A new method for dating tree-rings in trees with faint, indeterminate ring boundaries using the Itrax core scanner

Haines, Heather A.[a*], Gadd, Patricia S.[b], Palmer, Jonathan[c], Olley, Jon M.[a], Hua, Quan[b], Heijnis, Henk[b]

[a] Australian Rivers Institute, Griffith University, 170 Kessels Rd, Nathan, QLD, 4111, Australia; h.haines@griffith.edu.au, j.olley@griffith.edu.au

[b] Australian Nuclear Science and Technology Organisation, Locked Bag 2001, Kirrawee DC, NSW, 2232, Australia; psp@ansto.gov.au, qhx@ansto.gov.au, hhx@ansto.gov.au

[c] Palaeontology, Geobiology and Earth Archives Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, NSW, 2052, Australia; j.palmer@unsw.edu.au

[*] Corresponding Author.

Abstract:

Eastern Australia is known to experience multi-decadal periods of flood and drought. Subtropical Southeast Queensland is one region where these devastating extreme events occur regularly yet a full understanding of their frequency and magnitude cannot be determined from the short duration (<100 yrs) climate data available for the region. Tree-rings are a potential source of long-term (>100 yrs) proxy rainfall information but locating suitable forest stands is difficult due to extensive land clearing by European settlers. Another factor deterring the use of trees as proxy data sources is that longer-lived species frequently contain anomalous rings, particularly faint rings, hindering their use for paleoclimate study. Here we present a method which overcomes the problems of identifying faint ring boundaries in trees by using X-radiographs and density patterns developed on the Itrax core scanner. We analysed 39 tree cores from 20 trees at a site in D'Aguilar National Park located just north of Brisbane city in Queensland, Australia. Each core had a 2mm lath cut perpendicular to its rings which was then passed through an Itrax core scanner. The tree-ring boundaries were identified on the image by both the visual features in the radiograph and the change in density observed between rings. From this information we developed a tree-ring chronology. The chronology was checked using bomb-pulse radiocarbon dating on five trees to confirm the annual nature of the rings, and to correct dating errors in the chronology due to false rings which are common in this species. Climate response function analysis showed Austral annual rainfall (June-May) was the dominant environmental variable driving tree growth. Finally, a 69-year statistically significant reconstruction of Brisbane precipitation was produced showing that this non-destructive Itrax ring identification technique together with age validation by bomb-pulse radiocarbon dating is useful for dendroclimatological studies of trees with faint ring boundaries.

Keywords:

Dendroclimatology; *Araucaria cunninghamii*; Southeast Queensland; densitometry; Brisbane; D'Aguilar National Park

1.0 Introduction

Many tropical and subtropical regions of the world lack long-term (>100 year) climate records. These regions are known to have highly variable climates, specifically in regards to rainfall, with some areas such as the east coast of Australia known to experience multi-decadal periods of drought as well as floods of extreme magnitude (Warner, 1997; Erskine and Warner, 1998; Rustomji *et al.*, 2009). Proxy records that extend back over several hundred years are needed in such regions to understand these decadal climate patterns. Dendroclimatology has been suggested as a possible proxy technique for reconstructing long-term climate records in these environments (Baker *et al.*, 2008; Boysen *et al.*, 2014; Haines *et al.,* 2016). However, to date few tree-ring based studies have been carried out on Australia's east coast (Heinrich *et al.*, 2008; 2009). The main deterrent to such studies is the long-held belief, originating with work undertaken by Ogden (1978), that issues with ring anomalies in Australian tropical tree species make them unsuitable for dendroclimatological investigation. More recent studies have begun to investigate the climate response of some Australian tropical tree species (Baker *et al.*, 2008; Heinrich *et al.*, 2008; Drew *et al.*, 2011) but compared to temperate regions very little work has been undertaken in the tropics and subtropics. Recent reviews on the progress of Australian dendrochronological studies have suggested that multi-technique approaches should allow for both the development of ring-chronologies and climate reconstructions (Heinrich and Allen, 2013; Haines *et al*, 2016).

One subtropical Australian environment that is lacking in both historical and long-term instrumental climate data is Southeast Queensland (SEQ). This region, and more specifically Brisbane which is the major urban centre of SEQ, would benefit from a long-term, tree-ring rainfall reconstruction to understand its highly variable climate. SEQ and Brisbane are characterized by a history of high magnitude, destructive floods and decade long drought events related to interannual rainfall variability specific to Australia's east coast (Kiem *et al.*, 2003; Rustomji *et al.*, 2009, van den Honert and McAneney, 2011; Haines and Olley, 2017). Such extreme events are known to have major environmental and economic costs, with the recent Millennium Drought (1996-2010) causing billions of dollars in loss across the country and heavily affecting Queensland's agricultural sector, which is one of the main economies in SEQ (Bond *et al.*, 2008; ABS, 2011; van den Honert and McAneney, 2011; Heberger, 2012; BoM, 2015a). Understanding the frequency and long-term pattern of such events is a priority for climate scientists in SEQ. Recent rainfall analysis by Haines and Olley (2017) has indicated that while rainfall across the whole of SEQ is spatially variable there are regions that demonstrate strongly correlated rainfall patterns. This analysis indicated that to develop a precipitation reconstruction for Brisbane tree-ring sites in close proximity to the city should be selected. Urban settlement, land clearing, and logging have made such sites difficult to locate (Kemp *et al.*, 2015) but D'Aguilar National Park located directly to the north of the city does fall within Brisbane's rainfall zone as identify in Haines and Olley (2017). More importantly this park is known to contain species such as those in the *Callitris* and *Araucariaceae* families which grow in response to climate, and can therefore be used for climate reconstructions (Ash, 1983a; 1983b; Baker *et al.*, 2008). One of these species is *Araucaria cunninghamii* (Mudie) which was shown by Ash (1983a) to produce annual growth rings which are limited by precipitation. As such these trees can be used to reconstruct long-term past rainfall records. Unfortunately, coring of *A. cunninghamii* trees within D'Aguilar National Park demonstrated that the cores from these trees produced rings which are too faint to be identified visually. Previous studies in tropical environments elsewhere in the world have however used density patterns in wood to indicate ring boundaries and develop annual growth patterns (Worbes *et al.*, 1995; Tomazello *et al.*, 2000).

Wood density variation was first used as a dating method for tree-ring analysis by Polge (1970) and is based upon the magnitude of change in density between latewood and earlywood as seen through X-ray densitometric scanning (as detailed in Polge, 1966). Many improvements have been made since this early work on the X-ray scanning techniques but the principles in density analysis have remained the same. After X-ray scanning, we noted that the *A. cunninghamii* samples taken from D'Aguilar National Park demonstrate typical densitometric patterns where the change in density between the end of one ring's latewood and the beginning of the next ring's earlywood indicate the potential location of ring boundaries. Here we first date the core samples taken from *A. cunninghamii* trees in D'Aguilar National Park using X-radiographs and wood density patterns. From this, we develop a precipitation reconstruction for Brisbane, Australia and report on the usefulness of this method for wider paleoclimatic study in instances where the physical features of tree cores/slabs do not allow for easy visual ring identification.

2.0 Regional Setting

Southeast Queensland, Australia is located along the Queensland-New South Wales state border and extends from the coast on the east, to the Great Dividing Range to the west, and north to the Sunshine Coast region (Figure 1). Brisbane is located midway up the east coast of Australia and is the most populous urban area in subtropical Australia (ABS, 2016). Annual precipitation is around 1020mm with the majority falling between November to March. Average minimum and maximum temperatures range from 10°C to 21°C and 22°C to 30°C respectively (BoM, 2017). Directly to the northwest of the city is the South D'Aguilar section of D'Aguilar National Park which contains large regions of subtropical rainforest (QDNPSR, 2015a). Based on work by Haines and Olley (2017) that demonstrates spatially homogeneous regions of rainfall are located across SEQ, it was determined that the rainfall variability seen in Brisbane will be closely correlated to the rainfall variability observed within this park.

Brisbane and the regional areas surrounding the urban centre have been heavily modified since European settlement began in the 1820s. These changes include widespread logging activities and land clearing (Horne and Hickey, 2001; Kemp *et al.*, 2015). In subtropical Queensland most of the rainforest has been removed with the majority of remnant rainforest vegetation stands found in State Forest and National Parks (Horne and Hickey, 2001). This makes the D'Aguilar National Park a key location to help understand long-term rainfall conditions in Brisbane as there are few other locations within SEQ that a tree-ring based rainfall reconstruction can be created for the city.

