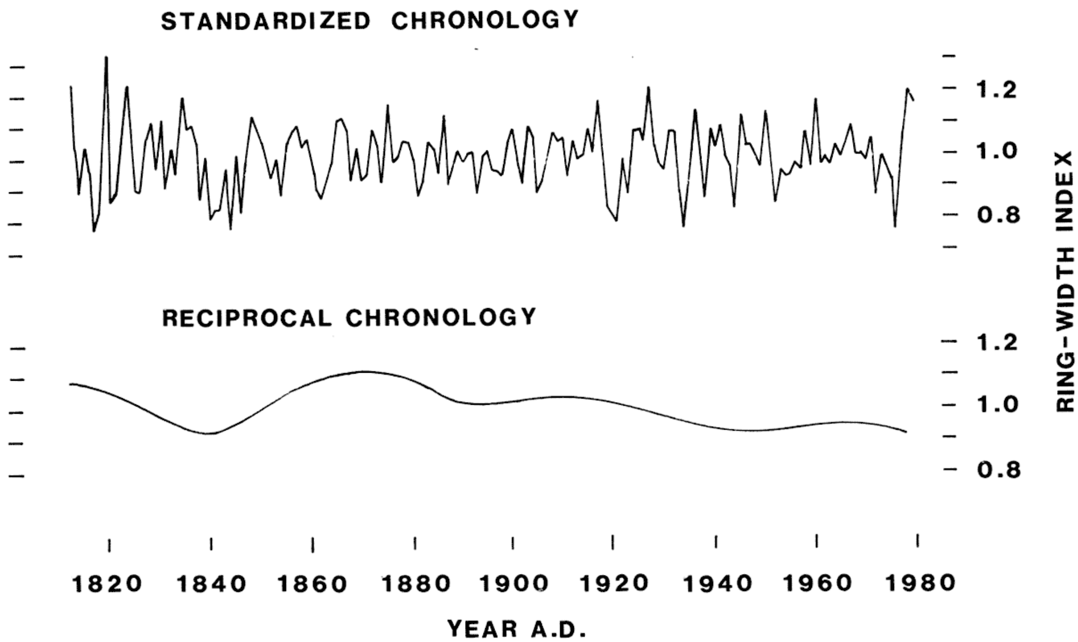

Figure 2: *The high frequency and low frequency components of the Radley Wood* Quercus *tree-ring chronology after standardization with a 30-year Gaussian filter (Briffa,* /984).

to define the spectral characteristics of the resultant indexed series. An additional advantage is that both parts of the filtered data can be used (Fig. 2). For climatic reconstruction, the high frequency variations are of most interest, so the residuals from the filtered series are used to develop the tree-ring chronology. However, in other applications, the low-frequency part might be of interest and can be used to produce 'reciprocal chronologies'.

Other approaches to standardization have been suggested but have not been widely used. In New Zealand, Bathgate (1981) has developed a standardization procedure that assumes that all trees have the same underlying, or 'universal', biological growth trend. This is determined by averaging ring-width sequences from large numbers of trees of different ages in such a way that rings of equivalent tree ages, rather than calendar dates, are matched (i.e. the growth rings in the first 50 years of a 500 year old tree are averaged together with the first 50 growth rings of a 100 year old tree). In this way, the age trend is isolated. This approach has not been widely used and has drawbacks. Firstly, it is not possible to quantify the nature of the variance removed during standardization and therefore it is difficult to judge the validity of any statistical comparisons with climate. Secondly, this procedure is inflexible in that it does not take into account trees with widely varying growth patterns.

Once the individual tree-ring time-series have been standardized they are averaged to form a tree-ring chronology, reducing growth variations unique to individual trees, while enhancing variations common to all trees. Tree-ring chronologies provide the main data set for most dendrochronological analyses. A number of statistics can be used to described the properties of tree-ring chronologies, the most important being mean sensitivity, first order autocorrelation, correlation coefficient, and subsample signal strength (Fritts, 1976; Wigley, Briffa and Jones, 1984a).

Mean sensitivity is a measure of the average absolute difference between two successive ring-width values divided by their mean value, and is a measure of the year-to-year variation in ring-width (related to standard deviation). Autocorrelation (or lag-one correlation) is a measure of the average dependence of ring-width in one year on that in the previous year. The correlation coefficient is used to determine the similarity of the individual ring-width series in a chronology.

The subsample signal strength statistic has been developed to determine the minimum number of time-series (n) that can be used to provide a reliable estimate of the mean chronology (N) (Wigley, Briffa and Jones, 1984a). This is an important, and often overlooked, question in dendrochronology, as with increasing chronology length there are usually fewer time-series in the chronology. This has important implications for reconstructing past climates because an n becomes smaller, the n-chronology and the N-chronology become less similar, and therefore the quality of any climate reconstruction based on the former must diminish.

Tree-ring/climate relationships

Much has been written about the techniques available for studying the relationships between tree-ring chronologies and climate. Details on both the philosophical basis and statistical techniques are given by Fritts (1976), Hughes *et al*. (1982) and Briffa *et al*. (1983). Climate analysis falls into two parts; response function analysis and transfer function analysis.

In response function analysis the main climatic factors influencing tree growth are identified. Correlation and principal-components multiple-regression techniques (Fritts, 1976; Guiot, Berger and Munaut, 1982; Blasing, Solomon and Duvick, 1984; Fritts and Xiangding, 1986) are commonly used to relate climate variables to tree-ring chronologies. In the regression approach, time-series of monthly climate data (often temperature and rainfall) are first subjected to principal-components analysis in order to remove inter-correlations within these data and the resulting orthogonal variables regressed against the tree-ring chronology. It has, however, been argued that the statistically more straightforward correlation coefficient provides a more easily interpreted approach to quantifying the growth-climate link (Blasing, Solomon and Duvick, 1984). However, spuriously inflated correlation coefficients can occur because of inter-correlated climate variables. An alternative to response function analysis has recently been proposed (Kienast and Schweingruber, 1986) involving analysis of the effect of various weather patterns on spatial growth patterns in particular years.

