Anomalous ring identification in two Australian subtropical *Araucariaceae* species permits annual ring dating and growth-climate relationship development

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Highlights:

- Subtropical *A. cunninghamii* and *A. bidwillii* grow in response to climate
- Several types of ring anomalies are prevalent in *Araucariaceae* species
- Potential exists to create tropical tree-ring chronologies by applying multiple techniques
- Long-term subtropical rainfall reconstructions can be made using *Araucariaceae* trees

Abstract:

Almost all Australian tropical and subtropical regions lack annually-resolved long-term (multi-decadal to centennial scale) instrumental climate records. Reconstructing climate in these regions requires the use of sparse climate proxy records such as tree rings. Tree rings

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often archive annually-resolved centennial-scale climate information. However, many tropical and subtropical species have short life-spans, the timbers are poorly preserved, and there is a belief that the proxy records of these species are often compromised by ring anomalies. Additionally, for many species the relationship between climate (e.g. temperature and/or rainfall) and tree growth has not been established. These factors have led to tree-ring data being underutilized in the Australian subtropics. Trees in the *Araucariaceae* family, a common family in northern and eastern Australia, are both longer lived than many species in the Australian subtropics, present growth rings that are annual in nature, and their growth is known to vary with climate. In this study we examine two subtropical *Araucariaceae* species, *Araucaria cunninghamii* and *Araucaria bidwillii*, and quantify the relationship between their radial growth and climate variability. Ring anomalies including false, faint, locally absent, and pinching rings, are found to be present in these species, however, bomb-pulse radiocarbon dating of *A. cunninghamii* samples together with a whole tree approach helped to identify annual growth patterns despite such anomalous ring boundaries. Additionally, to determine which climate variables most influence growth in these species dendrometers were installed at two locations in subtropical Southeast Queensland, Australia. We found that rainfall variability drives annual ring growth, while temperature constrains the onset and conclusion of the growth season each year. Our results demonstrate that through the use of *A. cunninghamii* and *A. bidwillii* trees which demonstrate annual growth in relation to climate variables there is potential to develop centennial scale climate reconstructions from the Australian subtropics. We provide recommendations on how to best identify ring anomalies in these species to help in the future development of long-term chronologies and climate reconstructions.

Keywords:

Araucaria cunninghamii; *Araucaria bidwillii*; ring anomalies; dendrometer; bomb-pulse
radiocarbon dating; Southeast Queensland

Introduction

Rainfall variability in Australia is a major factor contributing to economic loss, with both multi-decadal periods of drought and flood having significant effects. Historic and instrumental records of rainfall in most tropical and subtropical regions are sparse and typically extend back less than 100 years from present (BoM, 2001). Understanding and forecasting multi-decadal rainfall variability is difficult without centennial- to millennial-length precipitation records (see for example, Graham *et al.*, 2007; Seager *et al.*, 2007). Proxy records of rainfall based on annual tree-ring widths and chemistry have been extensively applied in climate studies worldwide (Watson and Luckman, 2004; Wilson *et al.*, 2005; Cullen and Grierson, 2009). However, very few Australian tropical and subtropical tree species have been evaluated for their utility as climate proxies (Haines *et al.*, 2016). Additionally, trees growing in northeastern Australia are often difficult to date using ring-width analysis as they regularly produce non-annual growth rings, as well as exhibit ring anomalies such as pinching, false, and/or locally absent rings (Ogden, 1981; Worbes, 2002; Heinrich and Allen, 2013). Growth in tropical/subtropical tree species can also be affected by localized influences such as competition, vine coverage, and insect infestation among others (Worbes, 2002). Due to these complications early research suggested that trees in northern Australia were not suitable for use in climate reconstructions (see Ogden, 1978). Recently studies that quantify the drivers of tree growth using modern analysis techniques have resulted in successful dendroclimatic reconstructions of tropical and subtropical environments (e.g. Shah *et al.*, 2007; Heinrich *et al.*, 2008; 2009).

Only one climate reconstruction currently exists for eastern subtropical Australia; a 146-year precipitation reconstruction from *Toona ciliata* M. Roem. tree-rings developed by Heinrich *et al.* (2009). There is also a millennial scale reconstruction of climate for all of eastern Australia (Palmer *et al.*, 2015) which does not include any tree-ring data from

northeastern Australia. Yet several species have been identified as having dendroclimatic potential in northeastern Australian environments. Many of these species (eg. those in the *Callitris* genus) have relatively short life spans (Ash, 1983a; Baker *et al.*, 2008) and preserved wood material (from any species) is rarely found in tropical/subtropical environments, making the development of centennial-scale or longer proxy climate records difficult. Species in the *Araucariaceae* family typically have longer lifespans (Ogden, 1978) and Ash (1983b) showed that some species in this family developed annual rings in response to climate. Ash (1983b) observed that tropical *Agathis robusta* (C. Moore ex F. Muell.) F.M. Bailey growth responded to precipitation and *Araucaria cunninghamii* Mudie growth was positively related to precipitation and to a lesser extent temperature. Research undertaken on tropical South American *Araucaria angustifolia* (Bertol.) Kuntze trees also found a climate relationship that relied on both temperature and rainfall to determine tree growth (Oliveira *et al.*, 2010). This evidence suggests that trees in the *Araucariaceae* family may yield long-term climate reconstructions in northeastern Australia although such a reconstruction has yet to be completed.

Here we examine the potential of tree rings in two subtropical *Araucariaceae* species, *A. cunninghamii* and *Araucaria bidwillii* Hook for use in climate studies. The frequency and nature of ring anomalies is examined and bomb-pulse radiocarbon dating is used to validate the annual nature of the rings. We also quantify the relationship of ring-growth to local climate and investigate the potential for using these species to reconstruct climate in the eastern Australian subtropics.