D'Aguilar National Park was developed as a series of small national parks that were joined together under one title in 2009 (QDNPSR, 2015b). The subtropical rainforest in the Maiala section was the first region preserved in 1930. This region had been previously logged and replanted with *Araucaria cunninghamii* trees prior to including it in the National Park (QDNPSR, 2015b). Discussion with D'Aguilar park rangers and staff suggested that the replanting of this area had occurred during the mid to late 1800s. This location is similar to the few other remnant Australian subtropical rainforest settings in SEQ as the Maiala *A. cunninghamii* site (referred to herein as DMA) sits on a hillslope where a thin layer of soil covers a volcanic bedrock material. The vegetation in all of the SEQ *Araucariaceae* rainforest remnants is similar in composition but the understory, composed of vines and smaller plant species, is less dense at Maiala than rainforest stands which have never been logged such as the World Heritage Protected rainforest in Lamington National Park. *A. cunninghamii* is the dominant species in the Maiala rainforest with few trees of other species reaching canopy height at this location (Figure 2). It is unclear if the dominance of *A.*

cunninghamii at this site and/or the light understory cover is due to previous logging activity or if this is the natural vegetation condition found at this location.

The Maiala section was further developed for visitor use in the early 2000s when a parking area to access trails, a picnic shelter with barbeque facilities, and a toilet block were added. These facilities are found a few hundred meters away from the replanted *A. cunninghamii* trees. The researchers were not aware at the start of this study that the septic system for the toilet block involves a discharge of filtered groundwater which flows underground and is released within the forest at a location directly uphill from the *A. cunninghamii* DMA site. Park rangers undertaking works on the site confirmed evidence presented in aerial photographs that indicated the septic system was buried at this location in 2002.

3.0 Materials and Methods

3.1 Tree-ring Chronology Development

Trees selected for this study (n = 27) needed to meet the following criteria: to have reached canopy height, represent a dominant or subdominant tree in the stand, not appear to be competing for resources with another dominant/subdominant tree, and appear on visual inspection to not be affected by localized factors such as insect infestation or heavy strangler vine coverage. Two 12mm diameter cores were taken from each tree in the study (n = 54) at a minimum of 90^{o} apart. Each sample was labelled and placed in vented plumbers piping for transport back to the lab.

Samples were air dried for 3-5 days in the lab before being placed in a drying oven at 40^{o}C for 4-6 hours to remove any remaining moisture. Each sample was mounted using non-toxic acid-free glue and cut using a twin-bladed saw (Dendrocut 2003, Walesch Electronics). This cutting procedure provided three sections for each sample: the bottom section of the core remained glued into the mount, the middle section is a lath that is a consistent 2mm depth, and the top section of remaining sample can potentially be used for any destructive analysis (Figure 3). The mounted portions of all samples were progressively sanded with 400, 800, and 1200 grit sandpaper to attempt to bring out any visual ring boundaries or markings in the wood. Some features were identifiable but little variation could be observed relating to ring boundaries making traditional visual ring counting impossible. The 2mm lath from each core was run through an Itrax core scanner (Cox Analytical Systems) located at the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney, NSW, Australia. The scanned data provided an X-radiograph developed at a 20μm scale and a density pattern analysed perpendicular to the tree-rings. This scanning method is non-destructive allowing for further testing to be conducted on the lath once scanning is complete.

3.1.1 Use of the Itrax X-radiograph and Density Pattern for Dating *A. cunninghamii* Samples

The Itrax Core scanner produced radiographic images of the *A. cunninghamii* trees that allowed for ring boundaries not seen by the naked eye to be identified (Figure 4). The black and white radiographic images show numerous features in the wood, not just the latewood/earlywood boundaries that represent rings. Previous work by Ogden (1978) and Ash (1983a) indicated that false rings are prevalent in samples from *Araucariaceae* species and these appear as potential rings in the radiographic images as they do in *A. cunninghamii* trees where the ring boundaries are visually identifiable. Therefore, we also used the density pattern produced by the Itrax scan to help identify where ring boundaries are located in the tree cores (see Figure 4). The density pattern was overlaid on the X-radiograph using the program ReDiCore (Cox Analytical Systems) and the image was transferred into Adobe Illustrator where ring boundaries were visually identified and marked on the image. The ring widths were then measured in micrometers and ring width series created for each core using the program TELLERVO (Brewer *et al.*, 2010). It should be noted that any program where the image can be analysed and the ring boundaries measured could be used for this analysis; Adobe Illustrator was selected in this instance due to its availability to the authors. Dating of this Southern Hemisphere tree-ring series was undertaken using the Schulman (1956) convention with the year assigned to the ring being the one in which growth began.

As with visual dating of this species it can, in some instances, be difficult using Itrax data to determine the difference between true and false ring boundaries. This is because false rings also show a change in density but the magnitude of change is generally lower than a true ring boundary. To accurately work out the ring dates, five trees from the DMA chronology had their ring ages dated through bomb-pulse radiocarbon analysis on two single rings from one core of each tree (Biondi *et al.*, 2007; Pearson *et al.*, 2011). This analysis is based on the atmospheric ^{14}C bomb curve for Southern Hemisphere mid-latitudes resulting from aboveground nuclear testing mostly in the 1950s and 1960s (see Hua and Barbetti, 2004). The Southern Hemisphere calibration curve peaks in 1965 so a single bomb radiocarbon date delivers two possible calendar ages for each specimen ^{14}C value, one being on the rise and the other one on the fall of the bomb curve (Hua and Barbetti, 2004). For this reason two single rings from each core were collected for radiocarbon measurement as the relative age of the two rings is known which can correctly place the dates on the curve. These specimens were wide rings formed in years close to the 1963-1967 bomb peak period to allow for the best possible calendar age resolution (Hua and Barbetti, 2004; Hua, 2009). All ten specimens were pre-treated to alpha-cellulose (Hua *et al.*, 2004) and then combusted and converted to graphite (Hua *et al.*, 2001) for accelerator mass spectrometry (AMS) ^{14}C analysis using the STAR Facility at ANSTO (Fink *et al.*, 2004).

Once the ^{14}C results were available to help determine the difference between true and false rings the dating of the DMA chronology was revised to remove ring anomalies. With the aid of the ^{14}C results we could determine the magnitude of density change between rings that was representative of a true ring boundary. This could then be extrapolated to the trees that did not undergo ^{14}C dating. Some trees were removed from the DMA master chronology due to localized influences effecting individual trees. In total 20 trees from this site were used in the DMA master chronology; for these trees quality control was conducted using COFECHA to ensure crossdating and measurement accuracy which confirmed the correct identification of false rings (Holmes, 1983; Grissino-Mayer, 2001). Mean sensitivity and mean series inter-correlation (see Table 2) were evaluated to determine the common signal within the chronology indicating if the chronology could be used to represent climate. Next, the series was power transformed and detrended in ARSTAN (Cook and Holmes, 1985) using a Friedman super smoother set at a high sensitivity (level 3 within the ARSTAN program). This form of detrending was selected as the region is known to present climate conditions that alternate between extreme wet and dry conditions and this form of smoother allows for these extreme shifts to be incorporated without biasing the overall dataset. It should be noted that we evaluated other ARSTAN detrending options and found little variation in the results from the different index series. The standard output chronology was selected for use in this study as analysis in ARSTAN indicated autocorrelation was not significantly present in the DMA tree-ring data, removing the need for autoregressive modelling. The EPS (expressed population signal) value was used to determine the acceptable level of commonality within the data series indicating a reliable chronology. While a standard value of EPS = 0.85 is considered a reasonable limit (Wigley *et al.*, 1984) tropical and subtropical species can be difficult to crossdate and several papers have used an EPS value of 0.80 when working with these species (Fowler *et al.*, 2004; Baker *et al.*, 2008; Chen *et al.*, 2015). As such we selected an EPS = 0.80 level as the higher 0.85 was not sustained through the entire time period of this analysis. Correlation statistics were developed for the DMA chronology using the dplR package (Bunn *et al.*, 2014).

