Progress in Australian dendroclimatology: Identifying growth limiting factors in four climate zones

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Abstract:

Dendroclimatology can be used to better understand past climate in regions such as Australia where instrumental and historical climate records are sparse and rarely extend beyond 100 years. Here we review 36 Australian dendroclimatic studies which cover the four major climate zones of Australia; temperate, arid, subtropical and tropical. We show that all of these zones contain tree and shrub species which have the potential to provide high quality records of past climate. Despite this potential only four dendroclimatic reconstructions have been published for Australia, one from each of the climate zones: A 3592 year temperature record for the SE-temperate zone, a 350 year rainfall record for the Western arid zone, a 140 year rainfall record for the northern tropics and a 146 year rainfall record for SE-subtropics. We report on the spatial distribution of tree-ring studies, the environmental variables identified as limiting tree growth in each study, and identify the key challenges in using tree-ring records for climate reconstruction in Australia. We show that many Australian species have yet to be tested for dendroclimatological potential, and that the application of newer techniques including isotopic analysis, carbon dating, wood density measurements, and anatomical analysis, combined with traditional ring-width measurements should enable more species in each of the climate zones to be used, and long-term climate records to be developed across the entire continent.

Keywords:

Australia; dendroclimatology; tree rings; climate change; paleoclimate

1.0 Introduction

The Australian climate is amongst the most variable in the world with many areas of the continent experiencing prolonged periods of drought and above average rainfall (Pittock 2003; Peel *et al.*, 2004; Gergis *et al.* 2012). Historic and instrumental records of both rainfall and temperature in most regions of the continent extend back less than 100 years (Bureau of Meteorology, 2001), and prior to 1910 there was no national network of climate observations. This makes assessments of the long-term significance of regional variations in rainfall and/or temperature difficult as these short records do not allow for the impact of low-frequency phenomena on climate variability to be determined. These types of assessments can only be made using multi-centennial to millennial length rainfall and temperature records (see for example, Neukom and Gergis, 2012; Graham *et al.* 2007; Seager *et al.* 2007).

In North America and Europe, climate records have been extended beyond the start of instrumental and historical records using tree rings (Briffa *et al.*, 1990; Cook *et al.*, 2007; Luckman *et al.*, 1997; Wilson and Luckman, 2005). In Australia, past reviews on the dendrochronological and/or dendroclimatological potential of Australian tree species have provided mixed views on the usefulness of this proxy for climate reconstructions (Ogden, 1978a; Worbes, 2002; Brookhouse, 2006). Many Australian species do not produce annual growth rings (Heinrich and Allen, 2013), exhibit ring wedging, false rings, and the growth patterns in many juvenile and dense understory trees are dominated by local factors rather than the regional environmental variables (Worbes, 2002). In addition, many Australian species are short-lived and suffer heartwood rot due to a shortage of nutrients and resources to support the large size of tropical trees (Ogden 1978a; 1981). As a result, potential records are short, and most parts of the continent lack depositional environments conducive to the preservation of ancient wood. Here we review 36 Australia-based dendroclimatology studies and summarize progress isolating climate relationships and the growth limiting factors in temperate, arid, tropical and subtropical environments. We report on the spatial distribution of tree-ring studies and identify the key challenges in using ring-records for

climate reconstruction in Australia. We then discuss the potential role of dendroclimatology in the development of long-term paleoclimate records within Australia.

2.0 Dendroclimatology

Dendroclimatology is the reconstruction of variations in climate through time using several parameters from tree-rings including ring width, wood properties (being features that are represented annually in tree records but are independent of ring-width), and isotopic analysis. The starting point is to determine which environmental variable is the dominant factor limiting tree growth. Common climatic limiting factors are temperature, precipitation and/or moisture availability (Fritts, 1976). Careful site and tree selection is important to locate those trees which are growing at a threshold that would stress the tree so growth occurs when the intended climatic variable for reconstruction is at an optimum (Stokes and Smiley, 1968). For example, sites at high altitude or latitude where trees are stressed due to being at the threshold of their growth range provide the best temperature reconstructions (Brookhouse *et al.*, 2008). Reconstructions of moisture availability and/or rainfall are often derived from trees on well drained slopes that rely on seasonal precipitation to promote growth. However, other non-climatic factors may limit growth, these include: canopy effects, chronic insect or fungal infestation, and/or frost season, among others. These localized effects can cause difficulty in extracting climate data from a tree-ring record (Davidson and Reid, 1985; Fritts, 1976; Morrow and LaMarche, 1978) and are more prevalent in some regions, such as the tropics (Ogden, 1978a).

The regional significance of the tree-ring record is established by crossdating patterns of ring growth within and between individual trees (Fritts, 1976). Crossdating is typically based on variations in ring-width which involves matching the pattern of ring-widths of different radii to create one overall pattern of ring-width variations through time for the site. Crossdating is first applied between several radii within a tree, and then between different trees within a