The rationale for using transfer function techniques has been discussed by Fritts (1976) and Webb and Clarke (1977). Fritts *et al*. (1971), Fritts, Lofgren and Gordon (1979), Lofgren and Hunt (1982) and Briffa *et al*. (1983) discuss aspects of its use. There are several approaches to transfer function analysis; commonly several tree-ring chronologies are regressed against recent climate data, using principal-components multiple-regression or canonical-correlation techniques, to calibrate the transfer function. Once the regression equation has been calculated ('calibration'), the transfer function is then tested on independent data ('verification') and finally applied to the tree-ring data for the period prior to instrumental records to estimate past climate.

Verification is necessary to establish the reliability of the calibration and is undertaken by splitting the instrumental data into two subsets; one for calibration and the other for verification. The regression coefficients calculated for the calibration period are applied to the tree-ring data for the independent verification period and estimates of climate obtained. These are then compared with observed climate for this period using correlation coefficients and the reduction of error statistic (RE; Fritts, 1976). RE is the more rigorous statistic as it accounts for the position of the calibration mean relative to the observed and estimated means.

Forest history

Tree-rings have been widely used for aging trees and dating specific events affecting tree growth. By using dendrochronological techniques such as crossdating, considerably more precision can be attached to dating. The main application of tree-rings in reconstructing forest history is event dating (Shroder, 1980; Schweingruber, 1983; Lorimer, 1985; Kienast and Schweingruber, 1986). Both biotic and abiotic events can affect tree growth, either directly by causing physical damage to the tree or growth ring (Fig. 3) or indirectly by affecting the physiological activity of the tree causing either reductions or increases in radial growth (Fig 4).

Normally, a large number of trees are sampled and the dates at which the event of interest (e.g. fire scars or growth releases) occurs noted. Crossdating between trees or with an existing chronology ensures that the dates are absolute (c.r. Madney, Swetnam and West, 1982). These dates are then combined to produce an event chronology which shows the number or percentage of trees affected in each year (Fig. 5). The accuracy of event chronologies declines further

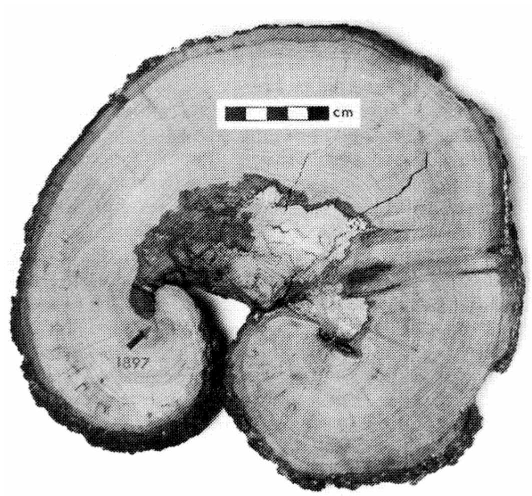

Figure 3: Nothofagus solandri *cross-section showing damage caused by rockfall, Purple Hill, Canterbury. Arrow indicates year in which damage occurred.*

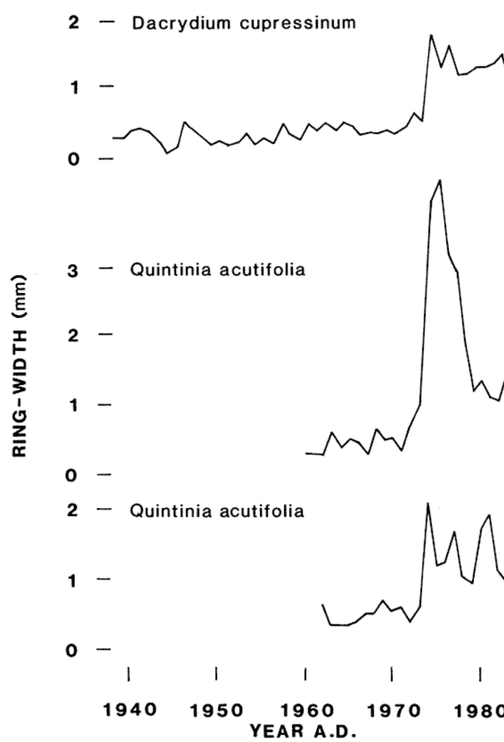

Figure 4: *Ring width plots for* Dacrydium cupressinum *and* Quintinia acutifolia *illustrating synchronous growth release in 1973 as a result of removal of surrounding trees by logging (Norton, unpubl.)*