3.2 Climate Response

The DMA chronology was compared to monthly precipitation, minimum temperature, and maximum temperature variables to determine climate response at this site. The climate data was sourced from the Bureau of Meteorology historical climate database (BoM, 2015b) which provides quality controlled data series. For Brisbane rainfall the 1940-2015 period from the Toowong Bowls Club (station 40245) was used as it is one of the longest and most complete records for Brisbane city. To fill in missing data, rainfall values were used from Ashgrove Bowls Club and Brisbane Botanic Gardens Mt Coot-tha (stations 40326 and 40976 respectively); least squares analysis demonstrated these three rainfall station datasets were not statistically different from each other. The SEQ temperature network is sparse compared to the rainfall data. However, temperature conditions are much more uniform across the region (BoM, 2015b) indicating that temperature data from location further from the tree-ring site would still be representative of the DMA temperature conditions. As such, the Amberley AMO (Station 40004) minimum and maximum temperature data, which has no missing values for the period of 1940-2015, was used in this study. Rainfall data were also evaluated seasonally and annually by summing the monthly variables together. Seasons are delineated as follows: winter = June, July, August; spring = September, October, November; summer = December, January, February; and autumn = March, April, May. Annual rainfall represents winter through autumn precipitation and is allocated to the year where the annual period commenced.

DendroClim2002 (Biondi and Waikul, 2004) was used to evaluate correlation and response coefficients between the climate and growth variables. The annual DMA site index was compared to monthly, seasonal, and annual precipitation as well as monthly minimum and maximum temperatures. Temporal response was tested with forward evolutionary modelling using a 24 year moving window. Pearson correlation analysis was undertaken to analyse for statistical significance at the 95% confidence level ($p < 0.05$) for all static and temporal correlation and response variables.

Based on the results of the climate response analysis it was determined that a rainfall reconstruction of Brisbane precipitation could be developed using the DMA chronology. The program PCReg (http://www.ldeo.columbia. edu/tree-ring-laboratory/resources/software) was used to develop a point to point linear regression model of annual rainfall. Calibration and verification analysis was undertaken using linear regression with a split period method for the part of the record prior to site disturbance which occurred in 2002 (Fritts, 1976). Early calibration was run from 1946-1971 and late calibration from 1972-2001. Verification statistics from PCReg were utilized to test the reconstructed output for robustness. The reconstruction presented is based upon the full 1946-2001 calibration period.

4.0 Results

4.1 DMA Chronology Development

Ring boundary identification was completed by analysing both the radiographic images and the density pattern produced by the Itrax core scanner. Features that appeared in the radiograph to be ring boundaries were then compared to the density pattern changes between latewood and earlywood. Boundaries were determined to be true only if the visual feature on the radiograph correlated with a significant change in the overlaid density plot. In some instances, as demonstrated in Figure 4 what would appear to be a ring boundary on the radiograph did not correspond to a change in density indicating this was not a true ring. Once the boundaries were identified each of the cores were dated and comparisons made between the two cores from each tree to compensate for any locally absent rings which are known to be common in these species (Ash, 1983a). To account for false ring boundaries that may be observed in both the radiograph and density plot, dating verification was undertaken using bomb-pulse radiocarbon dating.

In order to develop the master chronology five trees were dated using bomb-pulse radiocarbon and the results are presented in Table 1. In all but one of the ten rings dated the original age given to the ring was incorrect. This was expected for trees of the *Araucariaceae* species as they are known to have many issues with ring anomalies (Ogden, 1981; Ash, 1983a). Dating was off by 0-6 years and in most cases false rings were the prominent ring anomaly although missing rings were seen in sample DMA014. Through the use of bomb-pulse radiocarbon dating where the results could be compared to the Itrax data false ring identification became clearer by looking at the magnitude of change in density between earlywood and latewood. The missing rings in tree DMA014 occurred at the outer most portion of the core where the image was unclear due to some damage to the wood lath that made ring boundary identification problematic. This issue arose in two other trees in the series and was easily corrected due to the knowledge gained from bomb-pulse radiocarbon dating tree DMA014. All series were redated after the ^{14}C dating was analysed to reflect the improved awareness of what constituted an annual ring using the radiograph and density dating method.

Quality control was undertaken on all tree cores and samples that were overly influenced by localized factors were removed (eg. Heavy vine coverage; proximity to other dominant trees). Crossdated tree-ring measurements developed from twenty trees extended from 1941-2014, however the DMA chronology was truncated at 1945 based on an EPS values of 0.80 and a low sample size (below 5 prior to 1945; Table 2). The common signal strength weakens prior to this point and becomes more representative of variability within individual trees and therefore does not provide a robust representation of environmental variables. Maximum and minimum tree series length was found to be 74 and 32 years respectively and a mean series length of 56 years. While the oldest tree in the series dated to 1941, the youngest started growing in 1968; all trees in the series were living when they were cored in 2014. This dataset is representative of a single age cohort of tree growth which was to be expected as the site was planted after being completely cleared by logging and was not of sufficient age for a second younger cohort to have developed.

The DMA chronology has a mean ring width of 0.4186mm, a median ring width of 0.3571mm, and a skew of 1.200 (Table 2). These indicate similarity between the cores in the DMA dataset. Several correlation statistics were also calculated to determine the environmental sensitivity of the chronology (Table 2; see Biondi and Qeadan, 2008). While there is almost always a contribution from conditions observed in previous years to a trees growth, the Gini value of 0.292 indicates that year to year variability in this series is moderate and therefore the chronology is more sensitive to environmental conditions. Narrow rings indicating heavy drought conditions (such as in 1990, 1968, 1960-61) are found to be consistent between most tree series in the chronology (Figure 5A) with the Millennium drought from 1996-2010 suggested to be effecting the region. Wide rings appear to be in agreement across some series in the chronology (Figure 5A) but evidence of heavy rainfall associated with known floods in the Brisbane region, such as the major floods of 2011 and 1974 (see BoM, 2016), do not appear to be captured here.

4.2 Correlations with Climate

Analysis of the DMA chronology climate response to Brisbane rainfall and regional temperature variables demonstrate that precipitation is more closely connected to ring growth than temperature (Figure 6). Seasonal and annual precipitation conditions are more strongly correlated to growth than individual monthly variables (Figure 6A). The significant relationships between rainfall and growth are positive indicating that in years with little rainfall tree-ring width will be reduced. No significant relationships were found between tree growth and maximum temperatures (data not shown) and only November minimum temperature conditions were seen to be significant (Figure 6B). This correlation is negative and indicates that lower minimum temperatures during the start of the growth season could affect tree growth. This matches with observations of climate-growth relationships made using dendrometers in other areas of SEQ on *Araucariaceae* species that demonstrated minimum temperatures influence the commencement and conclusion of the growth season (Haines *et al.*, under review). Our observations match those found by Ash (1983a) indicating that precipitation was the climate variable most strongly connected to *A. cunninghamii* growth but that temperature variables also had an observable effect. However, in line with Ash's (1983a) conclusions, it is annual Brisbane precipitation that the DMA chronology can be used to reconstruct.

4.3 Rainfall Reconstruction

To develop the reconstruction Brisbane rainfall and the DMA tree-ring chronology were calibrated over three time periods: early (1946-1971) and late (1972-2001) periods were used to validate the statistics via a split period method and the full period (1946-2001) is used for the rainfall reconstruction (Figure 7). Calibration and verification statistics for all three periods are presented in Table 3; these were all determined to be statistically significant. There is little variation between the statistics for the two split calibration/verification periods indicating that the relationship observed between the chronology and rainfall remains steady over time. Reduction of error (RE) and coefficient of efficiency (CE) values were all positive (Table 3) indicating that the developed model is a robust (albeit modest) representation of annual rainfall. However, the correlation value is low which suggests that while rainfall has an influence on the growth of the DMA *A. cunninghamii* trees there are other localized influence(s) also affecting these trees. Nevertheless, the developed reconstruction can still be considered sound due to the statistical validity of the analysis.