group. The pattern created represents the fluctuations in the limiting environmental variable through time. Issues arise when there are localized influences on tree growth (eg insect infestation of an individual tree) but also from the nature of the wood itself. Ring boundaries can be difficult to identify due to faint banding, wedging/pinching rings, narrow ring series, missing rings due to harsh growth conditions, and false rings from variable climatic conditions, among others and this is especially prominent in certain environments such as tropical or arid regions (for details and images of these features see Speer, 2010: Figure 4.23). Care must be taken at this stage of analysis as it is normal for some trees to not be included in the final chronology due to a lack in crossdating. Once a series of trees have been crossdated they must be checked for quality and measurement accuracy allowing the researcher to determine if there are issues in the dating and work out the cause of any errors. A well crossdated set of tree-ring measurements can then be developed into a chronology for the tree/site/region. Several computer programs exist to assist for quality control and chronology which include, but are not limited to, COFECHA, ARSTAN, Tellervo, dplR, WinDendro all of which have different advantages and disadvantages and are described in more detail elsewhere (see Cook, 1985; Guay *et al.*, 1992; Grissino-Mayer, 2001; Bunn, 2008; 2010; Brewer, 2014). Once a chronology is developed several statistical tests are evaluated to determine the strength of the chronology such as the interseries correlation, mean sensitivity, and expressed population signal (EPS) among others. These statistics have threshold values that determine which portion of the record is statistically sound, for example an EPS value greater than 0.85 indicates a chronology is useful in representing climate (Wigley *et al.*, 1986). The robust portion of the tree-ring chronology is then used to reconstruct the limiting environmental variable. This record is calibrated using an instrumental or proxy climate record that overlaps for at least a proportion of the time period. The overlapping portions of the two records, the tree-ring chronology and the measured data set, are divided into two, with one part used to establish the correlation and the other used to validate the calibration. When there are good results for both the statistical

analysis of the calibration and validation phases of a proxy record a dendrochronological climate reconstruction can be deemed representative of past climate conditions.

Table 1: Existing Australian tree ring chronologies by region and the potential climate related variable that could be reconstructed. Those shown in bold indicate studies for which a reconstruction was developed.

Environmental Variable with Potential for Reconstruction				
Region	Temperature	Precipitation	Streamflow	SOI, IPO
Temperate	Allen <i>et al.</i> , 2011 (<i>Athrotaxis</i> sp.) Allen <i>et al.</i> , 2012 (<i>Athrotaxis cupressoides</i>) Pearman <i>et al.</i> , 1976 (<i>Athrotaxis selaginoides</i>) Brookhouse, 2006; Brookhouse and Brack, 2006 (<i>Eucalyptus</i> sp.) Brookhouse and Bi, 2009; Brookhouse <i>et al.</i> , 2008 (<i>Eucalyptus pauciflora</i>) Allen <i>et al.</i> , 2013; Buckley <i>et al.</i> , 1997; Cook <i>et al.</i>, 1991; 1992; 1996; 2000; Drew <i>et al.</i> , 2013 (<i>Lagarostrobos franklinii</i>) Allen, 2002; Allen <i>et al.</i> , 2001; 2012 (<i>Phyllocladus aspleniifolius</i>) McDougall <i>et al.</i> , 2012 (<i>Podocarpus lawrencei</i>)	Brookhouse and Bi, 2009; Brookhouse <i>et al.</i> , 2008 (<i>Eucalyptus pauciflora</i>)	Allen <i>et al.</i> , 2012 (<i>Athrotaxis cupressoides</i>) Brookhouse <i>et al.</i> , 2008 (<i>Eucalyptus pauciflora</i>) Drew <i>et al.</i> , 2013 (<i>Lagarostrobos franklinii</i>) Allen <i>et al.</i> , 2012 (<i>Phyllocladus aspleniifolius</i>)	Allen <i>et al.</i> , 2011 (<i>Athrotaxis</i> sp.)
Arid	Cullen and Grierson, 2007 (<i>Callitris columellaris</i>)	Sgherza <i>et al.</i> , 2010 (<i>Callitris</i> sp.) Cullen and Grierson, 2007; 2009 (<i>Callitris columellaris</i>)		
Tropical	Ash, 1983a (<i>Araucaria cunninghamii</i>) Baker <i>et al.</i> , 2008 (<i>Callitris intratropica</i>)	Ash, 1983a; Boysen <i>et al.</i> , 2014 (<i>Agathis robusta</i>) Ash, 1983a (<i>Araucaria cunninghamii</i>) Baker <i>et al.</i> , 2008; Drew <i>et al.</i> , 2011 (<i>Callitris intratropica</i>) Ash, 1983b (<i>Callitris macleayana</i>) Mucha, 1979 (<i>Eucalyptus</i> sp.) Heinrich <i>et al.</i>, 2008 (<i>Toona ciliata</i>)		
Subtropical		Heinrich and Banks, 2005; Heinrich <i>et al.</i>, 2009 (<i>Toona ciliata</i>)		

3.0 Regional applications of dendroclimatology in Australia

The following section reviews the progress and potential for dendroclimatic study in four major climate regimes across Australia; based upon the Bureau of Meteorology's (BOM) Climate Classification of Australia (BOM, 2005), specifically the Temperate, Tropical, Subtropical, and Arid zones. Table 1 provides a list of the Australian tree ring chronologies by region and the most likely environmental variable limiting tree growth. Studies that developed reconstructions are shown in bold. Figure 1 shows the location of these studies.

Figure 1: The climate zones of Australia and the locations of the studies reviewed in this paper. The studies associated with each location are A (Mount Read) = Allen *et al.*, 2012; 2013; Buckley *et al.*, 1997; Cook *et al.*, 1991; 1992; 1996; 2000; Ogden, 1978b, B = Allen *et al.*, 2001; 2011; 2012; 2013, Buckley *et al.*, 1997; Drew *et al.*, 2013; Pearman *et al.*, 1976, C = Allen, 2002, Allen *et al.*, 2011; Ogden, 1978a; 1978b, D = Allen *et al.*, 2001, E = Allen *et al.*, 2001, F = Brookhouse and Brack, 2006; 2008, G = Brookhouse *et al.*, 2008; McDougal *et al.*, 2012, H = Brookhouse and Bi, 2009; Heinrich and Banks, 2005, I = Cullen and Grierson, 2007, J = Cullen and Grierson, 2009; Sgherza *et al.*, 2010, K = Baker *et al.*, 2008; Drew *et al.*, 2011; Mucha, 1979, L = Ash, 1983a; 1983b; Boysen *et al.*, 2014; Heinrich and Banks, 2006a; Heinrich *et al.*, 2008; Ogden, 1981, M = Heinrich and Banks, 2005, N = Heinrich and Banks, 2006a; Heinrich *et al.*, 2009

3.1 Temperate Zone

The temperate climate zone of Australia includes portions of the coasts and ranges of mainland Western Australia, South Australia, Victoria, and New South Wales, as well as the island state of Tasmania (Figure 1). The earliest instrumental climate records for the temperate region begin in 1832 in New South Wales, with a useful coverage across this zone achieved in the 1850s (BOM 2015).