Regional Setting

Subtropical eastern Australia encompasses a narrow band along the Queensland coast from just south of the Atherton Tablelands near Cairns to the southeastern quarter of the state

near Brisbane (see Figure 1 in Haines *et al.*, 2016). Southeast Queensland (SEQ) is the most populated region in subtropical Australia and is located along the Queensland-New South Wales border from the coast inland to the Great Dividing Range, extending north through the Somerset and Sunshine Coast catchments (Figure 1). The region has mean annual temperatures ranging from 21°C to 29°C and annual rainfall between 900 and 1800mm mostly falling in the austral summer warm season from October to March (Saxton *et al.*, 2012; Kemp *et al.*, 2016). Rainfall in SEQ is highly variable with a recent paper by Haines and Olley (2017) indicating that the pattern of rainfall through time across the catchment is dynamic with clear multi-decadal periods of wet and dry noted in the instrumental records.

Southeast Queensland is a heavily modified environment with intense land clearing following European settlement in the 1820s and imported agricultural practices beginning in the 1840s (Kemp *et al.*, 2015; Coates-Marnane *et al.*, 2016). Grazing occurs over 25% of this region and has led to significant removal of native vegetation (Saxton *et al.*, 2012). However, regions of unharvested forest cover can be found in the higher altitudes of SEQ with the majority of remnant rainforest regions found within National Parks (Horne and Hickey, 2001). In these areas, unlogged forest stands can still be found on steep hillsides composed of basalt or rhyolite bedrock covered in a thin layer of soil and organic matter (Willmott *et al.*, 1995; Horne and Hickey, 2001; Strong *et al.*, 2011).

Site selection

Within these stands of unlogged forest, we selected sites with the best possible prospects for developing long-term climate reconstructions for Southeast Queensland. We identified stands of greater than 25 *Araucariaceae* trees that reached canopy height within three National Parks of SEQ. While there are three species of *Araucariaceae* found in Southeast Queensland only two, *A. bidwillii* and *A. cunninghamii* are known for preferring

the poor, volcanic soils present in SEQ National Parks (Cronin, 2009). We took samples and measurements from one site of *A. bidwillii* in Bunya Mountains National Park (BDT site) and two sites of *A. cunninghamii* located in Lamington National Park (LBB site) and D'Aguilar National Park (DMA site) (Figure 1). The BDT and LBB sites were selected as they contain old-growth remnant forest. The DMA site trees were planted sometime after 1830 when D'Aguilar National Park was established on previously logged land (QDNPSR, 2015). In addition, the three rainforest sites selected for this study are all located within different regional rainfall groups as identified in Haines and Olley (2017), with each group showing a distinct temporal pattern of rainfall.

Methods

Sample collection and preparation

Trees selected in this study ($n = 84$) only included those that reached canopy height, represented a dominant or subdominant tree in the stand, appeared on visual inspection to be healthy, and did not look to be affected by localized factors such as heavy vine coverage around the trunk or signs of insect infestation. Diameter breast height (DBH), slope, and aspect were recorded for each tree. Four 4mm cores were taken where possible from the upslope, downslope, and the across-slope sides of each tree. In some cases only three cores could be safely collected from a tree. In total 99 cores from 25 *A. bidwillii* trees, 105 cores from 28 *A. cunninghamii* trees, and 120 cores from 31 *A. cunninghamii* trees were collected at the BDT, LBB, and DMA sites, respectively. From these individual *A. cunninghamii* trees, two additional 12mm cores were also taken from 23 of the study trees at the LBB site ($n = 46$ cores) and 27 of the study trees at the DMA site ($n = 54$ cores). The 12mm cores were taken where possible at 45° from the 4mm core locations with upslope and downslope choice determined by best possible access to the tree; in a few cases a core was taken much closer to

a 4mm core (eg. 5°) for access reasons. The length of the core and bark depth were recorded for each sample. Samples were stored in ventilated plastic straws (4mm cores) or plumbers piping (12mm cores) and transported back to the lab for processing.

Immediately upon return to the lab samples were air dried for 3-5 days and then placed in a drying oven at 40°C for 4-6 hours to remove any excess moisture. Samples were then mounted using non-toxic water-soluble acid free glue which would allow the sample to be removed from the mount with water and used for destructive analysis if needed. The 4mm cores were sanded using an electric hand sander progressively using 60, 120, 240, 400, 800, 1200, and 1500 grit sandpaper to polish the wood so that rings were clearly visible in the samples. The 12mm cores were cut using a twin-bladed saw (Dendrocut 2003, Walesch Electronics) so that each core was cut into 3 pieces; a bottom section glued into the mount, a 2mm lath from the centre, and a top section of remaining sample. The bottom mounted sections of the 12mm cores were then sanded in the same manner as the 4mm cores.

Visual analysis and bomb-pulse ^{14}C dating

Visual analysis of the LBB and BDT site trees was undertaken to determine the presence of any ring anomalies in these *Araucariaceae* samples. Cores from these sites were found to have visually identifiable ring boundaries (Figure 2A and 2B). In some cases these anomalies can be identified in the *Araucariaceae* samples with the naked eye while others required the use of a microscope for cell composition and boundary identification. The cores from these sites were visually dated with an 8-64x magnification microscope (following Stokes and Smiley, 1968) using the Schulman (1956) calendar age assignment. As several previous studies had indicated there is a tendency to find ring anomalies in *Araucariaceae* samples (Ogden, 1978; 1981; Ash, 1983b; Oliveira *et al.*, 2009; 2010) this preliminary study focused on the most recent 100 years of growth. This 100 year period was chosen as

instrumental records are available for most of this time and bomb-pulse radiocarbon dating could be used to validate the visual dating of the tree-ring series (Biondi *et al.*, 2007; Wood *et al.*, 2010; Pearson *et al.*, 2011). The bomb-pulse radiocarbon dating was used as a means of confirmation in identifying ring anomalies in the LBB study samples.