5.0 Discussion

Both the DMA chronology and the climate reconstruction presented here are the first developed using an Australian *Araucariaceae* species. This chronology is robust and well replicated as the thirty-nine cores used show coherent ring width patterns through the entire record (Figure 5, Table 2). Narrow rings representing low rainfall conditions, such as 1952, 1968, and 1990, appear in most cores across the entire series (Figure 5). This consistency suggests that the ring width measurements developed using the Itrax radiograph and density data to identify ring boundaries is of similar quality to traditional dating methods used elsewhere. The period of the Millennium Drought (1996-2010) demonstrates uniform ring widths that are narrower than average for most cores during this period (Figure 5) with the exception of 2002 (discussed below). While ring width studies are good at representing low rainfall conditions they do struggle to properly characterize heavy rainfall conditions in regions like SEQ where large amounts of a year's rain may fall within short periods. Trees are limited in how much material they can build up within a short period of time as growth is an effect of conditions averaged through time (eg. a growth season) rather than based on individual events (Fritts, 1976). In the DMA chronology some wide tree-ring widths do appear to match well with years where rainfall was found to be above the mean, such as

1966, 1970, and 1989 (Figure 7). In other instances, such as 1973 and 1995, the heavy rainfall which occurred is not captured in the tree-ring record (Figure 7). However, this can be explained by the way rainfall occurs during these years. If a large amount of rain falls over a short period only so much water and nutrients can be taken up by a tree and the rest is lost to groundwater and surface flow. If the remainder of the year does not have a lot of rainfall then the ring that is formed on the tree will not be very wide as it only had one key rainfall opportunity for improved growth. Yet if several moderate to large rainfall events occur over the course of a year then a tree can take advantage of numerous opportunities to intake water and nutrients, therefore increasing their growth potential allowing for a wider ring to form. Looking at the rainfall data for Brisbane it is clear how these two situations have both occurred during the study period. In 1973 and 1995 the majority of rainfall occurred during a few short events. For example in 1973 over a third of the growth season rainfall occurred during one event and 50% of the year's rainfall occurred over only six days, which represented 1973's three largest precipitation events (lasting one, three, and two days respectively). The rainfall during years where wider rings occur was spread more evenly throughout the growth season. For comparison, in 1966 the three largest rainfall events occurred over a total of nine days (each lasting three, one, and five days respectively) and represented less than a third of the rainfall that fell during the growth season.

Another issue that needs to be considered when looking at this rainfall reconstruction is alternative, specifically localized, influences on tree growth. Discussion with National Park staff prior to the commencement of this project suggested that the trees at this site had been replanted in the mid to late 1800s. However, the chronology suggests that the trees were in fact planted in the 1930s or 1940s around the time that the Maiala region became part of the National Park. Therefore, the trees at this site are all from one individual cohort which is less than 100 years old and limits the variability of responses to environmental conditions.

Due to the young age of the trees the DMA chronology was not as lengthy as originally intended which did not allow for a long-term rainfall reconstruction to be developed. Nevertheless, the chronology presented a significant overlap with reliable Brisbane precipitation data and provided an opportunity to apply and test the Itrax ring boundary identification technique. Annual rainfall was found to account for nearly 15% of growth variability in this series (Table 3) which is low even for other Australasian tropical/subtropical reconstructions (see Shah *et al.*, 2007; Heinrich *et al.*, 2008; 2009). Yet the documentation of significant relationships between tree growth and climate (Figure 6) as well as the development of a statistically valid rainfall reconstruction (Figure 7), even one with low variability, suggest that this technique can be applied to tree-ring samples with non-visual rings that are intended for use in dendroclimatology. Climate response analysis demonstrated that even though this is a short tree-ring record there is a significant observable influence of annual rainfall on tree growth. However, we do acknowledge that this 69-year reconstruction developed from one cohort of trees is of insufficient length and lacks variety in response to growth variables to account for all trends related to localized issues such as resource competition. Standardization has greatly reduced some of the growth trends associated with a single age cohort (Fritts, 1976), but cannot provide the same range of environmental interpretations that occur within a long-term chronology developed from multiple cohorts. This is a bias caused by the selection of this site which occurred due to misinformation provided prior to the start of the study. Such bias in site selection is commonly unavoidable in SEQ as there are few locations that remain in unmodified, natural condition that also contain tree species useful for climate studies.

Other localized effects may also be contributing to the low percentage of reconstruction variance explained by the rainfall data. Disturbance such as the major work conducted at the Maiala site where the septic system was buried to complete the building of the amenity block appears to have affected the tree ring record. This could account for the wide 2002 ring observed in the DMA trees during a year with little rainfall as conditions at the site would have been heavily influenced by the ongoing construction and the discharge of nutrient-rich water from the septic tanks. Beyond 2002 there is a period of eight years with little variability in ring width which occurs during the Millennium Drought where narrow ring widths would be expected. This could be a lasting effect of the amenity block construction as the septic system is likely to be providing nutrients uphill of the DMA site that are cancelling out the environmental growth requirements of the trees. However, this period of muted variability in the record seems to begin prior to 2002. As such, this may be an artefact of the Millennium Drought itself. While most of SEQ was suffering from low moisture conditions the high elevation DMA site located within a small catchment may have had more moisture available than on the agricultural valley plains. In order to further investigate this change, a 26-year moving window analysis of the correlation values between the chronology and the instrumental rainfall was undertaken for the entire 1946-2015 period (Figure 8). A drastic decrease in the correlation between variables is evident in the early 2000s, in line with the disturbance at the Maiala site. This would suggest that it is the localized influence of the work occurring at the site that is influencing the low variability in ring-widths and that any analysis of rainfall based on the DMA reconstruction should be truncated in 2001. However, both Figures 7 and 8 appear to show that in the last few years of the record the tree-ring pattern is again matching well with rainfall and that the correlation between the variables is increasing. This may suggest that the trees at the DMA site are equalizing to the conditions at the site and that environmental conditions may again be driving tree growth.

Other long-term rainfall studies that have been undertaken in southeastern Australia have investigated the low-frequency variability related to phenomena such as the El Niño

Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (Chiew *et al.*, 1998; Verdon *et al.*, 2004; Heinrich *et al.*, 2009; Gergis *et al.*, 2012). Such an undertaking would provide a better understanding of how climatic conditions are influencing the tree-ring data at the DMA research site. However, the short duration record produced here precluded such analysis from being performed. Preliminary spectral wavelet analysis demonstrated no significant relationships as would be expected on a 69-year record. For such a low-frequency analysis to be performed a longer chronology from the SEQ region, such as the one developed by Heinrich *et al.* (2009) would be required. As the majority of the *Araucariaceae* trees within D'Aguilar National Park were logged and those in existence now represent a replanting program after National Park status was granted, it is unlikely that an extension to the current DMA chronology is possible. While there are a few sites of unlogged remnant *Araucariaceae* forest located within SEQ none of these are in close proximity to Brisbane.

Regardless of length, the creation of this ring width chronology, from a site with non-visual ring boundaries, is a very important development for tropical dendrochronology. Faint ring boundaries are very common in tropical species (Biondi and Fessenden, 1999). Here we have demonstrated that tree-ring boundaries can be identified using the radiographic images and the density pattern generated by the Itrax core scanner. This technique is non-destructive and while used here on a tropical/subtropical species it can be applied to any environment or species as long as the researcher has access to an Itrax core scanner, or equivalent technology, to produce both radiographs and density patterns for comparative analysis.

6.0 Conclusions

Long-term understanding of climate variations along the tropical/subtropical east coast of Australia cannot be developed from the short historical and instrumental records available. Consequently proxy climate records need to be developed. Within Southeast

Queensland there are tree species such as *A. cunninghamii* that show potential for use in developing rainfall reconstructions but ring anomalies, including faint, indeterminate ring boundaries, make analysis problematic. This issue can be overcome in some instances by the method presented here where true ring boundaries are identified, dated, and widths measured through the use of radiographic images and density plots developed using the Itrax core scanner. In order to be confident in the dating a multi-technique approach involving bomb-pulse radiocarbon dating should be undertaken. Our results from applying this method to trees at the DMA site in D'Aguilar National Park demonstrated i) that a chronology can be created, ii) that tree growth is responding to climate at this location, and iii) that a statistically valid rainfall reconstruction can be developed using this method. While the reconstruction indicates that at the DMA site tree growth is certainly affected by localized influences the analysis does show that annual rainfall is the driving environmental factor for tree growth at this location. By selecting a tree-ring site where a longer, multi-cohort record can be developed there is a high probability that a long-term record of SEQ precipitation can be reconstructed. The results clearly show that the Itrax dating method can prove useful for undertaking tropical dendrochronological and climatological studies.

Acknowledgements

The authors would like to thank Jack Coates-Marnane, Tanya Ellison, and Dr Craig Woodward for assistance in the field and both the Queensland Government Parks and Wildlife Service and the Queensland Department of Environment and Heritage Protection for allowing permitted access to the field site. Thanks also to ANSTO for H.A. Haines' access to the radiocarbon lab and assistance in preparing and analysing samples for radiocarbon dating. We acknowledge the financial support from the Australian Government for the Centre for Accelerator Science at ANSTO through the National Collaborative Research Infrastructure Strategy (NCRIS). The authors appreciate comments from Dr Craig Woodward, Dr James Speer, and two anonymous reviewers on early drafts of this manuscript.