In the seminal review of Australian dendrochronological research, Ogden (1978a) indicated that the greatest potential exists within Tasmania, which possesses several tree genera that have long-lived individuals as well as ring-width characteristics that are suitable for crossdating. Glacial-interglacial climate and sea-level changes over the Quaternary have led to a high level of endemism in the Tasmanian flora, such that the Tasmanian pine species found there are not present on the mainland. Dendroclimatic study in the temperate zones of the mainland has been less extensive than in Tasmania, owing to early suggestions that Tasmanian species would provide stronger dendroclimatic results. Four Tasmanian pine species were identified as being the most suitable for dendrochronology; namely *Athrotaxis cupressoides*, *A. selaginoides*, *Lagarostrobos franklinii* (*L. franklinii*; then *Dacrydium franklinii*, see Molloy, 1995), and *Phyllocladus aspleniifolius*. Ogden (1978a) suggested that *Lagarostrobos franklinii* possessed great dendrochronological potential, prompting several researchers to focus on this species. An international research team began studying *L. franklinii* in the late 1980s, beginning with a millennial length chronology developed from the high elevation (950 m asl) temperate rainforest at Mount Read in western Tasmania (Figure 1; Cook *et al.*, 1991). This research developed a 1089-year record and correlated the growth of the Mount Read trees to November–April (Austral summer) instrumental temperatures records between 1885 and 1989 (Cook *et al.*, 1992). The resulting reconstruction extended from 900 to 1989 and clearly identified years with either cold or warm temperatures outside the normal range. This record is one of the longest annual temperature reconstructions for the Southern Hemisphere (Cook *et al.*,

1992), as well as the longest dendrochronological record in Australia. Incorporation of subfossil *L. franklinii* specimens and updated analysis techniques has extended this temperature reconstruction to 1600 BC and improved its quality (Cook *et al.*, 2000). This additional work made the Mount Read *L. franklinii* reconstruction one of the longest reconstructions in the world (see Figure 7; Cook *et al.*, 2000). The existence of this 3592-year record allows aspects of Tasmanian temperature to be analysed that was not possible with shorter records. For example, Cook *et al.* (2000) note that the extent of recent warming since the 1900s is matched with a period of temperature variability in the tree-ring record prior to AD 100, suggesting that the amplitude of recent change may not be anomalous. Cook *et al.* (1996; 2000) also identified long-term oscillations of 31, 57, 78, and 200 years in the *L. franklinii* temperature reconstruction. The extensive study of *L. franklinii* at Mount Read has exemplified the benefits of persistent research into growth patterns in Australian tree species.

Elsewhere in Tasmania, the effect of elevation on the temperature response of *L. franklinii* was examined from a network of seven *L. franklinii* sites including Mount Read at elevations ranging between 200 and 950 m asl (Buckley *et al.* 1997). This showed that, in Tasmania, a threshold exists at 700 m asl, above which temperature becomes the main limiting factor to growth in *L. franklinii*. Stands of *L. franklinii* at low elevations in Tasmania were difficult to crossdate and showed little conformity with the temperature response of high alpine specimens (Buckley *et al.*, 1997). These findings provided insight into the environmental growth relationships in *L. franklinii* and reinforced decisions to prioritize high elevation sites in western Tasmania over lower elevations. However, as indicated by Ogden (1978a), the scarcity of suitable tree species across the various climate regions in Australia, requires dendroclimatic studies to be undertaken on trees in suboptimal locations. Drew *et al.* (2013) noted some temperature relationships based on wood properties, in this case tracheid radial diameter and microfibril angle, of *L. franklinii* from a low elevation (60 m asl) rainforest in western Tasmania. Several wood properties were also tested by Allen *et al.* (2013) using X-

ray densitometry, with strong correlations to Austral summer regional temperature being observed in both tracheid radial diameter and microfibril angle. This demonstrates the need to use alternate dendrochronological techniques to explore the full potential of Australian species.

The dendroclimatic potential of several other long-lived, temperate pine species in the Tasmanian rainforests have also been investigated. Ogden (1978b) showed that both *Athrotaxis cupressoides* and *Athrotaxis selaginoides* were of a useful length and had measureable ring boundaries allowing for the creation of long-term tree-ring chronologies. Pearman *et al.* (1976) also found a relationship between *A. selaginoides* and Austral summer temperature through the use of $\delta^{13}\text{C}$. *Athrotaxis* species proved more challenging to crossdate than *L. franklinii* owing to frequent occurrences of false and missing rings, as well as the presence of frost rings (Ogden, 1978b). However, *Athrotaxis* species have proved to be better suited for regional scale climate reconstructions than *L. franklinii*, as they are present across a large climatic and geographical range (Allen *et al.* 2011). Allen *et al.* (2011) utilized seven *Athrotaxis* chronologies from across Tasmania to assess the potential for reconstructing several climate variables including temperature, precipitation, and atmospheric oscillation indices. The climate sensitivity observed in *Athrotaxis* was strongly related to temperature and had very few significant correlations to precipitation or oscillation variables. However, Allen *et al.* (2011) did notice that there appears to be a link between the *Athrotaxis* species and drought variables which would make this species useful for inclusion in large scale multi-proxy studies of Australian drought conditions. Attempts to strengthen the climatic signal represented in *A. cupressoides* in eastern Tasmania have been made by using a limited number of wood density chronologies following evidence of a relationship between wood density patterns and temperature (Allen *et al.*, 2012). This was the first time a wood density relationship had been published in Australia but several studies had found this to be a viable technique for dendroclimatic reconstruction elsewhere in the world (Allen *et al.*, 2012; Briffa *et al.*, 2002; D'Arrigo *et al.*; 1992; Polge, 1970). The low sample size