Two individual rings per core of ten 12 mm cores from the LBB site were dated using accelerator mass spectrometry (AMS) ^{14}C analysis at the Australian Nuclear Sciences and Technology Organisation (ANSTO). Wide rings were selected in order to get enough material for AMS ^{14}C analysis. In addition, rings that were formed close to the timing of the bomb peak period of 1963-1967 (based on visual dating) were chosen so the greatest calendar age resolution determined by the bomb-pulse ^{14}C dating method could be achieved (Hua and Barbetti, 2004; Hua, 2009). Tree-ring specimens were pre-treated using an alpha-cellulose extraction method outlined in Hua *et al.* (2004) before undergoing combustion and graphitization as per methods in Hua *et al.* (2001). ^{14}C analysis was performed using the STAR AMS Facility at ANSTO using the procedures described in Fink *et al.* (2004). Calibrated ^{14}C calendar ages at 95% confidence level for each single-ring specimen were calculated using the bomb ^{14}C data for the Southern Hemisphere zone 1-2 (Hua *et al.*, 2013) extended back in time using the SHCal13 data (Hogg *et al.*, 2013), and the CaliBomb calibration program (Reimer and Reimer, 2004). A full documentation of all twenty radiocarbon specimens, their measured ^{14}C content in percent modern carbon (pMC) and their calibrated age ranges can be found in Table 1.

For each specimen ^{14}C value two possible calendar ages are delivered by bomb radiocarbon with one on the rising arm and the other on the falling arm of the bomb curve (Hua, 2009). Therefore, for each ring specimen there were two values of errors for the assumed year of growth (based on visual dating) compared with its calibrated age (see Table 1). As two single rings in each core with only several years apart were sampled, very similar

errors (in size and direction) for the two assumed year of growth should be expected. This approach allows for precise estimation of error values for the two assumed year of growth in each core (Pearson *et al.*, 2011).

A. cunninghamii cores from the DMA site were processed in the same manner as those from the LBB site, however, the ability to visually date the wood from these two locations were vastly different. While ring boundaries were clearly visible in the LBB cores, the DMA cores yielded faint ring boundaries which in most cores could not be distinguished even under high magnification (Figure 2C). For this reason the DMA site could not be used to identify other ring anomalies present in *A. cunninghamii* trees and was not included in the remainder of this study.

Dendrometer analysis

At both the BDT and LBB sites radius dendrometers (DR Radius Dendrometers, Ecomatic) were installed at breast height on four *A. bidwillii* trees in October 2014 and three *A. cunninghamii* trees in May 2015 respectively, to continuously monitor tree growth. These point-based dendrometers record the expansion and contraction of the tree in microns (μm) every 15 minutes. The raw data was recorded by a data logger at each location with site visits conducted every 13-16 weeks to download the data and check the equipment.

One issue that arose in the placement of the dendrometers in this study was related to the amount of bark present on the study trees. *Araucaria* trees have very large amounts of bark present (Table 2) which makes it impossible to place the radius dendrometers directly on the xylum of a tree without removing so much bark that the tree would be harmed and the readings would be biased and inaccurate. As such a modified placement was undertaken where all 'inactive bark', that which was flaking off and clearly no longer attached and responding to tree growth, was removed and the dendrometer placed against the 'active'

surface of the tree. In all study trees the amount of bark removed was between $\frac{1}{4}$ to $\frac{3}{4}$ of a centimetre and did not cause any damage to the tree that would bias readings.

The raw dendrometer data was transformed into daily data for growth-climate analysis. As the goal of this study was to understand how daily climate variability affected daily tree growth we transformed data into daily measurements (see Deslauriers *et al.*, 2007 for more details on the daily approach to data transformation). We used the daily mean method (Tardif *et al.*, 2001) as it was least likely to bias the data with an anomalously high or low dendrometer reading such as those caused by interference to the trees by flora and fauna. For this study daily data from the BDT site was used from October 22, 2014 until September 20, 2016. Data between February 10 to 23, 2015 is missing due to a failure in the data logger. The daily data from the LBB site was used from May 20, 2015 until September 18, 2016 with data missing from March 13 to 15, 2016 due to the need to remove the logger from site for minor repairs. These logger failures did not occur during the onset or shut down of the growth season or during a major climate event and the loss of this data should not bias the overall outcome of this study. Additionally, on June 17, 2016 dendrometer Lam2 at the LBB site had to be removed from the tree, repaired, and replaced. After a removal a dendrometer will settle and the values may change which accounts for the spike in growth seen in early July for this dendrometer. For each individual dendrometer the raw data measurements for each day ($n = 96$) were averaged together to give one daily value using the software dendrometerR (van der Maaten *et al.*, 2016) providing 686 and 482 days of data for each of the BDT and LBB dendrometers respectively. At each site the data from the respective dendrometers were standardized to a zero start value so accurate comparisons between trees could be achieved. While no universal method was applied to deal with anomalous readings most were removed by the standardization procedure. The few that did remain, such as that in the Lam2 dataset on June 17, 2016, were individually considered to make sure that they

were in fact an anomaly. As there were very few instances of significantly high or low values, all that did exist could be identified as relating to a specific event (eg. large wind storm), and the form of analysis conducted did not allow for individual values to heavily bias the data no values were removed from the dataset.

Daily rainfall, minimum temperature, and maximum temperature data from BoM climate stations (BoM, 2015) were compared to the daily tree growth measurements. Rainfall and temperature data from Vincent Vale (Station 40307) and Dalby Airport (Station 41522), respectively, were used for the BDT site and stations Numimbah (Station 40550) and Beaudesert Drumly Street (Station 40983), respectively, were used for the LBB site. Multiple linear hierarchical regression analysis was run on the collective set of climate variables in comparison with each dendrometer for both the annual growth and dormant seasons each year. Due to the placement of the dendrometers over several centimetres of bark an effect was observed that related to bark swelling occurring after rainfall events. Tree bark sucks up the water during rainfall so the bark swells and growth appears to occur but when the water drains out of the bark over time the tree appears to shrink. This event based phenomena had never been noted previously in the literature, there is a long history of evidence of diurnal variation in dendrometer readings due to uptake in water by tree bark (eg. Holmes and Shim, 1968; Lassoie, 1973; Offenthaner *et al.*, 2001; Drew and Downes, 2009) as well as indications that the onset of a rainy season can cause tree stem swelling (Krepkowski *et al.*, 2011) but no species with as much bark as those in this study have previously been reported on. Therefore to better understand the effect precipitation has on tree growth and to disentangle the effects of bark swelling a modified epoch analysis (mEA) was performed on the ten largest rainfall events during each growth and dormant season. A rainfall event was deemed to be a period of n days where rain occurred consecutively, once a day passed without precipitation the rainfall event was deemed to be over. Rainfall events at