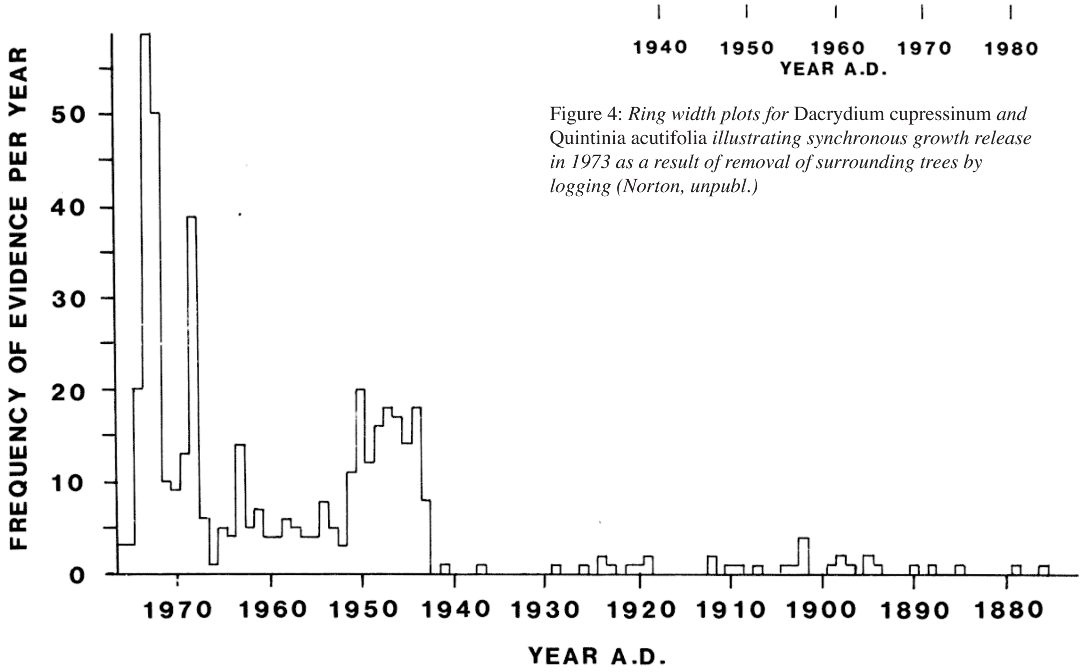

Figure 5: *A valanche damage event histogram from* Nothofagus solandri, *Craigieburn Valley, Canterbury (Conway, 1977).*

back in time as the number of trees sampled decreases.

Physical damage to growth rings (e.g. by fire or frost) is usually easy to identify, but caution is needed in interpreting abrupt changes in growth rates, especially in separating climatic and non-climatic changes. Lorimer (1985) has suggested that a minimum criterion for identifying non-climatic growth releases may be 15 years of rapid growth that average 50-100% greater than the previous 15 years. Similar criteria will be needed for defining other growth changes. Careful standardization removing high-frequency ring-width variation should assist in identifying such non-climatic growth changes.

A difficulty in extracting information on forest history from growth rings arises because several factors including climate influence ring-width. An approach to overcome this may be to first regress the tree-ring chronology against climate and then study the residual series. Such series should contain variations in growth independent of climate. Kienast (1982) used a similar approach to separate the influence of atmospheric pollution from climate in Switzerland.

Tree-ring counts are widely used in forest ecology for determining tree ages, primarily for studying tree population dynamics. Two main types of problem arise in using tree-ring counts in such studies: (a) difficulties in counting growth rings because of narrow ring-widths and missing rings; (b) estimation of tree age from increment cores which fail to reach the tree centre (partial cores). Further difficulties can occur in estimating the time taken to grow to sampling height and in estimating tree-ages based on age-diameter relationships. If these problems are not properly taken into account, tree age estimates, and the population age structures derived from them, may be considerably in error (Ogden, 1985b; Norton, Palmer and Ogden, 1987).

The New Zealand Dendrochronological Data Base

Considerable progress has been made in dendrochronological research since the earlier reviews of Dunwiddie (1979), Burrows and Greenland (1979) and Ogden (1982). The initial impetus for this recent work came when staff from the Tree-Ring Laboratory, University of Arizona, visited New Zealand in 1977 and 1978, and developed the first properly cross dated and replicated tree-ring chronologies (Dunwiddie, 1979; LaMarche *et al.*, 1979). Twenty one chronologies were developed from seven species *(Libocedrus bidwillii, Phyllocladus alpinus, P. trichomanoides, P. glaucus, Lagarostrobos colensoi, Halocarpus biformis,* and *Agathis australis).* However, no climatic analyses of these chronologies have been published. A further 13 species, including *Nothofagus* species, were also sampled but their ring-width series were not crossdated.

Subsequent research has seen an expansion in this chronology base. In the North Island a number of studies have been undertaken with *Agathis australis.* Palmer (1982) developed a chronology on Te Moehau and was also able to confirm the crossdating of the *A. australis* chronology developed by Dunwiddie (1979). A further eight chronologies from throughout the north of the North Island have been developed (Ahmed and Ogden, 1985) and relationships between ring-width and climate assessed (Ahmed, 1984).

In several areas of the northern part of the North Island, *Agathis australis* logs have been found buried in peat mires. Bridge and Ogden (1986) have crossdated some of these sub fossil logs and developed a 'floating chronology' (a chronology whose dating has not been fIXed to the present) which, based on radiocarbon dates, spans the period 3500-3000 years BP. A second floating chronology has recently been developed by J.G. Palmer (pers. comm.) using buried logs of *Phyllocladus trichomanoides.* As these trees were buried by the 1800 BP eruption of Lake Taupo, it is probable that the 400 year chronology spans the period 2200-1800 BP.

In the South Island, Norton (1983a,b,c, 1985) has developed 32 tree-ring chronologies from three species *(Libocedrus bidwillii, Nothofagus menziesii,* and *N. solandri).* These chronologies form the basis for the first dendroclimatological reconstructions of the past climates of New Zealand (see below). Variations in ring-width patterns within trees have also been investigated (Norton, 1986).

The locations of all crossdated New Zealand tree-ring chronologies are shown in Fig. 6 and chronology statistics summarized in Table I. In total, 64 modern and 2 sub fossil chronologies have been developed from 9 tree species.