precluded definitive correlations with climate; however, the average wood density values could be reliably crossdated between individual trees and linked to temperature variables as well as to streamflow values which indicates a larger scale study could be used to develop a climate and/or hydrological reconstruction (Allen *et al.*, 2012).

Included in the Allen *et al.* (2012) wood density study were *Phyllocladus aspleniifolius* samples from eastern Tasmania which is another species identified by Ogden (1978a) as being of strong dendroclimatic potential. Allen *et al.* (2001) had previously utilized samples from 16 *P. aspleniifolius* sites across Tasmania to determine how growth in this species was related to temperature during the previous growth season. While *P. aspleniifolius* is a shorter lived species it is a strong choice for use in dendroclimatology as it has a large altitudinal and geographical range that covers most of Tasmania (see Figure 1 in Allen *et al.*, 2001). Allen (2002) investigated the potential of an altitudinal (temperature) signal in *P. aspleniifolius* samples from four elevations between 100 and 900 m asl in the Warra Long Term Ecological Research site in southern Tasmania. They concluded that there was no relationship between altitude/temperature and ring-widths in *P. aspleniifolius*.

In mainland Australia dendrochronological studies have focused heavily on the widely distributed genus *Eucalyptus* (Brookhouse, 2006). Only a few of the 700 species known to exist in Australia, specifically *E. delegatensis*, *E. obliqua*, *E. sieberi*, *E. cypellocarpa*, *E. baxteri*, *E. pauciflora*, and *E. camaldulensis* have been targeted. Research was undertaken on montane forest *E. delegatensis* and *E. obliqua* trees in the Central Highlands of Victoria (Brookhouse and Brack, 2006). Each species was developed into a separate ring-width chronology and compared to climatic variables which showed significant correlations between average ring width and mean minimum and mean maximum temperatures for the preceding winter in *E. delegatensis* and both the preceding and current summer in *E. obliqua*. This was the first instance in which climate signals were identified in eucalypt ring-width series supporting the hypothesis of Brookhouse (2006) that eucalypts show

dendroclimatic potential and should be targeted for study. Brookhouse and Brack (2008) extended this study of eastern Victorian eucalypts looking at the effect of age and site position on ring-widths in four temperate *Eucalyptus* species; *E. obliqua*, *E. sieberi*, *E. cypellocarpa*, and *E. baxteri*. Brookhouse and Brack (2006) determined that the first ten years of growth in the species they examined did not show a strong climatic signal.

For a targeted climate reconstruction Brookhouse *et al.* (2008) located a treeline site on the Kosciuszko plateau of New South Wales at an elevation of about 1800 m asl that has a representative sample of *Eucalyptus pauciflora* which were growth limited by climatic conditions. A 31 year chronology from 1963 to 1994 was developed for this alpine treeline site. Ring-width was found to be significantly correlated with temperature prior to and during the current growing season as well as to precipitation in the preceding winter and autumn of the current growing season. To help determine the full climatic conditions of the area ring-width was compared to snow depth in the preceding winter and spring and a strong negative correlation was observed for all months with snow on the ground. A follow-up study using *E. pauciflora* from the Brindabella Range, along the western boarder of the Australian Capital Territory, was undertaken to determine if this species' climate response was dependent on elevation (Brookhouse and Bi, 2009). Samples were collected at 1350, 1475, and 1600 m asl and ring-width chronologies were developed that were compared to mean minimum and mean maximum temperatures as well as to precipitation. The high elevation site was significantly correlated with spring mean maximum temperature, the low elevation site to Austral summer precipitation, and the mid-elevation site was not significantly correlated to any climate variables.

More recent work in temperate New South Wales has utilized a non-*Eucalyptus* species, *Podocarpus lawrencei*, which is the only alpine conifer found in Australia (McDougall *et al.*, 2012) and is known to form annual rings (Barker, 1991). In the Australian Alps *P. lawrencei* grows in a lobate stem form which causes ring wedging; consequently to enable crossdating

full-stem cross-sections were used to develop a 114 year chronology. Significant correlations between growth-rings and spring air temperature as well as winter snow cover were observed. While McDougall *et al.* (2012) showed the high dendroclimatic potential of *P. lawrencei* they did note that preservation of non-living trees is rare and the need for cross-sections for dating is a destructive sampling method reducing the usefulness of this conifer species.

Figure 2: Existing regions of forest and shrubland across Australia.