the study sites ranged in length from 1 to 7 days and in some cases occurred within 1 day of the completion of the previous rainfall event. mEA was undertaken for a one week period after the start of a rainfall event (Day 0 to Day 6) where the first day of the rainfall event is listed as Day 0. Growth during the 7 days was compared to the tree diameter on the day before the rainfall event (Day -1). This was done by subtracting the tree diameter on Day -1 from the tree diameter measured on Days 0 through 6. This allowed for bark swelling occurring during a rainfall event to be noted. As *Araucariaceae* trees have very thick bark the growth seen during and immediately after a rainfall event in these species is representative of both tree growth and the water held in the bark. By observing changes in the dendrometer values for a 7 day period the effect of bark swelling and the actual growth occurring in the tree can be detached and true growth assessed. All growth and climate data analysis was undertaken using Microsoft Excel.

Results and Discussion

Ring anomalies, ring-width dating, and AMS ^{14}C analysis

Ring anomalies observed in trees from the LBB and BDT sites included pinching, locally absent, and false rings as well as ring boundaries that were too faint for visual identification (see Figure 3). Pinching rings found at both sites are generally caused when a tree either sustains damage or when not enough nutrients are available within a growth year to provide for wood formation around the entire circumference of the tree (Speer *et al.*, 2004; Speer, 2010). In tree species with large trunk diameters and high nutrient demands (*ie. Araucariaceae* family) pinching rings are common. In such species the best way to develop chronologies is to use full cross-sections cut from a trunk (Speer *et al.*, 2004; Speer, 2010). However, as the study sites utilized here are within National Parks taking cross-section samples was not feasible. Our approach (multiple cores from approximately 90° apart)

attempts to develop a robust ring record from each tree that accounts for the common instances of pinching rings. While on occasion a core was taken at a spot where the pinching of rings could be clearly observed (Figure 3A) more often what was found is locally absent rings. Generally, locally absent rings are found during years when the rings tend to be narrow, representing less than ideal conditions for growth, but there are some instances where this is not the case which may in fact be a representation of damage occurring to a specific tree such as from a wind storm or another tree falling against one side.

Similar to locally absent rings, missing rings occur when there is no growth during a year around the entire tree circumference. In the 100 year period focused on in this study there is no evidence of missing rings occurring in any of the study trees that can be used in master chronology building for either species. Additionally, we identified numerous micro rings, those only a few cells wide (Speer *et al.*, 2004; Speer, 2010), especially approaching the exterior of the tree. These very narrow rings are common and are easily misidentified. We would suggest that in this tree family micro rings cannot be considered anomalous and researchers working with these trees should make sure they account for very narrow rings when dating samples.

False rings, those where an annual boundary between latewood and earlywood appears to exist but in fact is not an annual ring, are very common in the LBB and BDT site trees (Figure 3B and 3C respectively). Generally false rings occur in tropical trees when growth begins to shut down for a season due to a change in environmental conditions but conditions reverse and growth again becomes favourable allowing for a return to earlywood growth (Ogden 1978; 1981). Often in these species false rings are identified under the microscope when it is clear that a true latewood boundary has not formed. The results from Ash (1983b) indicated that when tropical/subtropical tree species growth is driven by precipitation, as is seen in *Araucariaceae* trees, false rings can be expected due to the fact

steady rainfall may not always occur throughout the entire growth season. This occurs in SEQ where there are well-defined wet and dry seasons, however, significant (>30 days) droughts within the wet season regularly occur (BoM, 2015).

The final ring anomaly identified in these species was faint ring boundaries. While the samples from the DMA site were an extreme manifestation of this type of anomaly there are also faint ring boundaries within the LBB *A. cunninghamii* and BDT *A. bidwillii* samples (Figure 3D). Faint rings are true annual ring boundaries that cannot be identified visually as there is no change in the appearance of the wood between latewood and earlywood and are a form of ring anomaly clearly described as being an issue in *A. cunninghamii* samples (see Ogden, 1981). Under high magnification a difference in cell properties is also not able to be determined in faint wood cores. In some instances just one or two rings appear faint and the actual boundaries can often be identified by looking at multiple cores from a single tree. Rarely, in some LBB cores, there are entire sections that appear very faint occurring in all cores from an individual tree and causing issues with dating. The occurrence of an entire set of cores with non-visually dateable ring boundaries as seen in the DMA site is unexpected as the literature does not describe situations where this has occurred before in Australia. The faint sections observed in the LBB samples in this study are typically excluded from the final dated ring series when the actual boundaries cannot be determined with certainty from any of the cores.

Due to the knowledge that there are many ring anomalies present in the study trees bomb-pulse radiocarbon dating was undertaken to assist in both identifying possible anomalies and to confirm dating of the series. Based on 20 ^{14}C dates obtained (Table 1), none of the visually determined ring dates assigned after preliminary traditional dendrochronological analysis were correct indicating the importance of dating verification when working with trees in this family. However, we used these dates to help identify

anomalous rings in the LBB cores and improve our visual dating of the series. Radiocarbon dating presents a true calendar age range (at 95% confidence level) that in most cases is quite small (with the exception of Category C as explained below) and can be assigned to a likely year through the use of traditional dendrochronological techniques and two-ring analysis as discussed in the methods section. After radiocarbon dating was completed the ring patterns for the entire series in this study were reanalysed looking for marker rings as well as conducting quality control to confirm that the chronology developed was correct. Prior to the undertaking of this study no detailed description of the ring anomalies in *Araucariaceae* species existed. The classification system outlined herein should assist in future work identifying and dating rings within tropical/subtropical *Araucariaceae* species.