Applications of Dendrochronology

In this final section we outline the main applications of dendrochronology applicable to New Zealand, citing local examples where possible and emphasizing ecological applications. We have included 'non-dendrochronological' tree-ring studies (i.e. those in

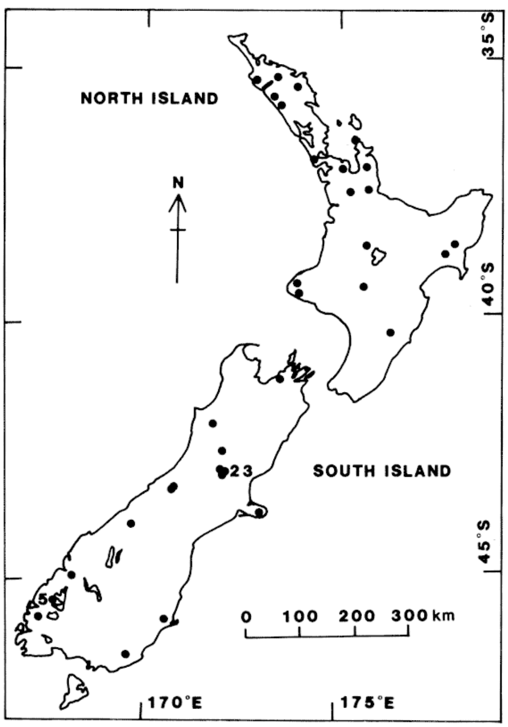

Figure 6: *Locations of New Zealand tree-ring chronology sites. At several sites more than one chronology has been developed.*

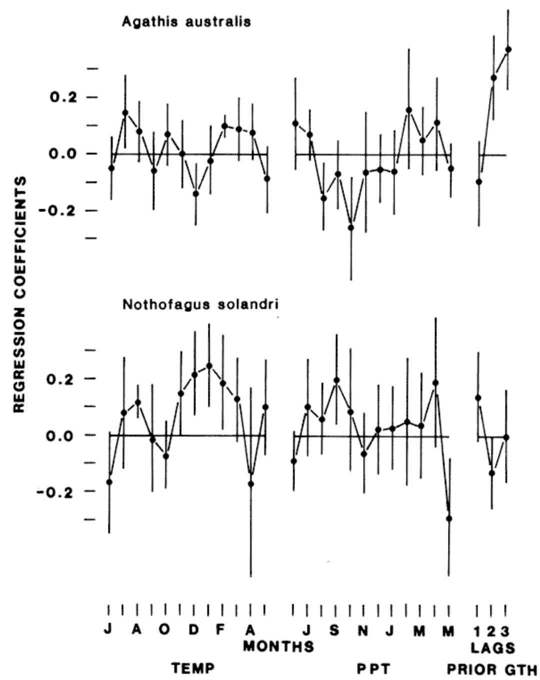

Figure 7: *Regression coefficients plotted for typical* Agathis australis *and* Nothofagus solandri *response functions. Regression coefficients relate tree-ring indices to monthly mean temperature and rainfall, calculated over a series of years (see p.* 81 *for methodology, also Ahmed (1984) and. Norton* (1984)). 95% *confidence limits are plotted for each coefficient; significant coefficients are those where the confidence limits are either both below or above the zero line. The analyses ran from June, before growth, to May, at the end of the growing season.*

which crossdating and other common dendrochronological techniques were not utilized) where appropriate, as we believe that adherence to strict dendrochronological techniques can overcome some of the difficulties associated with the use of tree growth-rings in ecology. For example, 'event dating' is concerned with identifying specific events affecting tree growth and building up a chronology of these events. Often the primary objective is to date the event, rather than to study its affect on tree growth. The use of crossdating can greatly improve the accuracy of dated events.

Climatic reconstruction

Response function analysis can be used to interpret the relationships between growth and climate (e.g. Schweingruber *et al.* 1978; LaMarche and Pittock, 1982; Kuivinen and Lawson, 1982; Pilcher and Gray, 1982). In New Zealand response functions have been calculated for *Agathis australis, Libocedrus bidwillii, Nothofagus menziesii* and *N. solandri* (Norton 1984, 1985, unpubl; Ahmed, 1984). Examples of response functions for *A. australis* and *N. solandri* (Fig. 7) illustrate their use.

In *Agathis australis* a negative association between spring (October) rainfall and growth is evident. If conditions at the start of the growing season are cloudy and damp, then the commencement of growth is delayed resulting in a narrower growth ring (Ahmed, 1984). A similar conclusion was reached

Table 1: *Synopsis of New Zealand tree-ring chronologies at time of publication. Sources* (1) *Ahmed and Ogden* (1985), (2) *Bridge and Ogden* (1986), (3) *Dunwiddie* (1979), (4) *Fowler* (1984), (5) *Norton (1983a,b,c,* 1985), (6) *Palmer* (1982). *Period, period covered by chronology. A.C., lag-one autocorrelation. M.S., mean sensitivity.* 070 *abs rings, percentage of absent rings. R, mean correlation between all radii in chronology.*