3.2 Arid Zone

The arid zone of Australia is expected to be particularly vulnerable to climate change (IPCC, 2013) and the impact of long-term climatic variability on arid zone species is hypothesized to be significant (Pittock, 2003). In addition, this large geographic area lacks significant long-term instrumental climate records (BOM, 2001). The region contains not only extensive stands of trees but also shrubs (Figure 2), which can be used for dendrochronological

studies (Speer, 2010). Many of these tree and shrub species demonstrate an annual signal; however, they are often found in dense clusters which can create localized growth effects (Cullen and Grierson, 2007). Fires are also quite common in the arid zone, killing off stands across large areas and making it difficult to locate individuals of sufficient age for long-term study (O'Donnell *et al.*, 2011). Recent work has begun to use dendroclimatology to help understand this vulnerable ecosystem and how it is responding to climate change. Most of this research has involved drought tolerant *Callitris* species which are well distributed across the arid zone (Bowman and Harris, 1995) and are known to be dependent on precipitation for growth (Ash, 1983b; Bowman and Latz, 1993; LaMarche *et al.*, 1979).

A key dendroclimatic study from the central Pilbara region of Western Australia used isotopic signatures in *Callitris columellaris* trees to identify climatic variability (Cullen and Grierson, 2007). Isotope chronologies were used as they are better at excluding non-climatic information than ring-width records, allowing for less interference from local factors in climate comparisons (Panek and Waring, 1997; McCarroll and Loader, 2004). Analysis of $\delta^{18}\text{O}$ for the 1919-1999 period demonstrated a strong negative correlation with both summer rainfall and relative humidity and a positive correlation with January – August temperature (Cullen and Grierson, 2007). The authors developed a qualitative reconstruction of climate trends, as opposed to annual climatic values, from 1919-1999 for the central Pillbara. Following on from their qualitative isotopic climate trend reconstruction Cullen and Grierson (2009) developed the first annual ring width rainfall reconstruction in arid Australia for the Lake Tay region of Western Australia. *C. columellaris* trees were sampled to form a 1654-2005 reconstruction (Cullen and Grierson, 2009). Significant correlation was observed with monthly, seasonal, and annual rainfall values allowing for a March – September rainfall reconstruction to be developed. This reconstruction has a multi-decadal variability in the 350-year record that highlights periods of above and below average rainfall, with the persistence of dry periods being 5-15 years greater than wet periods (Cullen and Grierson, 2009). A weak but significantly negative correlation to the Southern Oscillation Index was

also observed in the Lake Tay chronology. Cullen and Grierson (2009) predict that the low-frequency rainfall variability observed in this rainfall reconstruction is related to the natural variability of El Niño Southern Oscillation (ENSO).

Cullen and Grierson's (2009) Lake Tay *C. columellaris* chronology was utilized in a truncated form (1871-2005) along with proximal chronologies at two *Callitris preissii* sites and one *Callitris canescens* site to look at developing both ring-width and $\delta^{13}\text{C}$ chronologies from the same datasets which have different climate signals and therefore allow multiple climate variables to be reconstructed (Sgherza *et al.*, 2010). All four ring-width chronologies and some of the $\delta^{13}\text{C}$ chronologies showed significant positive and negative correlations to seasonal rainfall variables, respectively. Sgherza *et al.* (2010) used principal component analysis (PCA) that combined the tree-ring and isotopic chronologies at each site, to reduce the local noise in the signals, in an attempt to develop a stronger climate signal following results reported in studies at other locations (McCarroll and Loader, 2004). The outcome for the isotopic *Callitris* samples was not encouraging, as a weaker relationship to rainfall was observed in the combined PCA analysis when compared to the ring-width reconstruction alone. Sgherza *et al.* (2010) suggest that for *Callitris* trees in arid environments it may be sufficient to focus on developing a long-term ring-width chronology if the desired outcome is a rainfall reconstruction.

The limited dendroclimatological research undertaken on *Callitris* species in the arid zone of Australia has been successful at showing a link between tree growth and climate in this region. Several other studies have been undertaken on the dendroecological potential and fire histories of these species with some beginning to attempt to link climate interactions with ecological studies (see O'Donnell *et al.*, 2010; 2011). Additionally, several multi-proxy climate reconstructions for Australia have included the Cullen and Grierson (2009) arid zone *C. columellaris* chronology and several of the major long-term Tasmanian temperate

chronologies (see Gergis *et al.*, 2012; Mills *et al.*, 2013; Palmer *et al.*, 2015), demonstrating the strength of these dendroclimatic works.

3.3 Tropical Zone

The tropical region of Australia is located above 20°S latitude and is found in portions of Queensland, the Northern Territory, and Western Australia (see Figure 1). This region encompasses both dry and wet rainforest as well as sections of cloud forest containing many tropical tree species in which growth is known to relate to the climate conditions of the area. Tropical dendrochronology within Australia is poorly studied, however; this topic has generated great interest worldwide in the past two decades (Stahle, 1999; Zuidema *et al.*, 2012). Compared to temperate zone sites, dendroclimatological analysis in tropical locations is more difficult as the majority of tropical tree species do not form a distinct annual growth ring and many produce false and missing rings (Stahle, 1999; Worbes, 2002).

In the late 1970s and early 1980s several studies identified some Australian tropical species that had both dendrochronological potential as well as a relationship to climatic variables. Notably, Mucha (1979) investigated three eucalypt species from northern Australia, *E. tetradonta*, *E. miniata*, and *E. nesophila*. He observed that these tropical eucalypt tree species were not as long-lived as their temperate counterparts, often lost their inner rings to decay and/or insect damage, and required someone with knowledge of dendrochronology and ring characteristics to properly identify annual rings for counting. However, the study results showed that not only were the rings generally identifiable but that growth occurred seasonally with a strong relationship to rainfall. Around the same time Ash undertook two studies (1983a; 1983b) utilizing three other tropical species, *Araucaria cunninghamii*, *Agathis robusta*, and *Callitris macleayana* which he determined to all have annual growth patterns although those of *A. robusta* were sometimes more than annual (Ash, 1983a). Ash (1983a) noticed a relationship to rainfall for both *A. cunninghamii* and *A. robusta* as well as a connection to temperature for the *A. cunninghamii* specimens. In his other study undertaken

on *C. macleayana* trees from the Atherton Tablelands in Queensland, Ash (1983b) identified a strong correlation between ring width and wet season duration indicating strong dendroclimatic potential. It was noted however that none of the *C. macleayana* trees from the study site were of sufficient age to extend past instrumental records and that some localized growth effects were observed (Ash, 1983b). Nevertheless, these three studies by Mucha and Ash demonstrated that tropical Australian trees could be used as climate proxies.