Category A trees represents those with locally absent rings, those where a ring pinches out and are only found around part of the circumference of the tree (Table 1, Figure 4A). Three of the radiocarbon dated trees; LBB-001, LBB-015, and LBB-016, were placed in this category and had between 2 and 9 locally absent rings. For these trees a whole tree approach was applied, this involves looking at all cores from a single tree at once and viewing them laid out in a 365° pattern as they would appear on a full cross-section. Trees were then analysed in decadal increments so that marker rings could be identified between trees and anomalous rings identified. This allowed for all rings to be found in at least one core from the 4-6 cores taken from each tree and a tree master series to be developed. Several other trees from the 28 *A. cunninghamii* trees in the LBB dataset fit into category A and these were also dated using a whole tree approach. All trees within category A were able to be dated and had their reassigned calendar ages confirmed via site level marker rings as well as passing quality control analysis with COFECHA (as per Grissino-Mayer, 2001). Therefore Category A trees from this dataset can be combined together and assessed for inclusion in a site master chronology. It should be noted that any form of anomalous ring can

be found in trees placed in any category however, locally absent rings was the main issue identified in Category A trees and was the common factor found to be linking them together.

Classification B represented trees where false rings were observed (Figure 4B). This classification was further broken down into B1, where false rings could be identified under high magnification using a whole tree approach, and B2, where the growth conditions and wood properties caused many occurrences of false rings. Trees in B1 such as LBB-007 and LBB-018 showed false rings that typically occurred in years where two periods of rainfall surrounded a dry period within the growth season. The use of a whole tree approach was applied here as these false ring boundaries tend to be easier to identify at certain points around the tree circumference. Under high magnification the false rings do not always demonstrate a continuous solid boundary edge as is found in true ring boundaries. Therefore, by comparing all cores from a single tree instances of discontinuous boundary edges are more easily located. The trees in category B2, such as LBB-002 and LBB-027, were found to grow on shallower slopes where water could pool at the base of the trees during the wet season. The wood properties of these trees made it difficult to identify where the true ring boundaries were located and sections were truncated, similar to the procedure undertaken by Oliveira *et al.* (2010), so that bias due to unclear dating in a master chronology was minimized.

The final classification C identified in the LBB series was observed in three radiocarbon dated trees, LBB-009, LBB-020, LBB-028. Trees found in this category cannot be included in a master dataset as they contain many pinching and locally absent rings (Figure 4C). In total six trees from the LBB site were placed into category C and were removed from further analysis. Field investigations were conducted to investigate why these trees demonstrated series of rings that could not be reliably dated. Each tree was found to be either i) proximally located to another large tree causing limited resources to be shared between both trees or ii) have heavier vine coverage around the upper portion of the tree

only. During initial field sampling these trees were considered for use in this study as there are few *A. cunninghamii* trees available for use in this region. The distance between trees was considered sufficient upon field sampling but this study has indicated that trees in such a resource limited setting require large areas without resource competitors to provide a potential climate related growth signal. It was also initially assumed that upper level vines would not have a great impact on tree growth which this study has proven to be incorrect in regards to this species. Site and tree selection when undertaking a tropical/subtropical tree-ring study are therefore shown to be important as trees in categories B2 and C should be avoided. However with few *Araucariaceae* trees available for study, as was the case at the LBB site, some potentially inferior trees may need to be sampled. Based on these results and those presented by others that demonstrate issues with ring anomalies in tropical/subtropical trees (see Ogden, 1978; Ash 1983) multiple analysis techniques are needed to allow for the development of tree-ring chronologies in these types of environments. This research suggests that combining radiocarbon dating, marker ring identification, and truncation of series where dating cannot be confirmed can allow for the development of tree-ring chronologies from subtropical environments.

Climate-growth relationships

The dendrometer analysis at both the BDT and LBB sites indicate relationships between tree growth and climate. The pattern of daily growth for each tree demonstrates that the large amount of bark found on the study trees has an effect on the observations made from the point dendrometers (Table 2, Figures 5 and 6). When a rain event occurs, either a large volume falling on a single day or over several consecutive days, tree bark absorbs water and swells, causing a point dendrometer on an *Araucaria* tree to overestimate the actual amount of growth occurring. Trees with greater bark cover, such as BM1 and BM3, have a

greater apparent growth after a rainfall event than those with less bark cover, such as BM2 and BM4 (Table 2, Figure 5). However, regardless of the amount of bark exaggeration, as the water is removed from the bark the point dendrometers show a decrease in diameter that then allows for an indication of whether or not growth had actually occurred due to the rain event. The bark swelling due to rain can be observed in both growth and dormant seasons but only during the growth seasons in any overall change in tree diameter observed (Figures 5 and 6). As the bark swelling response occurs in all the dendrometer records from this study this phenomena should be considered normal for this taxon and accounted for in future analysis.

To take the effects of bark swelling into account seasonal analysis was performed to avoid any event based bias in the data. The Bunya Mountains location demonstrated four distinct periods: a 2014 growth season, a 2015 dormant season, a 2015 growth season and a 2016 dormant season (Figure 5) which relates well to South American studies on *Araucariaceae* species that also demonstrate an annual nature to ring formation (Oliveira *et al.*, 2009). Based on these results it was determined that the growth season for the *A. bidwillii* trees in Bunya Mountains National Park runs from the start of November to the end of May. This growth season is developed from two years of data only and as such cannot be given with high certainty however, growth is occurring in the study trees during this approximate period and growth clearly ceases during the remainder of the year. To better define this period data collection over several more years is required, but for the purpose of this preliminary study the November to May growth period can be considered representative as other dendrometer studies have also estimated growth periods from short time periods (Worbes, 1999; Bouriaud *et al.*, 2005; Deslauries *et al.*, 2007).