Funding Source

This work was supported by an Australian Research Council Linkage Grant (LP120200093) and an Australian Institute of Nuclear Science and Engineering Postgraduate Research Award (ALNSTU11387). Heather A. Haines received PhD scholarships from Griffith University, the Australian Research Council, and the Australian Institute of Nuclear Science and Engineering.

Declaration of interest

The authors declare no conflicts of interest.

References

Ash, J., 1983a. Growth rings in *Agathis robusta* and *Araucaria cunninghamii* from Tropical Australia. Australian Journal of Botany 31, 269-275. doi: 10.1071/BT9830269

Ash, J., 1983b. Tree rings in tropical *Callitris macleayana* F. Muell.. Australian Journal of Botany 31, 277-281. doi:10.1071/BT9830277

Australian Bureau of Statistics (ABS). 2011. Australian Bureau of Statistics

Australian Bureau of Statistics (ABS). 2016. Australian Bureau of Statistics

Baker, P.J., Palmer, J.G., D'Arrigo, R., 2008. The dendrochronology of Callitris intratropica in northern Australia: Annual ring structure, chronology development and climate correlations. Australian Journal of Botany, 56, 311-320. doi: 10.1071/BT08040

Biondi, F., Fessenden, J.E., 1999. Radiocarbon analysis of *Pinus lagunae* tree rings: Implications for tropical dendrochronology. Radiocarbon 41(3), 241-249. doi: 10.1017/S0033822200057118

Biondi, F., Qeadan, F., 2008. Inequality in Paleorecords. Ecology, 89(4), 1056–1067. doi: 10.1890/07-0783.1

Biondi, F., Waikul, K., 2004. DENDROCLIM2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies. Computers & Geosciences, 30, 303-311. doi: 10.1016/j.cageo.2003.11.004

Biondi, F., Strachan, S., Mensing, S., Piovesan, G., 2007. Radiocarbon analysis confirms the annual nature of sagebrush growth rings. Radiocarbon 49, 1231-1240. doi: 10.1017/S0033822200043149

Bond, N.R., Lake, P.S., Arthington, A.H., 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. Hydrobiologia, 600, 3-16. doi: 10.1007/s10750-008-9326-z

Boysen, B.M.M., Evans, M.N., Baker, P.J, 2014. $\delta^{18}O$ in the tropical conifer *Agathis robusta* records ENSO-related precipitation variations. PloS ONE 9(7), e102336. doi: 10.1371/journal.pone.0102336

Brewer, P.W., Sturgeon, K., Madar, L., Manning, S.W., 2010. A new approach to dendrochronological data management. Dendrochronologia, 28 (2), 131-134. doi: 10.1016/j.dendro.2009.03.003

Bunn, A., Korpela, M., Biondi, F., Campelo, F., Mérian, P., Mudelsee, M., Qeadan, F., Schulz, M., Zang, C., 2014. dplR: Dendrochronology Program Library in R. R package version 1.6.0. http://CRAN.R-project.org/package=dplR

Bureau of Meteorology (BoM), 2015a. Recent rainfall, drought and southern Australia's long-term rainfall decline. http://www.bom.gov.au/climate/updates/articles/a010-southern-rainfall-decline.shtml (accessed March 2017)

Bureau of Meteorology (BoM), 2015b. Climate Data Online. http://www.bom.gov.au/climate/data/ (accessed October 2016)

Bureau of Meteorology (BoM), 2016. Known Floods in the Brisbane and Bremer River Basin. http://www.bom.gov.au/qld/flood/fld_history/brisbane_history.shtml (accessed March 2017)

Bureau of Meteorology (BoM), 2017. Climate Statistics for Australian Locations: Brisbane. http://www.bom.gov.au/climate/averages/tables/cw_040913.shtml (accessed March 2017).

Chen, F., Yuan, Y., Wei, W., Shulong, Y., Wang, H., 2015. Tree-ring response of subtropical tree species in southeast China on regional climate and sea-surface temperature variations. Trees 29, 17-24. doi: 10.1007/s00468-013-0951-4

Chiew, F.H.S., Piechota, T.C., Dracup, J.A., McMahon, T.A., 1998. El Nino/Southern Oscillation and Australian rainfall, streamflow and drought: Links and potential for forecasting. Journal of Hydrology 204, 138-149. doi: 10.1016/S0022-1694(97)00121-2

Cook, E.R., Holmes, R.L., 1985. Program ARSTAN and user's manual. Laboratory of Tree Ring Research, University of Arizona, Tuscon, AZ.

Drew, D.M., Richards, A.E., Downes, G.M., Cook, G.D., Baker, P.J., 2011. The development of seasonal tree water deficit in *Callitris intratropica*. Tree Physiology 31, 953-964. doi: 10.1093/treephys/tpr031

Erskine, W.D., Warner, R.F., 1998. Further assessment of flood and drought dominated regimes in south eastern Australia. The Australian Geographer 29, 257-261. doi: 10.1080/00049189808703218

Fink, D., Hotchkis, M., Hua, Q., Jacobsen, G., Smith, A.M., Zoppi, U., Child, D., Mifsud, C., van der Gaast, H., Williams, A., Williams, M., 2004. The ANTARES AMS Facility at ANSTO. Nuclear Instruments and Methods in Physics Research Section B 223-224, 109-115. doi:10.1016/j.nimb.2004.04.025

Fritts, H.C., 1976. Tree Rings and Climate. Academic Press Inc. (London) Ltd., London, 567 pages. http://dx.doi.org/10.1038/scientificamerican0572-92.

Fowler, A., Boswijk, G., Ogden, J., 2004. Tree-ring studies on Agathis australis (kauri): A synthesis of development work on late Holocene chronologies. Tree-Ring Research 60(1), 15-29.

Gergis, J., Gallant, A.J.E., Braganza, K., Karoly, D.J., Allen, K., Cullen, L., D'Arrigo, R., Goodwin, I., Grierson, P., McGregor, S., 2012. On the long-term context of the 1997-2009 'Big Dry' in South-Eastern Australia: insights from a 206-year multi-proxy rainfall reconstruction. Climatic Change 111(3-4), 923-944. doi: 10.1007/s10584-011-0263-x

Grissino-Mayer, H.D., 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Research 57(2): 205-221.

Haines, H.A., Olley, J.M., 2017. The implications of regional variations in rainfall for reconstruction rainfall patterns using tree rings. Hydrological Processes. doi: 10.1002/hyp.11238

Haines, H.A., Olley, J.M., Kemp, J., English, N.B., 2016. Progress is Australian dendroclimatology: Identifying growth limiting factors in four climate zones. Science of the Total Environment 572, 412-421. doi: 10.1016/j.scitotenv.2016.08.096

Haines, H.A., Olley, J.M., English, N.B., Hua, Q., under review. Anomalous ring identification in two Australian subtropical *Araucariaceae* species permits annual ring dating and growth-climate relationship development. Dendrochronologia.

Heberger, M., 2012. Australia's millennium drought: impacts and responses. In The world's water (pp. 97-125). Island Press/Center for Resource Economics. doi: 10.5822/978-1-59726-228-6_5

Heinrich, I., Allen, K., 2013. Current issues and recent advances in Australian dendrochronology: Where to next? Geographical Research, 51(2), 180-191. doi: 10.1111/j.1745-5871.2012.00786.x.

Heinrich, I., Weidner, K., Helle, G., Vos, H., Banks, J.C.G., 2008. Hydroclimatic variation in Far North Queensland since 1860 inferred from tree rings. Palaeogeography, Palaeoclimatology, Palaeoecology, 270, 116-127. doi: 10.1016/j.palaeo.2008.09.002

Heinrich, I., Weidner, K., Helle, G., Vos, H., Lindesay, J., Banks, J.C.G., 2009. Interdecadal modulation of the relationship between ENSO, IPO and precipitation: insights from tree rings in Australia. Climate Dynamics 33, 63-73. doi: 10.1007/s00382-009-0544-5

Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M., Zimmerman, S.R.H., 2013. SHCal13 Southern Hemisphere calibration, 0-50,000 cal yr BP. Radiocarbon 55, 1889-1903, doi:10.2458/azu_js_rc.55.16783.