Callitris intratropica was the focus of a more recent study by Baker *et al.* (2008) that developed two chronologies for the Northern Territory, Australia; the first, Howard Springs, spanned 1965-2004 while the second, Pine Creek, covered the period 1847-2006. The two chronologies were of significant quality with inter-series correlation greater than 0.65 in both cases, which was the best correlation for a tropical tree series when reported (Baker *et al.*, 2008). The rejection rates of cores that did not fit into the chronologies were also quite low for a tropical species study. Baker *et al.* (2008) compared their chronologies to several climate variables and found significant positive correlations to rainfall during the early monsoon (October - December) and the end of monsoon (March - April) seasons. Mean maximum temperature was found to have a significant positive correlation in the Pine Creek record for the Austral winter months (June – September) and a significant negative correlation during December and March. Baker *et al.* (2008) also compared the Pine Creek chronology to the Palmer Drought Severity Index, a metric used to analyse plant moisture stress, and found a significant positive correlation for the duration of the monsoon and early dry season. These climate relationships indicate that growth in *C. intratropica* in this region is limited by water availability, a fact supported by a similar relationship observed between the Howard Springs chronology and October - December rainfall (see Figure 7 in Baker *et al.*, 2008). Baker *et al.* (2008) indicate that false and missing rings were observed in several of their cores but that the samples were highly crossdateable making this species viable for further tropical study. This work was furthered by Drew *et al.* (2011) who looked at the

seasonal water deficit in *C. intratropica* in the Northern Territory, Australia and noted a relationship between tree growth and water availability. Additionally, Drew *et al.* (2011) found that *C. intratropica* was a strong choice for tropical climate reconstruction as growth clearly ceased during the dry season indicating that the ring banding observed in their samples is annual. However, a difference in behaviour was noted between isolated trees and grove trees (those with no and much competition, respectively). Seasonal water deficit was stronger in grove trees where the competitions for water was greater, thus indicating grove trees would be more limited by water stress and therefore represent a better rainfall reconstruction (Drew *et al.*, 2011). Once water stress reached a significant level tree growth was found to cease all together in grove trees. Drew *et al.* (2011) indicated that a tropical *C. intratropica* chronology sensitive to rainfall conditions would be best developed from a mix of both grove and isolated trees to increase dating accuracy.

Another species that has been studied for climate relationships in the Queensland tropics is *Toona ciliata*. Heinrich *et al.* (2008) developed a chronology from this species from 1860 – 2000 and compared it to monthly and annual climate variables determining that growth in this species was limited by late growth season precipitation. Extreme wet/dry climate anomalies were also noted to relate to growth anomalies in the ring width record. Based on this analysis Heinrich *et al.* (2008) were able to create the only current rainfall reconstruction for the Queensland tropics which represents 140-years of March to June (late season) rainfall from 1860 – 2000. While this reconstruction does not extend much past the instrumental record there is potential to extend it further as tree-ring data exists from 1591 but the sample size is too low before 1860 to confirm the chronology (Heinrich *et al.*, 2008).

Isotopic dendroclimatological analysis has also been undertaken in the tropical zone.

Boysen *et al.* (2014) looked at *A. robusta* samples from the Atherton Tablelands and ran both ring width measurements and $\delta^{18}\text{O}$ analysis on the rings. Boysen *et al.* (2014) had a lot of difficulty creating a ring width chronology for this site as there were a large number of

false rings in their samples which made it difficult to identify true annual boundaries.

However, their isotopic analysis on a 15-year composite chronology from two samples was able to identify and date false ring growth in one sample. This suggests that a combination of isotopic and ring width techniques could allow for long-term chronology development if false ring identification could occur. The isotopic $\delta^{18}\text{O}$ composite chronology was also found to be correlated with mean seasonal rainfall further promoting the usefulness of isotopic dendroclimatic study for this tropical species (Boysen *et al.*, 2014) and suggesting that other tropical species may also benefit from similar isotopic study.

3.4 Subtropical Zone

The subtropical Australian climate zone is located predominantly on the east coast of Queensland with some representation in the northeastern part of New South Wales and a small region on the west coast in Western Australia (see Figure 1). As with the tropical zone very little dendroclimatological work has been undertaken in the subtropical regions of Australia. The range of species occurring in this zone often overlaps with the tropical and temperate regions but as yet little research has been done to determine if the subtropical zone trees respond similarly to their species counterparts in other climate regions. The only species used for dendroclimatic studies in the subtropics is *Toona ciliata* (Heinrich *et al.*, 2009). Heinrich and Banks (2005) began researching this species at both a temperate site in the Australian National Botanic Gardens in Canberra and at two subtropical sites in NSW (Robertson and Upper Kangaroo Valley) using dendrometer bands to understand the seasonality of growth. Results from all three sites showed a dormant period in the winter with the majority of growth occurring between mid-December to mid-April and early December and late March for the temperate and subtropical sites respectively. Differences were noted in their climate relationship with growth based on climate zone location, as only temperature was found to be a significant factor in growth at the temperate site but both rainfall and temperature were significant at the subtropical sites. This result indicated that the dendroclimatological potential of *T. ciliata* is dependent on zonal location (Heinrich and

Banks, 2005). The Upper Kangaroo Valley subtropical site was selected for ring width analysis with a chronology from 1970-2001 to be developed (Heinrich and Banks, 2005). Climate response in this 31 year chronology indicated that growth preferences in spring were to dry and warm conditions with precipitation becoming important later in the year when soil water reserves had been depleted. High maximum and mean temperatures were also found to cause stress in *T. ciliata* trees as high temperatures limit the moisture available for growth (Heinrich and Banks, 2005). The results from this preliminary study showed that *T. ciliata* is a viable tree for dendroclimatic study but that a greater understanding of the trees growth was needed before a long-term rainfall reconstruction could be developed.