Code	No. trees/ radii	Period (A.D.)	A.C.	M.S.	% abs rings	R	Source
Agathis australis							
CASC	12139	1558-1982	0.31	0.35	N.A.	N.A.	4
KATI	7/15	1698-1981	0.26	0.29	0.12	0.27	1
KON239	11/33	1712-1976	0.00	0.21	0.68	0.26	3
KONP	20/44	1619-1980	0.56	0.22	0.04	N.A.	6
LTBR	14/23	1790-1981	0.37	0.23	0.09	0.35	1
MOEH	18/27	1707-1980	0.16	0.24	0.16	N.A.	6
MWIL	6/11	1580-1981	0.45	0.22	0.10	0.29	1
PUBL	8/20	1630-1982	0.23	0.31	0.43	0.40	1
PUKE	5/9	3500-3000BP	0.20	0.42	0.15	N.A.	2
PUKF	10/20	1700-1981	0.53	0.20	0.12	0.31	1
TROU	13/22	1630-1980	0.58	0.20	0.10	0.25	1
WAIT	8/15	1720-1981	0.04	0.33	0.03	0.36	1
WARA	16/30	1640-1979	0.19	0.29	0.44	0.27	1
Halocarpus biformis							
MAP229	7/25	1567-1976	0.75	0.10	0.15	0.20	3
Lagarostrobos colensoi							
AHA209	11/33	1403-1976	0.69	0.13	3.00	0.14	3
MWO209	10/36	1464-1976	0.54	0.12	0.10	0.20	3
Libocedrus bidwillii							
AHA189	10/32	1525-1976	0.17	0.16	0.28	0.31	3
ARM189	12/39	1450-1958	0.62	0.16	0.60	0.22	3
CRC601	15/25	1460-1978	0.71	0.16	0.21	0.30	5
CRG189	12138	1492-1975	0.75	0.16	0.00	0.38	3
EMT189	12142	1616-1975	0.50	0.16	0.03	0.27	3
MWO189	11 /28	1662-1976	0.87	0.12	0.00	0.40	3
NET189	14/53	1625-1976	0.58	0.15	0.00	0.29	3
OKA189	14/40	1732-1976	0.66	0.12	0.11	0.28	3
TKP189	14/37	1256-1976	0.79	0.14	0.77	0.31	3
TRK602	20/27	1526-1978	0.58	0.17	0.24	0.20	5
UMR189	12/39	1346-1976	0.66	0.17	2.17	0.32	3
Nothofagus menziesii							
KEA637	8/15	1580-1980	0.18	0.37	0.74	0.33	5
LKE636	10/19	1676-1980	0.43	0.35	0.49	0.34	5
OBL610	12120	1584-1980	0.43	0.31	0.34	0.37	5
UHV635	9/18	1710-1980	0.50	0.24	0.19	0.40	5
UTV611	10/16	1622-1979	0.56	0.30	0.33	0.29	5
Nothofagus solandri							
AST630	13/26	1720-1979	0.43	0.38	1.98	0.35	5
CGB625	12124	1740-1979	0.45	0.37	1.43	0.47	5
CMP614	16/35	1759-1979	0.47	0.31	0.50	0.42	5
DBT629	13/26	1780-1979	0.46	0.35	1.23	0.47	5
ENT615	12/23	1744-1979	0.54	0.38	1.96	0.57	5
GHC607	12120	1795-1980	0.44	0.32	0.23	0.31	5
HDC632	12121	1730-1979	0.49	0.34	1.37	0.42	5
LCV631	11 /20	1730-1979	0.42	0.35	0.70	0.46	5
LGH617	13/13	1800-1979	0.38	0.29	0.18	0.40	5
LGH618	11 /20	1740-1979	0.50	0.40	2.30	0.51	5
LGH619	16/25	1740-1979	0.55	0.33	2.14	0.45	5

LGH620	11/21	1745-1979	0.49	0.29	0.53	0.39	5
LGH621	14/27	1810-1979	0.64	0.21	0.25	0.38	5
LGH622	11/21	1800-1979	0.50	0.21	0.04	0.35	5
LGH623	7/13	1710-1979	0.74	0.21	0.21	0.32	5
LG5624	15/28	1760-1979	0.46	0.33	1.43	0.40	5
LKP6O9	6/11	1833-1978	0.56	0.25	0.00	0.37	5
MKW626	12/24	1730-1979	0.56	0.34	2.24	0.40	5
MTB613	14/36	1758-1979	0.57	0.39	1.15	0.49	5
RBW628	14/28	1760-1979	0.44	0.31	0.76	0.41	5
RTA6O6	12/21	1787-1980	0.26	0.20	0.12	0.26	5
555627	13/26	1760-1979	0.55	0.30	0.96	0.49	5
TKV633	11/19	1630-1979	0.43	0.30	1.37	0.41	5
T5T634	11/19	1840-1979	0.56	0.36	1.24	0.55	5
WDC616	11 /22	1747-1979	0.59	0.30	1.01	0.42	5
Phyllocladus alpinus							
PLC259	12/38	1717-1976	0.57	0.13	0.00	0.19	3
Phyllocladus glaucus							
TEH168	9/25	1779-1975	-0.28	0.53	1.51	0.51	3
WMN169	14/24	1745-1976	-0.65	0.34	2.63	0.47	3
WKT169	11/37	1535-1976	-0.15	0.44	0.72	0.41	3
Phyllocladus trichomanoides							
OWI179	9/31	1724-1976	0.06	0.29	0.28	0.32	3
PAP178	12/37	1779-1975	0.26	0.22	0.47	0.34	3
WMUl79	10/35	1664-1976	0.15	0.24	0.69	0.23	3
WPA179	12/41	1585-1976	0.06	0.30	0.26	0.41	3

by Fowler (1984) using correlation coefficients between monthly climate and ring-widths.

In *Nothofagus menziesii* and *N. solandri* significant relationships occur between ring-width in subalpine trees and temperature during the growing season (Norton, 1984) and between ring-width in lower altitude trees and growing season rainfall (Norton, unpubl.). Scott (1972) also obtained positive correlations between current growing season temperature and ring-width in *N. solandri*. Changes in growth-climate relations in *N. solandri* along an altitudinal gradient have also been investigated (Norton, 1985).