Holmes, R., 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin 43, 69–75.

Horne, R., Hickey, J., 2001. Ecological sensitivity of Australian rainforests to selective logging. Australian Journal of Ecology 16(1), 119-129. doi:10.1111/j.1442-9993.1991.tb01487.x

Hua, Q., 2009. Radiocarbon: A chronological tool for the recent past. Quaternary Geochronology 4, 378-390, doi:10.1016/j.quageo.2009.03.006.

Hua, Q., Barbetti, M., 2004. Review of tropospheric bomb radiocarbon data for carbon cycle modelling and age calibration purposes. Radiocarbon 46, 1273-1298. doi:10.2458/azu_js_rc.46.4182

Hua, Q., Jacobsen, G.E., Zoppi, U., Lawson, E.M., Williams, A.A., Smith, A.M., McGann, M.J., 2001. Progress in radiocarbon target preparation at the ANTARES AMS Centre. Radiocarbon 43, 275-282. doi:10.1017/S003382220003811X

Hua, Q., Barbetti, M., Zoppi, U., Fink, D., Watanasak, M., Jacobsen, G.E., 2004. Radiocarbon in tropical tree rings during the Little Ice Age. Nuclear Instruments and Methods in Physics Research Section B 223-224, 489-494. doi:10.1016/j.nimb.2004.04.092

Hua, Q., Barbetti, M., Rakowski, A.Z., 2013. Atmospheric radiocarbon for the period 1950-2010. Radiocarbon 55, 2059-2072, doi:10.2458/azu_js_rc.v55i2.16177.

Kemp, J., Olley, J.M., Ellison, T., McMahon, J., 2015. River response to European settlement in the subtropical Brisbane River, Australia. Anthropocene 11, 48-60. doi: 10.1016/j.ancene.2015.11.006

Kiem, A.S., Franks, S.W., Kuczera, G., 2003. Multi-decadal variability of flood risk. Geophysical Research Letters 30(2). doi: 10.1029/2002GL0159992

Ogden, J., 1978. On the dendrochronological potential of Australian trees. Australian Journal of Ecology 3, 339-356. doi:10.1111/j.1442-9993.1978.tb01184.x

Ogden, J., 1981. Dendrochronological studies and the determination of tree ages in the Australian tropics. Journal of Biogeography, 8, 405-420. doi: 10.2307/2844759

Pearson, S., Hua, Q., Allen, K., Bowman, D.M.J.S., 2011. Validating putatively cross-dated Callitris tree-ring chronologies using bomb-pulse radiocarbon analysis. Australian Journal of Botany 59, 7-17, doi:10.1071/BT10164.

Polge, H., 1966. Établissement des courbes de variation de la densité du bois par exploration desitométrique de radiographies d'échantillons prélevés à la tarière sur des arbres vivants. Annales des Sciences Forestieres Vol23, EDP Sciences, pp. 1-206. (In French)

Polge, H., 1970. The Use of X-Ray Desitometric Methods in Dendrochronology. Tree-Ring Bulletin 30, 1-10.

Queensland Department of National Parks, Sport and Racing (QDNPSR), 2015a. D'Aguilar National Park: About D'Aguilar National Park [online]. Available from http://www.nprsr.qld.gov.au/parks/daguilar/about.html (Accessed September 2015).

Queensland Department of National Parks, Sport and Racing (QDNPSR), 2015b. D'Aguilar National Park: Nature, culture, history [online]. Available from http://www.nprsr.qld.gov.au/parks/daguilar/culture.html (Accessed September 2015).

Reimer, P., Reimer, R., 2004. CALIBomb radiocarbon calibration. Interactive program available on-line at: http://intcal.qub.ac.uk/CALIBomb/frameset.html (Accessed March 2016)

Rustomji, P., Bennett, N., Chiew, F., 2009. Flood variability east of Australia's Great Dividing Range. Journal of Hydrology 374, 196-208. doi: 10.1016/j.jhydrol.2009.06.017

Schulman, E., 1956. Dendroclimatic change in semiarid America. University of Arizona Press, Tuscon, AZ, 142 pp.

Shah, S.K., Bhattacharyya, A., Chaudhary, V., 2007. Reconstruction of June-September precipitation based on tree-ring data of teak (Tectona grandis L.) from Hoshangabad, Madhya Pradesh, India. Dendrochronologia 25, 57-64.

Tomazello, M., Botosso, P.C., Lisi, C.S., 2000. Potencialidade da familia Meliaceae para dendrocronologia em regiões tropicais e subtropicais. In: Roig, F.A. (ed.), Dendrocronología en América Latina (pp 381-434). EDIUNC, Mendoza. (In Portuguese).

van den Honert, R.C., McAneney, J., 2011, The 2011 Brisbane Floods: Causes, Impacts and Implications. Water 3, 1149-1173. doi: 10.3390/w3041149

Verdon, D.C., Wyatt, A.M., Kiem, A.S., Franks, S.W., 2004. Multidecadal variability of rainfall and stramflow: Eastern Australia. Water Resources Research 40, W10201. doi:10.1029/2004WR003234.

Warner, R.F., 1997. Floodplain stripping: another form of adjustment to secular hydrologic regime change in Southeast Australia. Catena 30, 263-282. doi: 10.1016/S0341-8162(97)00014-3

Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average of correlated time series, with applications in dendroclimatology and hydrometeorology. Journal of Climate and Applied Meteorology 23, 201-213. doi: 10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2

Worbes, M., Klosa, D., Lewark, S., 1995. Rohdichtestruktur von Jahresringen tropischer Hölzer aus zentralamazonischen Überschwemmungswäldern. European Journal of Wood and Wood Properties 53, 63–67. (In German)

Table Captions

Table 1: The assumed and actual dates of 10 radiocarbon samples obtained from 5 trees from the DMA site. ***Age calibration was performed using SH1-2 data set (Hua *et al*., 2013) extended back in time using SHCal13 (Hogg *et al*., 2013), and CALIBomb program (Reimer and Reimer, 2004). **Actual ages given are those determined through redating the tree cores after radiocarbon analysis.

Table 2: Summary Statistics for the DMA Master Series.

Table 3: Calibration and verification statistics for the Brisbane annual rainfall reconstruction.

Figure Captions

Figure 1: Map out Southeast Queensland with urban areas including Brisbane marked in grey and National Parks in green. The location of the DMA site at Maiala is indicated in yellow, the three rainfall stations used in this analysis in blue, and the temperature station in red.

Figure 2: The DMA site: Subtropical rainforest with minimal understory vegetation.

Figure 3: Sample DMA026E after being cut with a twin-bladed saw. Each core is comprised of A) the bottom section of the core which is glued into the base, B) a lath of 2mm depth for scanning on the Itrax core scanner, and C) the remaining portion of the core which can be used for destructive analysis such as radiocarbon dating. While some evidence of ring boundaries are present in the DMA samples there are large parts of the cores where such boundaries cannot be identified as evidenced by the central portion of DMA026E.

Figure 4: A) Sample DMA026E for the period 1986-1998 and B) Sample DMA012F showing their Itrax Radiograph image overlaid with density pattern (blue line), actual ring boundaries (red line), fake ring boundaries observed in the radiograph and density pattern (white solid line), and a fake ring boundary observed only in the radiograph (white dotted line). The oldest rings are found to the right of the image with the youngest on the left. In A) ring 1990 is indicated with one red dot and in B) ring 2000 is indicated with four red dots.

Figure 5: The raw ring width series (A) and STD chronology from ARSTAN overlaid on sample depth (B) for the DMA data.

Figure 6: Climate response values for the DMA chronology series and both the Brisbane rainfall and SEQ temperature data. Correlation coefficients are given for monthly, seasonal, and annual precipitation (A), average monthly minimum temperature (B) and average monthly maximum temperature (C) for the year prior to growth (lowercase), the year of growth (uppercase). Correlations are significant when they surpass the dashed lines. Note: significance levels are dependent on the climate variable being calculated.

Figure 7: Reconstructed (black line) and instrumental (grey line) annual precipitation for Brisbane over the period 1946-2014. The calibration period (1946-1972) and verification period (1973-2001) are indicated. The precipitation records are extended through the Maiala post-construction period for reference. The Millennial Drought occurrence in eastern Australia is indicated by the light grey background.