To better understand the wood anatomical structure of *T. ciliata* Heinrich and Banks (2006a) undertook a study to identify false and missing rings in both the Upper Kangaroo Valley samples as well as new samples from a subtropical site in Lamington National Park in Southeast Queensland. Indistinct ring structures were identified as a feature in these samples causing difficulty in ring boundary identification (Heinrich and Banks, 2006a). In their study Heinrich and Banks (2006a) visually crossdated some of their samples and found that false rings were present. Results from their 2006a paper lead to further analysis of the younger portions of tree-ring series which determined that there was a strong ability in young trees to adapt to variations in environmental conditions (Heinrich and Banks, 2006b). This caused growth patterns to be based on localized and short term conditions which may increase the number of false or missing rings. Heinrich and Banks (2006b) used their study of tree growth variations and phenology to determine that *T. ciliata* is a viable species for dendroclimatic study while noting that care should be taken in site and sample selection to optimize climate sensitivity and reduce age related variations. Such a detailed approach to tree anatomy and growth pattern analysis provided the authors with the ability to work around the difficulties common in tropical and subtropical Australian species. This detailed analysis then permitted further research to develop the first rainfall reconstruction for an Australian subtropical region (Heinrich *et al.*, 2009).

Twenty dominant and sub-dominant trees in Lamington National Park were used to develop a 146-year (1854-2000) subtropical chronology from *T. ciliata* (Heinrich *et al.*, 2009). This chronology was then compared to monthly temperature and precipitation data from the Brisbane climate station for the period 1900-2000 and it was determined that rainfall was the highest correlated variable with an r^2 value of 0.59 (Heinrich *et al.*, 2009). However, it should be noted that the rainfall stations were about 250 km from the tree sampling site. This precipitation reconstruction identified five periods of extended drought and four periods of extended wet conditions along with delineating four and six extremely dry and wet years respectively (Heinrich *et al.*, 2009). As this reconstruction fell within the historical period Heinrich *et al.* (2009) were able to compare the wet and dry events to historical events presented by Whetton (1997) which showed that actual events were well represented by the reconstruction.

4.0 Discussion

Analysis of the 36 dendroclimatic studies clearly indicates that each of the four major climate zones of Australia contain tree species which have the potential to provide high quality records of past climate. While the Mount Read Tasmanian temperate zone reconstruction of temperature extending back to 1600 BC (Cook *et al.*, 2000) is currently anomalous within Australia, the arid, tropical, and subtropical zones have only recently begun to be studied in detail suggesting future long-term climate reconstructions are possible on a continental scale. A key development in Australian dendroclimatology is the movement away from a sole reliance on traditional ring width measurements to develop climate reconstructions. More varied research involving isotopic analysis, wood density measurements, and wood anatomy studies have proven useful in extracting dendroclimatic information from species that would have been abandoned in a more traditional approach. A recent review paper by Heinrich and Allen (2013) highlights this in stating that Australian dendrochronology needs to take a different course than just placing a heavy reliance on traditional ring-width

measurements. They note the numerous non-standard chronologies developed in Australia, many of which are included in this paper, and highlight the need for a multi-technique approach.

Table 2: Australian dendroclimatic studies for which a reconstruction was developed.

Region	Reconstructed Environmental Variable	
	Temperature	Precipitation
Temperate	Cook <i>et al.</i> , 1991; 1992; 1996; 2000 (<i>Lagarostrobos franklinii</i>)	
Arid	Cullen and Grierson, 2009 (<i>Callitris columellaris</i>)	
Tropical	Heinrich <i>et al.</i> , 2008 (<i>Toona ciliata</i>)	
Subtropical	Heinrich <i>et al.</i> , 2009 (<i>Toona ciliata</i>)	

Four dendroclimatic reconstructions have been published for Australia, one from each of the climate zones (Table 2). The most extensive reconstruction of *Lagarostrobos franklinii* is for Mount Read in western Tasmania which has been reported on in successive iterations with the most detailed chronology presented in Cook *et al.* (2000). This reconstruction represents warm-season temperature for a 3592-year period from 1600 BC – 1991 AD. The relationship between tree-ring width and regional temperature had a correlation coefficient for the calibration period of $r = 0.683$ and $r = 0.518$ for the validation period. The length of this reconstruction has allowed for the identification of several long-term, multi-decadal as well as century-scale oscillation patterns that are driving climate in the temperate Tasmanian region (Cook *et al.*, 2000). This temperature reconstruction is the longest paleoclimate record found in Tasmania and is also one of the longest dendroclimatic reconstructions in the Southern Hemisphere (Cook *et al.*, 2006). However, Cook *et al.* (2000, 2006) make it clear that they have over 4000 years of tree-ring data but the EPS values and sample size prior to 1600 BC are too low to reliably reconstruct climate.

