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Determining the age and growth rate of *Acacia harpophylla* in central Queensland, Australia, using radiocarbon in trees lacking annual growth rings

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ABSTRACT

Context. Determining the age of culturally, historically or ecologically significant trees in Australia is hampered by a lack of annual tree growth rings in many species. In central Queensland, land clearing has decimated primary brigalow (*Acacia harpophylla* F.Muell. ex Benth.) forests and very little information about the age or growth rates of old brigalow trees in remnant forests is available to guide conservation and management. **Aims.** Determine the first quantitative estimates of age and growth rates of mature brigalow trees. **Methods.** We used radiocarbon dating of sequentially collected wood from the bark to the pith of four sampled trees. **Key results.** It is likely that three of the four standing-dead trees (~25 cm diameter at breast height) sampled began growing in the last quarter of the 19th century (1841–1881 Common Era (CE), ~150 years old), with one tree likely to have begun growth in the mid-20th century (1938 CE). All died in the early 21st century. The trees showed consistent growth rates of 1.3 mm year^{-1}, and two trees also displayed short periods of rapid growth (4–8 mm year^{-1}), which are likely to be associated with canopy openings. **Conclusion.** Brigalow trees take up to 150 years to mature. In-series radiocarbon dates are critical in dating trees such as these, because their true age is likely to be before the bomb-spike but within the radiocarbon plateau from ~1650 to 1950 CE. **Implications.** The lag time between tree establishment and maturity (~100 years) favours restoration that is based around assisting naturally regenerating brigalow through management rather than undertaking tree planting activities because of the inherent risk of failure owing to climate.

Keywords: *Acacia harpophylla*, Brigalow Belt bioregion, demography, dendrochronology, dendroecology, forest conservation, radiocarbon, woody regrowth.

Introduction

Knowing the age and demography of trees (e.g. growth rate, age structure, and time to maturity) is critical knowledge needed to conserve and manage forests. It is often difficult to easily determine either the age or growth rate of tropical and subtropical trees by using traditional dendrochronological methods (i.e. tree-ring dating, Speer 2012) because of the low seasonal variability they experience and their often opportunistic growth and irregular ring structure (Haines *et al.* 2016, 2018; Witt *et al.* 2017). This is the case with brigalow trees (*Acacia harpophylla* F.Muell. ex Benth.) in central Queensland, Australia.

Conservation and management of brigalow forests is of particular importance in Australia's 36.7 million hectare Brigalow Belt bioregion because of the legacy of historical broad-scale land clearing (Thornton and Elledge 2021, 2022). Since European settlement, 58% of this bioregion has been cleared and the rates of clearing in Queensland were among the highest in the world (Wilson *et al.* 2002; Lindenmayer and Burgman 2005; Reside *et al.* 2017). Woodlands containing brigalow were heavily cleared for agriculture, typically cropping or grazing. About 93% of these woodlands, colloquially known as brigalow scrub, have been cleared since European settlement (Butler and Fairfax 2003; Cogger *et al.* 2003; Tulloch *et al.* 2016). Conservation of the remnant brigalows depends on an understanding of species and community patterns (McDonald 1996). Restoration efforts to increase remnant patch size, establish or increase connectivity among remnants, or the consideration of broad-scale re-afforestation would all benefit from demographic information about these woodlands.

Most published research on brigalow growth is in the context of regrowth after clearing, and those studies focus on growth rates of young, single-stem and coppiced trees rather than single-stem primary brigalow trees (Ngugi *et al.* 2011; Johnson *et al.* 2016; Fensham *et al.* 2018; Le Brocque and Wagner 2018; Towers and Dwyer 2021). The one published maximum age ($A_{\max}$ 180 years) found in Ngugi *et al.* (2011) is not supported by the cited literature and is most likely an estimate by the authors. After obtaining the radiocarbon dates in this study, we found that McDonald (1996) had recorded repeated diameter at breast height (DBH) measurements of similar, single-stem trees adjacent to the Brigalow Catchment Study (BCS) ~20 years apart. To be clear, these were not the same trees we sampled for this study, but ones measured in the Brigalow Reference Area (BRA), which neighbours the BCS (Johnson 1980; Johnson and McDonald 2010). For these trees, some >30 cm DBH, McDonald (1996) did not attempt to estimate their maximum age or publish their growth rates; however, the recorded data yield brigalow growth rates between 1.2 and 1.4 mm year^{-1}.