Response function analysis is a precursor to the reconstruction of past climates. Information on past climates is important both for assessing likely future climate changes (e.g. as a result of increasing CO_2 levels) and for interpreting past climate changes and how these might have influenced present systems. Despite some of the limitations associated with palaeoclimate reconstructions, they can provide much useful information, particularly on the frequency of different climate conditions or 'events'.

A number of different climatic and related parameters have been reconstructed using tree-rings including temperature (e.g. Briffa *et al.,* 1983; Hughes *et al.,* 1984), rainfall (e.g. Cook and Jacoby, 1977; Fritts and Gordon, 1982), riverflow (e.g. Campbell, 1982; Jones, Briffa and Pilcher, 1984), sea ice conditions (Jacoby and Ulan, 1982) and synoptic pressure patterns (e.g. Fritts, Lofgren and Gordon, 1979). Reconstructions of New Zealand summer temperature back to 1760 AD (Fig. 8; Norton, unpubl.), and of rainfall and riverflow in Canterbury to 1879 AD (Norton, unpubl.), have been developed and illustrate the type of information that can be obtained. In the temperature reconstruction (Fig. 8) a distinct period of below average temperatures occurred in the 1780's while above average temperatures were characteristic of the 1830's.

A major constraint of palaeoclimate reconstruction, and one that is rarely acknowledged, relates to the spectral properties of the reconstruction. In calibrating a transfer function, modern climate data whieh have specific spectral properties are used. For example, in the 127 year New Zealand temperature series (Salinger, 1980) only 17% of the variance is associated with variations longer than 30 years (Norton, unpubl.). It is therefore unlikely that any tree-ring reconstruction based on these data will contain statistically reliable trends at frequencies of greater than 30 years. In reconstructing this

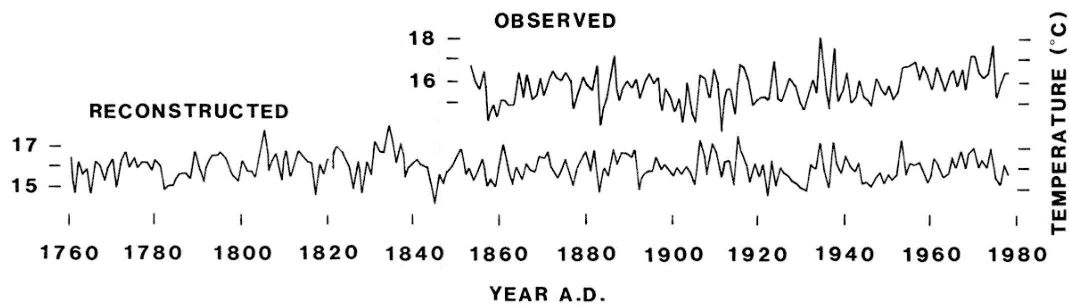

Figure 8: *Preliminary reconstruction of New Zealand summer temperature to 1760 AD derived from ten* Nothofagus menzisii *and* N. solandri *tree-ring chronologies. The transfer function was calibrated over the period 1916-1979 and verified over the period 1853-1915. Variance explained in calibration* 55% *and in verification* 42% *(Norton, unpubl.).*

temperature series, it was found that almost all of the variance explained in calibrating the transfer function regression equation was also at high frequencies (less than 30 years) (Norton, unpubl.). Because of this, it is possible that reconstructions of past climate that purport to show century-long climate change may be statistical artifacts reflecting trend in the tree-ring data rather than climate.

As part of an extensive study of the forests of the Longwood Range, Southland, Bathgate (1981) examined variations in ring-widths of *Dacrydium cupressinum* trees. Although he did not crossdate his ring-width series he developed 'chronologies' derived from decadal growth increment values. These were compared with climate; an increase in decadal growth increment since 1900 was thought to be due to the observed increase in temperatures over this period. However, these results must be viewed with caution given the lack of crossdating; *D. cupressinum* is a species known to have anomalous growth ring patterns (Norton, Herbert and Beveridge, 1988). Further difficulties with Bathgate's approach relate to the inflexible standardization procedure used (as discussed earlier) and the use of five-year running means to 'smooth' the temperature and ring-width data prior to comparison (both series were highly autocorrelated).

Attempts to reconstruct climate beyond the life of modern trees rely on the assumption that past growth-climate relations were similar to those in modern trees. However, although this assumption is implicit, we cannot be absolutely sure that it is justified. Different genotypes may have responded differently to climatic factors in the past. This may limit the use of the long tree-ring chronologies (e.g. *Pinus aristata* and *Quercus* in the Northern Hemisphere and potentially *Agathis australis* in New Zealand) for developing statistical reconstructions of palaeoclimate (c.r. LaMarche, 1974). However, by analysis of the properties of sub fossil tree-ring material (e.g. variability of ring-width from year-to-year) it should be possible to gain some general information on past environmental conditions, especially if such studies are coupled with other palaeoclimate analyses (e.g. pollen analysis). Based on the analysis of ring-widths of salicifed Upper Jurassic conifer tree stumps and associated sediments in Britain, Francis (1983) was able to suggest that climates at this time were strongly seasonal and were probably of semi-arid, Mediterranean type.

It has been shown that the relative proportions of different isotopes of oxygen, hydrogen and carbon in plants is dependent on the temperature at the time these compounds became incorporated into the plant. By analysing the relative amounts of these isotopes in the annual growth rings of trees it should be possible to reconstruct past temperatures. The analysis of stable isotopes in tree-rings is reviewed by Long (1982) and Wigley (1982). In New Zealand, Grinsted and Wilson (1979) studied the ratio of carbon-13 and carbon-12 in a 1000 year old *Agathis australis* tree and suggested that fluctuations in this ratio with time may represent a record of cool and warm periods.