Figure 5 demonstrates that there does appear to be some differences in the growth occurring in 2014 and 2015. In 2014 the trees grew about three times the amount seen in

2015 which may be attributed to several factors. Rainfall during the growth season (Nov 1 – May 31) was nearly the same in both years with 510.7mm falling in 2014 and 502.0mm in 2015, however, 70% of the 2015 rainfall occurred during the first half of the growth season compared to rainfall that was consistent through the entire 2014 growth season. The average temperature conditions were also similar for both years with conditions less than 1°C warmer but the onset of cooling occurring earlier in 2015 (Figure 5). The ecology of Bunya trees also needs to be considered. While *A. bidwillii* trees produce nuts every year they are known to be mast seeders that produce a bumper crop every three years (Smith and Butler, 2002). As only two years of dendrometer data is available for this study and mast seeding events did not occur in these years we cannot rule out an effect of this three year nut cycle as a possible cause for the discrepancy in growth between 2014 and 2015. Mast seeding occurred in 2013 and 2016 with 2013 producing a heavy crop of nuts but the 2016 crop being smaller than usual (personal communication QLD Parks and Wildlife Staff). Therefore several more years of data is needed to conclusively determine the actual effect of mast seeding and to fully understand the discrepancies in growth observed between 2014 and 2015.

Statistical relationships between growth of the *A. bidwillii* trees and climate variables were assessed through multiple regression. Table 3 demonstrates the r-values for seasonal variability and significant relationships between tree growth and climate for the growth seasons. While some tropical dendrometer studies indicate growth is only related to rainfall (see Worbes, 1999; Krepkowski *et al.*, 2011) our results suggested several climate connections (Table 3) as was found to occur at the North American tropical treeline by Biondi and Hartsough (2010). In our study a connection between temperature variables and tree growth is observed in the *A. bidwillii* samples for 2014 however, the situation for 2015 appears more complicated. Due to observations that in 2015 growth seemed to stop much earlier in the year (see Figure 5) multiple regression was also run based on the October 10th,

2015 to January 5th, 2016 period where definite growth is observed in the Bunya Mountains trees. When analysed on this shorter timescale temperature variables once again show significant correlations with tree growth (Table 4). Analysis of the temperature patterns presented in Figure 5 suggests that when minimum temperatures reach around 20°C growth begins in the *A. bidwillii* trees, additionally, growth cessation occurs when minimum temperatures drop to around 0°C. This would account for the significant correlations observed between the seasonal dendrometer growth data and temperature variables. At this time such an observation is speculative with only two years of growth data available. However, based on these preliminary results and Ash's (1983b) observations that growth in some *Araucariaceae* trees appear correlated to both rainfall and temperature this relationship should be considered for future monitoring of subtropical trees of this and similar species.

The dendrometers at the LBB site have only been recording data through one growth season; however, the results seem to show similar relationships to what is observed at the BDT site (Table 3, Figure 6). Multiple regression analyses demonstrated that temperature variables were also significantly correlated to growth for the three *A. cunninghamii* LBB dendrometer trees (Table 3). Growth at the LBB site appears to begin in mid-August and continues until the end of March which matches with temperature variability (Figure 6). It should be noted that there does appear to be a slight difference between the growth pattern in trees Lam1 and Lam2 when compared against Lam3 (Figure 6). As there is only one year of data and no obvious reason observed in field investigation of the Lam3 tree through the study period it is unclear what caused growth to stop early in this case. However, the general growth season pattern does appear to match up against the temperature conditions as shown in Figure 6.

Surprisingly the multiple regression analysis did not show strong connections between growth and precipitation for either species (Tables 3 and 4) even through both Ash's (1983b)

observations and the pattern of growth seen in Figures 5 and 6 would suggest this to be the case. However, regression analysis takes into account full seasonal data and since rainfall is event based and does not occur on every day it is possible that multiple regression analysis on its own does not give the entire picture of how *Araucariaceae* tree growth is responding to rainfall. To get a better understanding of how precipitation effects tree growth mEA was run for the individual growth and dormant seasons from the BDT and LBB sites. Figure 7 shows there is a relationship observed between rainfall events and tree growth in the four Bunya Mountains dendrometer trees with a more pronounced effect in 2014. Rainfall events cause bark swelling to occur in both the growth and dormant seasons but it is the effect through time that indicates if actual growth has occurred which can be seen clearly in the mEA plots. During the dormant seasons there is apparent growth after rainfall but through time the bark swelling decreases and no overall growth is recorded while during the growth seasons after bark swelling reduces there is still an increase in tree growth observed. Figure 8 demonstrates a similar relationship between rainfall events and tree growth in the 2015 dormant and growth seasons at the LBB site. It should be noted that there are a few instances where a rainfall event is sustained through 6 or 7 days causing the final assessment of how a tree responded after that event to not be observed in Figure 7 or 8. Continued analysis for a few days past the end of these long events indicated in all cases that no growth occurred during rainfall events occurring in dormant seasons. Additionally, Figure 7 does show in some cases that a tree has shrunk after bark swelling has receded. Detailed analysis indicated that in all cases the target rainfall event followed closely after another rainfall event which meant the growth pattern observed was a cumulative reduction in growth due to bark swelling from multiple events.

Furthermore, the LBB site shows an interesting effect at the start of the 2016 dormant season. The beginning of this period was very dry and the trees appear to shrink at this time

which may be related to the lack of water in the atmosphere (Figure 6). On the 4th and 5th of June that year a major rainfall event occurs that appears to show a reversal of the potential shrinkage (Figure 6). This is possibly a result of water being drawn out of the tree due to the extensive dry spell which was replenished during the major storm. A similar effect has been observed due to below freezing temperatures in temperate subalpine conifers (Zweifel and Häsler, 2000) indicating that bark tissue can shrink under poor climate conditions. As there are no other similar periods of long dry followed by intense wet this relationship can only be speculated upon.

The results of the multiple regression and mEA analysis demonstrate that the *A. cunninghamii* trees at the LBB site and the *A. bidwillii* trees at the BDT site both show growth connected to seasonal temperature and event based rainfall conditions indicating similar climate responses in these two subtropical species. While further monitoring is required to understand the full connection between growth and climate as well as to determine the exact growth seasons at these sites this preliminary data provides a starting point to understanding the growth response of these subtropical tree species.