Figure 8: Moving window of correlation values for 26-year calibration periods (black line) over the entire 1946-2014 reconstruction. The mean values (grey dashed line) and ±1 standard deviation (dotted lines) are given for the period up to 2001 and from 2002 onwards.

Table 1: The assumed & actual dates of 10 radiocarbon samples obtained from 5 DMA trees.

Tree	Sample Code	Assumed Year of Growth	^{14}C content ± 1 σ (pMC)	Calibrated ^{14}C age (95% confidence)*	Actual Year of Growth**
DMA006	OZU612	1962	159.57±0.38	1964.50-1965.24 1966.42-1968.33	1966
	OZU622	1970	139.41±0.36	1963.51-1963.93 1973.90-1976.20	1975
DMA010	OZU614	1964	150.29±0.43	1964.01-1964.39 1969.88-1972.23	1970
	OZU615	1967	142.68±0.38	1963.69-1964.06 1973.31-1974.83	1973
DMA012	OZU616	1964	152.46±0.36	1963.94-1964.82 1968.62-1971.41	1964
	OZU617	1968	149.72±0.41	1963.98-1964.37 1969.90-1972.25	1970
DMA014	OZU618	1964	120.42±0.31	1960.07-1963.22 1984.69-1988.12	1961
	OZU619	1967	160.82±0.39	1964.64-1965.65 1966.35-1968.30	1964
DMA025	OZU620	1963	162.27±0.41	1964.66-1967.73	1964
	OZU621	1967	151.77±0.37	1963.94-1964.82 1969.42-1971.84	1969

*Age calibration was performed using SH1-2 data set (Hua *et al.*, 2013) extended back in time using SHCal13 (Hogg *et al.*, 2013), and CALIBomb program (Reimer and Reimer, 2004). **Actual ages given are those determined through redating the tree cores after radiocarbon analysis.

Table 2: Summary Statistics for the DMA Master Series.

Chronology Length	1945-2014
No. of trees	20
No. of cores	39
Mean ring width (mm)	0.419
Standard deviation (mm)	0.232
Median Ring Width (mm)	0.357
Skew	1.20
1st year EPS > 0.80 and sample size > 5	1945
Correlation statistics	
Mean Sensitivity	0.384
Mean Series Intercorrelation	0.650
Gini	0.292
AR1	0.460
Rho	0.477

Table 3: Calibration and verification statistics for the Brisbane annual rainfall reconstruction.

	Calibration				Verification			
Time Span	First	Last	r	C-RE	First	Last	V-RE	V-CE
Full	**1946**	**2001**	**0.377**	**0.111**				
Early	1946	1971	0.413	0.170	1972	2001	0.118	0.107
Late	1972	2001	0.345	0.119	1946	1971	0.155	0.111

Highlights:

- New approach presented for tree-ring identification in cores with faint, indeterminate ring boundaries
- First tree-ring chronology from Australian *Araucariaceae* species
- 69-year annual rainfall reconstruction for Brisbane city

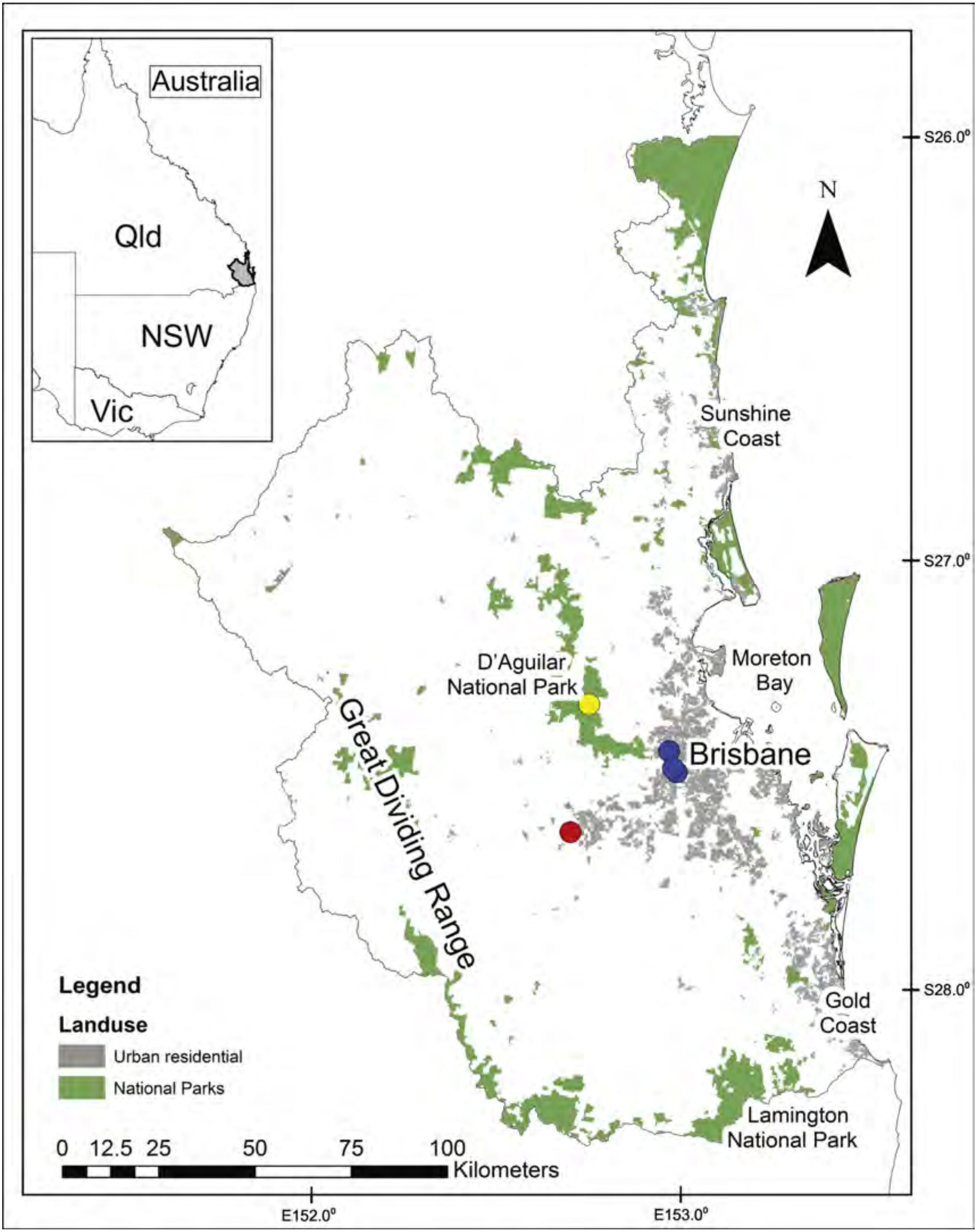

Australia
Qld
NSW
Vic
S26.0°
S27.0°
S28.0°
N
Sunshine Coast
Moreton Bay
D'Aguilar National Park
Brisbane
Great Dividing Range
Gold Coast
Lamington National Park
Legend
Landuse
Urban residential
National Parks
0 12.5 25 50 75 100 Kilometers
E152.0°
E153.0°