Atmospheric pollution

Tree-rings have been used extensively in both Europe and North America to study the impact of atmospheric pollutants on tree growth. Several studies have shown pronounced declines in growth rates of pollution affected trees in Europe (e.g. Eckstein *et al.,* 1981; Schweingruber, Kontic and Winkler-Seifert, 1983). Dendrochronological techniques have also been used to investigate the influence of increasing CO_2 levels on tree growth in North America (LaMarche *et al.,* 1984), although the interpretations presented have been questioned (Wigley, Briffa and Jones, 1984b). Although pollution (except for CO_2) is not a widespread problem in New Zealand, local impacts have been described (e.g. Daly, 1977) and dendrochronological techniques may prove useful for further analysing these, as well as for evaluating the effect of increasing CO_2 levels on tree growth.

Forest history

Tree-rings have a number of applications in reconstructing forest history although this may often rely more on obtaining tree ages than on using strict dendrochronological techniques. However, strict techniques will improve age-frequency distributions and tree age estimates used to date specific regeneration or mortality events, or particular surfaces (e.g. the study of regeneration on fallen logs).

Competitive interactions often have a significant influence on tree growth and can be clearly seen when trees are released by the death of adjacent trees (Fig. 4). A number of studies outside New Zealand have analysed ring-width time-series in order to identify periods of suppressed or released growth (e.g. Henry and Swan, 1974; Marchand, 1984) and used this information to reconstruct the past history of the forest. Tree fall events can be dated in a variety of ways ranging from crossdating the ring-width series of the fallen tree into an established chronology, to dating scars on adjacent trees, or simply counting the rings on released seedlings, saplings or branch sprouts in the gap.

Lorimer (1985) has shown that variations in growth patterns can be used to identify and date disturbance events (several trees showing synchronous growth releases) and to identify the conditions under which a tree became established. For example, at a site in Tasmania the present mature *Arthrotaxis selaginoides* trees reached a diameter of 5 cm in 15-30 years, while seedlings currently present in the stand take 60-110 years to reach the same diameter (Ogden, 1985a). It appears that the present mature trees regenerated under very different conditions from those present in the stand today (Le. in an open environment) .

In New Zealand, Palmer (1982) used periods of release, suppression, and stem reorientation and sprouting to construct an event chronology from living, prostrate *Agathis australis* trees on Te Moehau, and dated a major disturbance event to the period 1816-1856. In the Kaimai Range, Jane and Green (1983) were able to date two major disturbance events (1914, 1946) by analysing periods of suppressed and released growth. Although no ring-width chronologies were presented, crossdating was used to identify missing growth rings and construct an event chronology. Crossdating was achieved in eleven species, several new to dendrochronology *(Pseudowintera colorata, Pseudowintera axillaris, Weinmannia racemosa, Quintinia acutifolia, Lepidothamnus intermedius, Dracophyllum latifolium).*

Seed production

Flowering and fruiting involve a shift in the allocation of resources within a plant (Harper, 1977) and often occur at the expense of vegetative growth (e.g. Tuomi, Niemela and Mannila, 1982). Mast seeding, where trees fruit heavily at irregular intervals, has been widely documented in many northern temperate trees (Silvertown, 1980) and is also known to occur in several New Zealand woody and herbaceous taxa (Norton and Kelly, unpubl.). A pronounced reduction in radial growth occurs during masting years in various tree species (e.g. Eis, Garman and Ebell, 1965).

Although mast seeding has been described for several New Zealand trees, long records are only available for *Nothofagus* species (Wardle, 1984) and *Dacrydium cupressinum* (Norton and Kelly, unpubl.). Ogden (1982) has suggested that the pronounced biennial fluctuations in ring-width in *Phyllocladus trichomanoides* may be a result of a biennial cycle in reproduction, and in *D. cupressinum* ring-width was negatively correlated with the current year's seed fall (Norton and Kelly, unpubl.).

Insect epidemics and other biological influences

Insect epidemics are a common feature of forest ecosystems and often cause canopy defoliation with a resultant reduction in photosynthesis and hence ring-width. Several studies have used growth rings to both estimate the impact of defoliation on tree growth and to date past insect epidemics (e.g. Williams, 1967; Morrow and LaMarche, 1978; Schweingruber, 1979). Insect epidemics are a common and important feature of New Zealand *Nothofagus* forests (Wardle and Allen, 1983; Hosking and Kershaw, 1985). Hosking and Kershaw observed pronounced increases in radial growth in unaffected *N. fusca* and *N. menziesii* trees after mortality of adjacent defoliated *N. fusca* trees. In Switzerland, *Larix decidua* trees showed pronounced reductions in radial growth after attacks by the larch bud moth (Schweingruber, 1979). Schweingruber was able to quantify both the frequency and intensity of insect attacks since 1780 AD.

Thomson, Smith and Alfaro (1984) studied the influence of the dwarf mistletoe *Arceuthobium tsugense* on growth in *Tsuga heterophylla* in Canada. In a similar way, it may be possible to study the impact of the insect *Ultracoelostoma assimile* (which exudes 'beech honeydew') on *Nothofagus solandri* in New Zealand.

Fire

Fire is a major component in the ecology of many dry forest ecosystems such as in North America and Australia. The use of tree-rings to date past fires is reviewed by McBride (1983). Usually several trees with fire scars are identified and crossdated to produce a chronology for dating past fire events (e.g. Madney, Swetnam and West, 1982; Dieterich and Swetnam, 1984). In New Zealand, Druce (1957) dated past fires in forest near Taita by aging fire scars present in *Leptospermum scoparium* trees.