Conclusion

Australian tropical and subtropical regions lack the annually-resolved long-term (multi-decadal to centennial scale) instrumental climate records needed to understand patterns of climate variability. This study demonstrates the potential that exists for the use of trees from the *Araucariaceae* family in the development of long-term records of past-climate, but there are challenges. The biggest issue that must be overcome is appropriate chronology development in species that demonstrate several growth anomalies which must be accounted for. However, we found that most ring anomalies can be identified allowing for the dating of tree-ring series through validation techniques including radiocarbon dating and marker ring

identification as well as applying quality controlled chronology development. Several other means to increase success in building a master chronology with *Araucariaceae* trees were determined in relation to appropriate site and tree selection as this can assist in limiting the presence of ring anomalies within study trees. Selecting cross-sections where possible or using multiple cores from around the entire circumference of a tree that are analysed concurrently helps to identify potential locations of ring anomalies.

Bomb-pulse radiocarbon dating was found to be a necessary tool for tropical/subtropical dendrochronology. The prevalence of ring anomalies in these species requires confirmation of the visually assigned dates which ^{14}C analysis can assist with but must also be paired with standard dendrochronological techniques. This study demonstrates that accurate annual dating of trees in the *Araucariaceae* family is possible, disproving the long held belief that tropical/subtropical tree species are unsuitable for dendroclimatic analysis. The issues of growth anomalies can be overcome in the species presented and potentially others in the tropics/subtropics by the application of dendroecological study of species and the use of multiple analysis techniques, as was undertaken here.

Relationships between tree growth in these *Araucariaceae* species and climate have also been identified with distinct annual growth and dormant seasons that imply that the amount of growth occurring within a year is driven predominantly by rainfall. There is also evidence that species biology has an effect on growth which needs to be further developed. For subtropical Australia the use of *Araucariaceae* trees to develop long-term rainfall reconstructions should be further investigated and undertaken where possible as this species has the potential to provide much needed information on climatic variability for regions in need of long-term climate information.

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Figure Captions

Figure 1: Elevational profile map of Southeast Queensland with urban areas, including Brisbane, indicated in grey. Yellow dots indicate tree ring sampling sites and black dots climate stations utilized in this study: 40307 = Vincent Vale rainfall, 40550 = Numinbah rainfall, 40983 = Beaudesert Drumly Street temperature, 41522 = Dalby Airport temperature.

Figure 2: Ring boundaries of cores from the three study sites sanded with up to 1200 grit sandpaper a) sample LBB002H, a 12mm core from the LBB site; b) sample BDT013A, a 4mm core from the BDT site; and c) sample DMA011E, a 12mm core from the DMA site. The magnification of the 12mm cores are the same with a slightly higher magnification of the 4mm core for better comparison.

Figure 3: Examples of ring anomalies found in the LBB and BDT cores. a) pinching rings (outlined in black) observed in 4mm core LBB018A; b) false rings observed in 12mm core LBB007F, true rings are marked with black lines and false rings with white lines; c) false rings observed in 4mm core BDT013A, true rings are marked with black lines and false rings with white lines; d) faint rings observed in 4mm core BDT009D, clear rings are marked with black lines and faint rings with white lines.

Figure 4: Examples of LBB tree core classifications. a) Category A sample LBB018F demonstrating narrow rings, ring boundaries are marked with black lines; b) category B sample LBB002H with false ring boundaries, true rings are marked with black lines and false rings with white lines; c) category C sample LBB015F with pinching rings (pinching series outlined in black).

Figure 5: Daily growth measurements for the Bunya Mountains dendrometers compared to (A) minimum temperatures from the Dalby Airport Climate Station (red line) and (B) precipitation from the Vincent Vale Climate Station (blue bars) over the entire period of study. Grey bands in the background represent growth seasons of the *Araucaria bidwillii* trees at the Bunya Mountains site. Pulses in the growth record are evidence of bark swelling after rainfall events.

Figure 6: Daily growth measurements for the Lamington dendrometers compared to (A) minimum temperatures from the Beaudesert Drumly Street Climate Station (red line) and (B) precipitation from the Numimbah Climate Station (blue bars) over the entire period of study. Grey bands in the background represent the apparent growth season of the *Araucaria cunninghamii* trees at the Lamington site. Pulses in the growth record are evidence of bark swelling after rainfall events.

Figure 7: Epoch analysis plots of the ten largest rainfall events during each of the 2014 growth, 2015 dormant, and 2015 growth seasons for the four Bunya Mountains dendrometer trees. Each plot represents one week of dendrometer recordings from the start of the rainfall event. Days with rain are shown as a dark blue diamond and days without rain as light blue diamonds.

Figure 8: Epoch analysis plots of the ten largest rainfall events during the 2015 dormant and growth seasons for the three Lamington dendrometer trees. Each plot represents one week of dendrometer recordings from the start of the rainfall event. Days with rain are shown as a dark blue diamond and days without rain as light blue diamonds.

a **b** **c**

2014
Growth
Season

2015
Dormant
Season

2015
Growth
Season

2015
Dormant
Season

2015
Growth
Season

Lam1

Lam2

Lam3

Table 1: All radiocarbon dates for the LBB site indicating their assumed and actual dates and detailing their calibration information.* Southern Hemisphere trees assigned year of growth is that in which growth begins. Bold font in two columns (“Errors on ring counts” and “Interpretation”) shows our interpretation of the data.

