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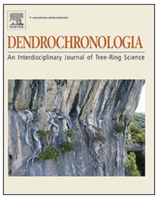

Anomalous ring identification in two Australian subtropical *Araucariaceae* species permits annual ring dating and growth-climate relationship development

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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 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.

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

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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; Heinrich et al., 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 Fig. 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 (Fig. 1). The region has mean annual temperatures ranging from 21 °C to 29 °C and annual rainfall between 900 and 1800 mm 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) (Fig. 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 4 mm 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 12 mm 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 12 mm cores were taken where possible at 45° from the 4 mm 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 4 mm 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 (4 mm cores) or plumbers piping (12 mm 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 h 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 4 mm 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 12 mm 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 2 mm lath from the centre, and a top section of remaining sample. The bottom mounted sections of the 12 mm cores were then sanded in the same manner as the 4 mm 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*