Vulcanism

Vulcanism can affect tree growth either through resultant fires or by chemical or heat scorching of foliage, causing a reduction in growth rate (e.g. Seymour *et al.,* 1983). In North America synchronous abrupt growth reductions in samples of trees allowed Yamaguchi (1983) to date two eruptions of Mt St. Helens, in 1480 and 1800 AD. The extent of the growth reduction was greatest at sites closest to the volcano. A different approach to dating past volcanic events was taken by LaMarche and Hirschboeck (1984). They argued that dust clouds associated with large eruptions are likely to cause cooling of the earth's atmosphere. They suggest that this cooling will increase the incidence of frost damage in trees, so, by dating synchronously-occurring frost events in trees over large areas of western North America they identified a number of 'notable' frost events, some of which they relate to volcanic eruptions. In New Zealand, Druce (1966) identified growth reductions in *Libocedrus bidwillii* which he suggested resulted from scorching during an eruption of Mt Taranaki (Egmont) and was thus able to date the eruption to 1655 AD.

Snow avalanches

Snow avalanches are a common feature of mountain environments and frequently extend down into the forest zone causing damage to trees. These damage events can be dated to provide information of special importance for the management of recreational activities (e.g. ski fields) or transportation links in mountain country. Burrows and Burrows (1976) describe the procedures that can be used to develop avalanche chronologies. The methods involve dating various damage events (e.g. scarring or reaction wood) in a number of trees along the side of the avalanche track. Using this approach Conway (1977) has developed detailed avalanche chronologies for avalanche paths in *Nothofagus* forest in the Craigieburn Range (Fig. 5) and in the Hollyford Valley. Older avalanche events could also be dated by crossdating wood buried in avalanche debris with local tree-ring chronologies.

Other geomorphic events

In a similar manner it is possible to date other events (e.g. rock falls) which damage, but do not kill trees (Shroder, 1980). Heikkinen (1984) was able to date abrupt decreases in ring-width which resulted from damage to trees caused by advancing glaciers, while Giardino, Shroder and Lawson (1984) used denrochronological techniques to date a number of growth responses to geomorphic activity. An attempt has also been made to date past earthquake events in northern California using the growth responses of tilted trees (LaMarche and Wallace, 1972).

Surface dating

Tree or shrub ring counts of first-generation plants can be used to estimate minimal ages of land-surfaces such as glacial moraines, landslides or debris flows (e.g. Wardle, 1973; Burrows and Heine, 1979).

Archaeology

Tree-rings have been used extensively in archaeology, primarily as a means of dating artifacts (Baillie, 1982). Much of the original dendrochronological research was archaeological (e.g. Douglass, 1921). A number of attempts have been made to use this approach in New Zealand (e.g. Batley, 1956; Bell, 1958; Cameron, 1960; Scott, 1964) but have been largely unsuccessful. This probably reflects the equable nature of the environment in which the prehistoric people of New Zealand lived, making it difficult to crossdate ring-width sequences lacking significant growth variations.

Nevertheless, further analysis should be made, using modern dendrochronological techniques, of the tree species most commonly used by the Maori (e.g. *Podocarpus totara)*. Emphasis should initially be given to identifying the most commonly used woods and trying to develop modern chronologies with these species.

Radiocarbon dating calibration

A major application of dendrochronology has been in calibrating the radiocarbon time-scale (see Radiocarbon 28, 1986, for several examples). High precision calibration curves based on dendrochronologically dated wood have been published for the period 1950 AD-2500 BC (Stuiver and Pearson, 1986; Pearson and Stuiver, 1986). Based on the successful study of Bridge and Ogden (1986) with *Agathis australis,* it should be possible to produce a long crossdated chronology for this species in New Zealand which can be used to calibrate the radiocarbon time-scale in the Southern Hemisphere. This would allow comparison with the Northern Hemisphere calibrations. A similar study is being undertaken with *Lagarostrobos franklinii* and *Phyllocladus aspleniifolius* in Tasmania (McPhail *et al.,* 1983; *Franceyet al.,* 1984) with promising results. Jansen (1962) and Jansen and Wardle (1971) used radiocarbon dates to check growth ring counts in long lived *Agathis australis* and *Dacrydium cupressinum,* but their work did not involve crossdating.

Conclusions

In the last section of this review we have emphasized the great diversity of applications for tree-ring studies. Furthermore, wood samples that have been accurately dated can themselves be of value for isotope analysis or radiocarbon dating. A critical factor in all of these applications is the accuracy of the dating. It is here that the value of true dendrochronological studies, utilizing crossdating, as opposed to simple ring counts, is evident.

Many of the applications of tree-rings discussed here have been tried in New Zealand, but often with limited success. It has only been in the last decade that real progress has been made, and this has been through the use of strict dendrochronological techniques.

We see the greatest future potential of dendrochronology in New Zealand falling in two main areas:

(1) Further expansion of palaeoclimate studies through the development of more chronologies from a wider range of species and where possible through the use of latewood density as well as ring-width. Particular emphasis should be given to long-lived species in order to produce long palaeoclimate reconstructions.

(2) A wider application of dendrochronological techniques in studying forest history (including stand dynamics). This should include both event dating and studies of growth-ring variations.

We hope that this review, as well as indicating the wide range of applications of tree-ring studies in New Zealand, will also provide a useful reference source to the wide range of dendrochronological techniques that have been developed. The challenge now is to utilize these techniques to better understand past environments and the history and present ecology of New Zealand forests.

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