Figure 1

Figure 2

Figure 3

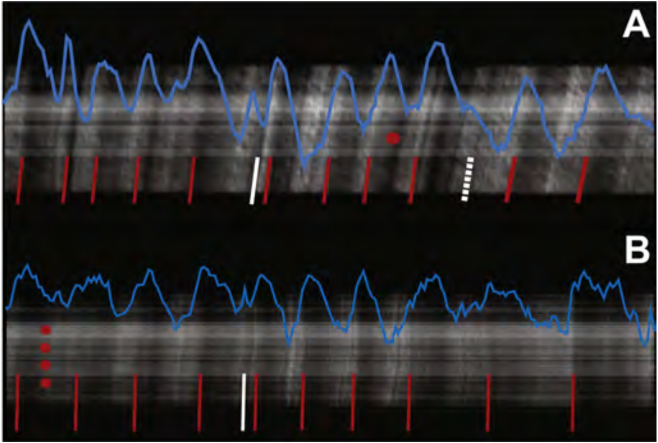


Figure 4

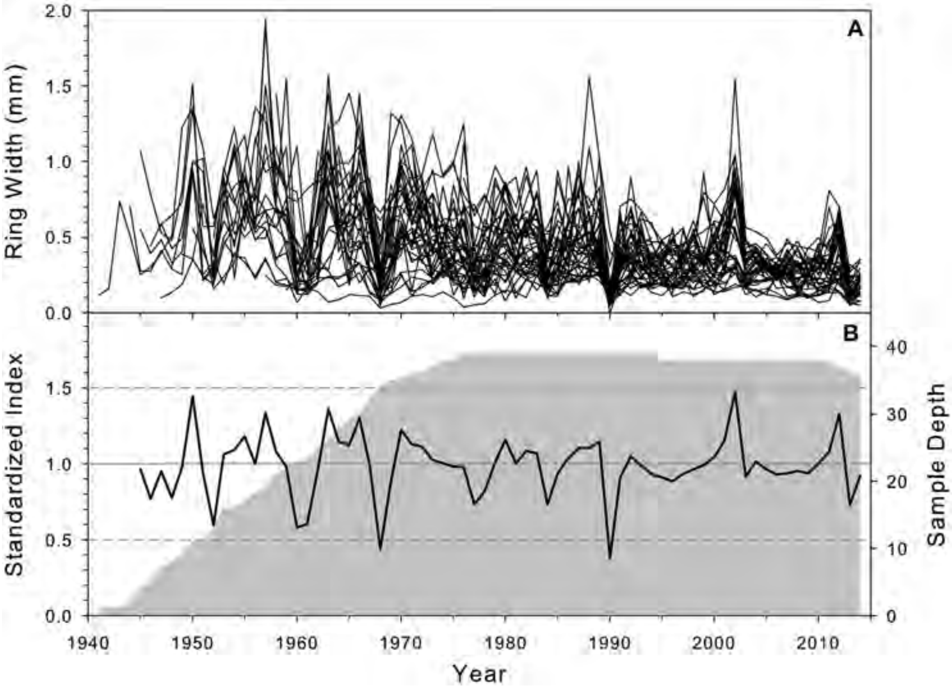

A
B
Ring Width (mm)
Standardized Index
Sample Depth
Year
0.0
0.5
1.0
1.5
2.0
0
10
20
30
40
1940
1950
1960
1970
1980
1990
2000
2010

Figure 5

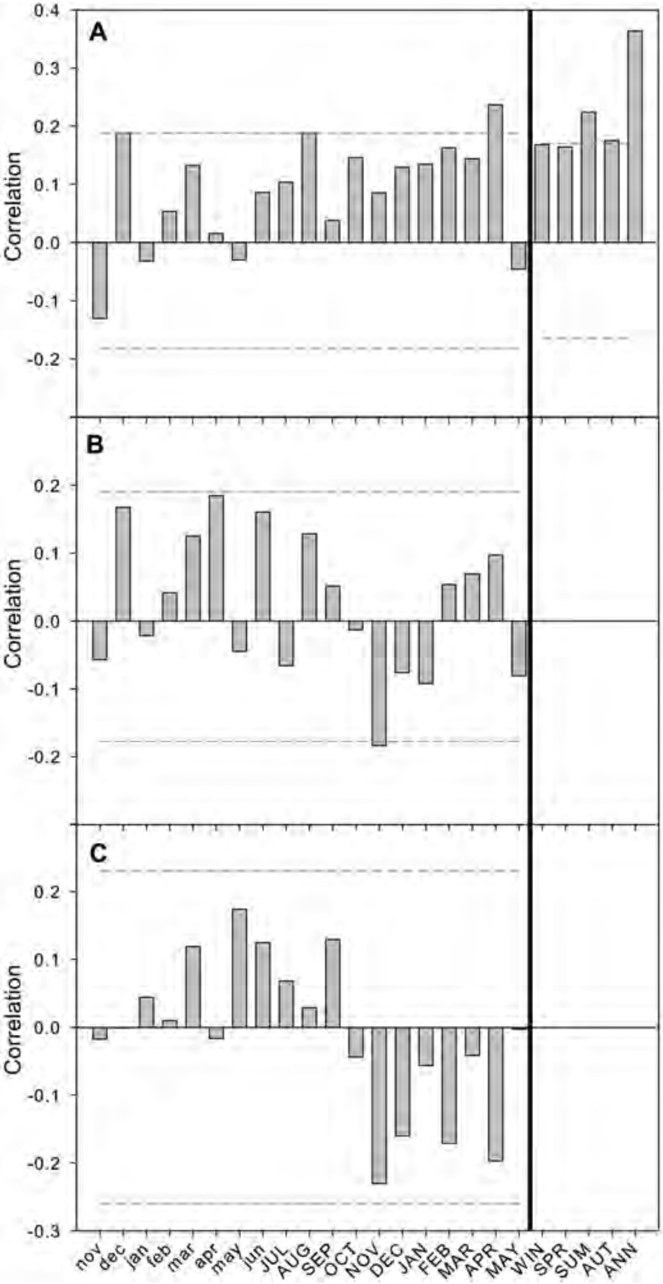
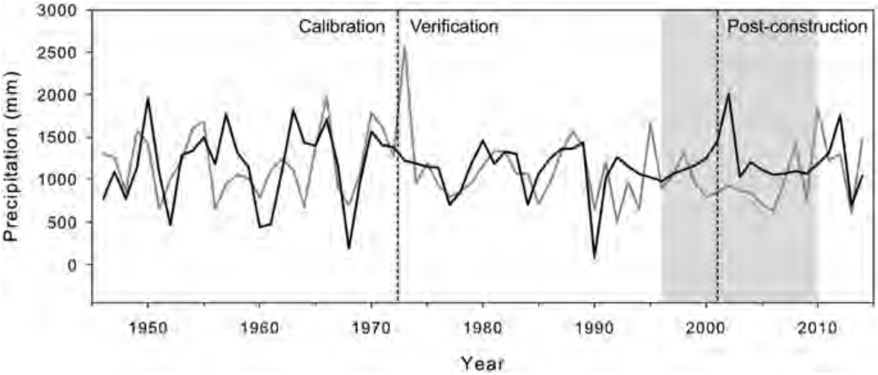
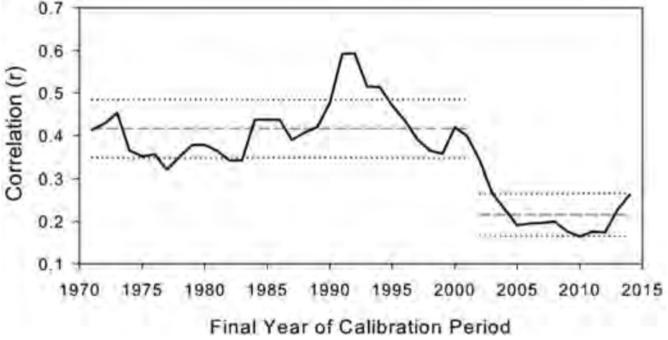

A
B
C
Correlation
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
nov
dec
jan
feb
mar
apr
may
jun
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
WIN
SPR
SUM
AUT
ANN

Figure 6



Calibration
Verification
Post-construction
Precipitation (mm)
3000
2500
2000
1500
1000
500
0
1950
1960
1970
1980
1990
2000
2010
Year

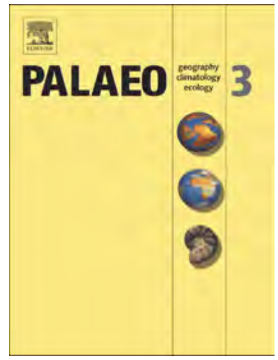
Figure 7



0.7
0.6
0.5
0.4
0.3
0.2
0.1
Correlation (r)
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Final Year of Calibration Period

Figure 8

Accepted Manuscript



A new method for dating tree-rings in trees with faint, indeterminate ring boundaries using the Itrax core scanner

Heather A. Haines, Patricia S. Gadd, Jonathan Palmer, Jon M. Olley, Quan Hua, Henk Heijnis

PII: S0031-0182(17)30697-1
DOI: doi:10.1016/j.palaeo.2018.02.025
Reference: PALAEO 8683

To appear in: *Palaeogeography, Palaeoclimatology, Palaeoecology*

Received date: 27 June 2017
Revised date: 19 February 2018
Accepted date: 25 February 2018

Please cite this article as: Heather A. Haines, Patricia S. Gadd, Jonathan Palmer, Jon M. Olley, Quan Hua, Henk Heijnis , A new method for dating tree-rings in trees with faint, indeterminate ring boundaries using the Itrax core scanner. The address for the corresponding author was captured as affiliation for all authors. Please check if appropriate. Palaeo(2017), doi:10.1016/j.palaeo.2018.02.025