Tree	Lab Code	Assumed Year of Growth	^{14}C content $\pm 1\sigma$ (pMC)	Calibrated ^{14}C age (95% confidence)	Radiocarbon Dated Period of Growth*	Errors on Ring Counts	Interpretation	Classification
LBB-001	OZS714	1964	127.30 $\pm$ 0.38	1962.66-1963.27 1979.78-1982.26	1962 1979-1981	-2 +15 to +17	2 locally absent rings	A
	OZS715	1967	159.23 $\pm$ 0.37	1964.50-1965.24 1966.44-1968.33	1963-1964 1965-1967	-3 to -4 -2 to 0		
LBB-015	OZS718	1961	97.11 $\pm$ 0.28	1650-1801 1950-1954	1650-1801 1950-1954	-160 to -311 -7 to -10	7 locally absent rings	A
	OZS719	1970	141.23 $\pm$ 0.51	1963.67-1963.94 1973.63-1975.46	1963 1973-1974	-7 +3 to +4		
LBB-016	OZT268	1964	96.84 $\pm$ 0.33	1636-1800 1950-1955	1636-1800 1950-1955	-164 to -328 -9 to -14	9 locally absent rings	A
	OZT269	1972	152.43 $\pm$ 0.32	1963.94-1964.82 1968.63-1971.41	1963-1964 1968-1970	-9 to -8 -2 to -4		
LBB-018	OZT266	1962	142.13 $\pm$ 0.51	1963.68-1964.10 1973.46-1875.14	1963 1972-1974	+1 +10 to +12	1 false ring	B1
	OZT267	1970	145.72 $\pm$ 0.53	1963.76-1964.23 1972.26-1973.99	1963 1971-1973	-7 +1 to +3		
LBB-007	OZT257	1962	162.93 $\pm$ 0.35	1964.67-1967.70	1964-1967	+2 to +5	2 false rings	B1
	OZT258	1970	148.65 $\pm$ 0.33	1963.92-1964.79 1969.91-1972.88	1963-1964 1969-1972	-6 to -7 -1 to +2		
LBB-027	OZS716	1965	142.25 $\pm$ 0.44	1963.68-1964.11 1973.45-1974.85	1963 1972-1974	-2 +7 to +9	7-8 false rings	B2
	OZS717	1968	137.38 $\pm$ 0.36	1963.48-1963.89 1974.39-1976.54	1962-1963 1973-1976	-5 to -6 +5 to +8		
LBB-002	OZS712	1961	137.58 $\pm$ 0.45	1963.48-1963.89 1974.38-1976.53	1962-1963 1973-1976	+1 to +2 +12 to +15	12 false rings	B2
	OZS713	1967	131.25 $\pm$ 0.44	1963.32-1963.54 1977.43-1979.90	1962-1963 1976-1979	-4 to -5 +9 to +12		
LBB-020	OZT272	1960	97.83 $\pm$ 0.24	1671-1893 1921-1955	1671-1893 1921-1955	-67 to -289 -5 to -39	11-39 locally absent rings	C
	OZT273	1966	97.74 $\pm$ 0.26	1669-1891 1923-1955	1669-1891 1923-1955	-75 to -297 -11 to -43		
LBB-028	OZT270	1960	97.64 $\pm$ 0.25	1667-1881 1925-1955	1667-1881 1925-1955	-79 to -293 -5 to -35	16-19 locally absent rings	C
	OZT271	1971	96.79 $\pm$ 0.24	1639-1797 1952-1955	1639-1797 1952-1955	-174 to -332 -16 to -19		
LBB-009	OZS710	1960	97.45 $\pm$ 0.38	1652-1884 1925-1955	1652-1984 1925-1955	-76 to -308 -5 to -35	18-35 locally absent rings	C
	OZS711	1973	97.44 $\pm$ 0.38	1652-1883 1925-1955	1652-1983 1925-1955	-90 to -321 -18 to -48		

Table 2: Trees used in the dendrometer analysis, their diameter at breast height at the start of the study period, and the average depth of bark for each tree based on eight short cores taken from around the DBH level circumference of each tree.

Tree	Tree Species	DBH	Average Bark Depth
BM1	<i>A. bidwillii</i>	1.20m	7.00cm
BM2	<i>A. bidwillii</i>	1.05m	4.00cm
BM3	<i>A. bidwillii</i>	1.60m	8.25cm
BM4	<i>A. bidwillii</i>	1.55m	5.75cm
Lam1	<i>A. cunninghamii</i>	0.85m	2.75cm
Lam2	<i>A. cunninghamii</i>	0.80m	2.50cm
Lam3	<i>A. cunninghamii</i>	1.00m	3.00cm

Table 3: The correlations (r values) between growth and the variables used in the multiple regression analysis for the four Bunya Mountains and three Lamington dendrometer trees during the 2014 and 2015 growth seasons. Values indicate the amount of variance explained by the given variable for the study tree over the entire season with the significance of the day to day correlation between tree growth and the target climate variable at a 95% confidence interval shown in bold and those at a 90% confidence interval shown in italics.

Growth Year	Tree	Rainfall	Minimum Temperature	Maximum Temperature
2014	BM1	0.04	-0.53	-0.60
2014	BM2	0.03	-0.47	-0.54
2014	BM3	0.06	<i>-0.46</i>	-0.56
2014	BM4	0.03	-0.52	-0.58
2015	BM1	0.11	<i>0.12</i>	-0.12
2015	BM2	-0.05	-0.06	-0.13
2015	BM3	0.07	-0.11	-0.30
2015	BM4	-0.02	-0.27	-0.36
2015	Lam1	0.17	0.74	0.51
2015	Lam2	0.15	0.72	0.52
2015	Lam3	0.22	0.76	0.48

Table 4: The correlations (r values) between daily growth and the variables used in the multiple regression analysis for the four Bunya Mountains dendrometer trees during the partial 2015 growth season from 10/10/2015 to 05/01/2016. Values indicate the amount of variance explained by the given variable for the study tree over the entire season with the significance of the day to day correlation between tree growth and the target climate variable at a 95% confidence interval shown in bold and those at a 90% confidence interval shown in italics.

Growth Year	Tree	Rainfall	Minimum Temperature	Maximum Temperature
2015	BM1	<i>0.23</i>	0.47	-0.07
2015	BM2	0.14	0.44	0.01
2015	BM3	0.26	0.50	-0.11
2015	BM4	0.18	0.52	0.02

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