The other three reconstructions within Australia are not nearly as long as the temperature record from Mount Read. The longest precipitation record is the arid zone Lake Tay *Callitris*

columellaris autumn-winter rainfall reconstruction, developed by Cullen and Grierson (2009) which extends for 350 years from 1655 – 2005. The relationship between tree-ring width and regional rainfall had a correlation coefficient of $r = 0.7$. It should be noted however that the nearest instrumental record was ~75 km from the studied site and, had more local records existed, the correlation may have been higher. Again there was a longer record of tree-ring data with cross-dated samples going back to 1601, but small sample size truncated the reconstruction at 1655. The record from Lake Tay showed that rainfall for that region has naturally varied over the last 350 years, from relatively dry periods lasting to 20–30 years, to periods of above average rainfall lasting ~15-years. Cullen and Grierson (2009) suggest that this multi-decadal variability relates to a low-frequency ENSO signal. They also suggested that the current sustained decline in rainfall, which began in the 1960s, that the region is experiencing may be part of the long-term natural variability.

Similar ENSO related signals are observed in the tropical and subtropical *Toona ciliata* reconstructions developed by Heinrich *et al.* (2008 and 2009 respectively). The tropical record from the Atherton Tablelands reconstructs late season (March – June) precipitation for 140-years from 1860-2000. The relationship between tree-ring width and rainfall had a correlation coefficient for the calibration period of $r = 0.59$ and $r = 0.45$ for the validation period. Once again a much longer cross-dated tree-ring series was developed with data extending back to 1591 however, with fewer than five trees representing each year prior to 1860 the EPS value drops below the critical 0.85 threshold (Heinrich *et al.*, 2008). This precipitation reconstruction demonstrated both high and low frequency multi-decadal signals identified by Heinrich *et al.* (2008) as representing the Interdecadal Pacific Oscillation (IPO) and ENSO signals respectively. This high and low frequency IPO and ENSO variability was also observed in the *Toona ciliata* annual precipitation reconstruction for subtropical Southeast Queensland (Heinrich *et al.*, 2009). This was also a short-term rainfall reconstruction covering 146-years from 1854 – 2000, with a correlation coefficient of $r = 0.59$. The tree-ring record was correlated with the longest rainfall record in the region which

was located at the Brisbane City about 250 km from the study site. Again had a more local record been used the correlation may have been higher. Heinrich *et al.* (2009) again indicated that the tree-ring record extended back further in time but analysis was limited to the 1854 and later period as the EPS value reached 0.85 at this time.

A clear theme is evident from these reconstructions that low sample size is truncating proxy climate reconstructions that in some cases could extend the reconstruction nearly three times the current length. By focusing on greater long-term replication or selecting other species that are longer lived and have been identified as having dendroclimatic potential there is the ability to create long-term proxy climate records across most of Australia. A recent large-scale undertaking to create a drought atlas for Australia can be found in Palmer *et al.* (2015) where long-term tree-ring records (as well as one coral record) were used to determine drought conditions across the eastern half of Australia as well as New Zealand. Within this drought atlas the mainland of Australia was highly underrepresented with only five tree-ring chronologies used (see Figure 1 in Palmer *et al.*, 2015). The development of long-term dendrochronological records for inclusion into datasets of large scale climate patterns such as that found in Palmer *et al.* (2015) is an important undertaking to move forward tree-ring studies within Australia.

Moreover, along with the ability to extend the length of their records, all four existing climate reconstructions demonstrate evidence of long-term natural variability of stable oscillation patterns. This indicates that Australian dendroclimatological reconstructions can be used for assessing how shifts in climate (both temperature and precipitation) relate to both natural and anthropogenic derived variability. For instance in the Mount Read temperature record a period of warming prior to AD 100 is noted as having a similar scale warming trend as is observed since 1900 (Cook *et al.*, 2000). The use of this long-term paleoclimate record indicates that such a trend in warming may be a natural phenomenon yet the general belief is that the post-1900 warming is entirely anthropogenic in design. The ability to identify long-

term natural variability in climate records is important in understanding current trends and human modifications to environmental conditions. Through the development of long-term tree-ring climate records true natural and modified conditions across Australia can be determined.

The studies covered in this review have demonstrated that the potential exists to produce long-term records of climate in each of the climate zones across the continent. However, there is still a lack of basic knowledge on the relationship between climate variables and tree growth, especially in tropical environments. Rather than working with well-studied and understood species, each Australian study must first assess the targeted species in terms of its growth response to the climate variable of interest. This is one of the reasons that little work has been undertaken in Australia, however, as each new study is completed the ecological knowledge base available to future investigations increases allowing for more paleoclimate knowledge to be developed.

5.0 Conclusion

The 36 studies identifying growth-climate relationships covered in this review clearly show that many species in Australia demonstrate dendroclimatological potential and can be used to develop long-term climate reconstructions. Only a fraction of the thousands of tree and shrub species in Australia have been assessed for an ability to provide such long-term paleoclimate data. The four climate reconstructions that do exist for this continent are already providing highly useful data enabling current climate conditions to be assessed against past variability. They are also enabling long-term effects of atmospheric oscillation patterns on the continent to be assessed. Further studies need to develop more climate reconstructions as well as extending records already developed across the Australian mainland. There is a great deal of potential for dendroclimatic research in this country and a critical need to fill in the gaps that currently exist in past climatic understanding. A move away from a sole reliance on traditional ring-width measurements to develop climate

reconstructions, using more varied techniques such as isotopic analysis, wood density measurements, and wood anatomy should enable more dendroclimatic information to be extracted from species that would have been abandoned in a more traditional approach.

Author's Post-print

Conflict of Interest

The author's declare no conflicts of interest.

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