For mature trees in Australia with rings that have not been visually confirmed to be annual, radiocarbon from sequentially sampled rings in a wood core or disc has been used to provide accurate estimates of tree age and growth rates (Santini *et al.* 2013; Sippo *et al.* 2020; Spry *et al.* 2020; Gillen *et al.* 2021; Goodwin *et al.* 2022; Ngugi *et al.* 2024). Sequentially sampled radiocarbon dating is used for any tree roughly 350 years old or younger because of the radiocarbon plateau from ~1650 to 1950 Common Era (CE) (Hua 2009). Typically, seven or eight in-sequence samples are used to match temporal variations in a terrestrial radiocarbon calibration curve (atmospheric radiocarbon content) to the radiocarbon in the wood sample (secondary growth in trees adds layers to the outermost stem so that the oldest wood is in the pith and youngest wood is near the bark). The oldest (samples closest to the pith) are dated first, followed by other dates if the first date is inconclusive (i.e. younger than 1650 CE). Previous work investigating the impact of clearing/thinning on growth rates of 27-year-old brigalow stands at the southern end of the Queensland Brigalow Belt (Bulli State Forest, Qld) yielded diameter growth estimates between 1 and 3 mm year^{-1} for brigalow trees in cleared settings and between agricultural fields respectively (Towers and Dwyer 2021). Whereas these estimates are from young stands deliberately thinned, our work focuses on determining the ages and growth rates of mature brigalow trees in an intact brigalow forest in central Queensland. Here, we use sequentially sampled radiocarbon to quantitatively estimate the date of death, age and growth rates of four large, standing-dead brigalow trees from the BCS that is in the heart of the Brigalow Belt bioregion in central Queensland, Australia.

Materials and methods

Four standing-dead brigalow trees 23–29 cm in diameter were sampled from the Brigalow Catchment Study 33 km south-west of Moura, Queensland, in May 2023 (Fig. 1). Radial discs (~6 cm thick) were cut with a chainsaw from the base of each tree immediately above the root collar, except where there was rot or damage present that would have yielded a poor sample. In that instance, samples were taken from further up the trunk. Each disc was progressively smoothed with a belt sander (40–120 grits), a random orbital sander (180–400 grits) and finally polished by hand (800–4000 grit). The average radius of each tree (Table 1) was determined by measuring the circumference using Image J (ver. 1.54g; National Institutes of Health, USA). Polished sections were examined and radials with the greatest number of rings and the fewest instances of wedging, missing rings or other aberrations were selected for sampling (Fig. 2). These radial sections (~1.5 cm wide and including all wood from the pith to the bark) were removed from the disc with a bandsaw, wrapped in aluminium foil and sent to the Accelerated Mass Spectrometry (AMS) radiocarbon facility at the Australian Nuclear Science and Technology Organisation (ANSTO) for analysis.

At ANSTO, each radial section was sampled for radiocarbon analysis six to seven times along its length at regular intervals by using a steel scalpel and chisel. Samples were pre-treated to cellulose (Němec *et al.* 2010) before being combusted and converted to graphite (Hua *et al.* 2001). Radiocarbon samples were measured at the VEGA AMS facility (Wilcken *et al.* 2015). The ^{14}C results are reported in percent modern carbon (pMC) and age calibrations (Table 1, Supplementary Table S1) of measured pMC values were performed using OxCal program (ver. 4.4, https://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey 2009) and the SHCal20 calibration curve (Hogg *et al.* 2020) extended to the recent time by using bomb ^{14}C data for SH zone 1–2 (Hua *et al.* 2022). The chronology for each tree was constructed using the Sequence model in the OxCal program (Bronk Ramsey 2008; a method similar to how age/depth models are derived for sediment cores), with constraint in the chronological ordering of dates (i.e. outer samples are younger than inner samples; Tables 1, S1, Supplementary Fig. S1*a*–*d*). The mean of the modelled calibrated age is used in all figures and growth rate calculations, but we note that the 95% confidence intervals (CI) on these ages can span decades to centuries (Fig. S1). Growth rates were calculated by dividing the radius added (mm) over the number of years (yr) elapsed between dated sections of the radius. Total growth rates were calculated by dividing the length of the measured section by the total time elapsed between the earliest age and the latest age.

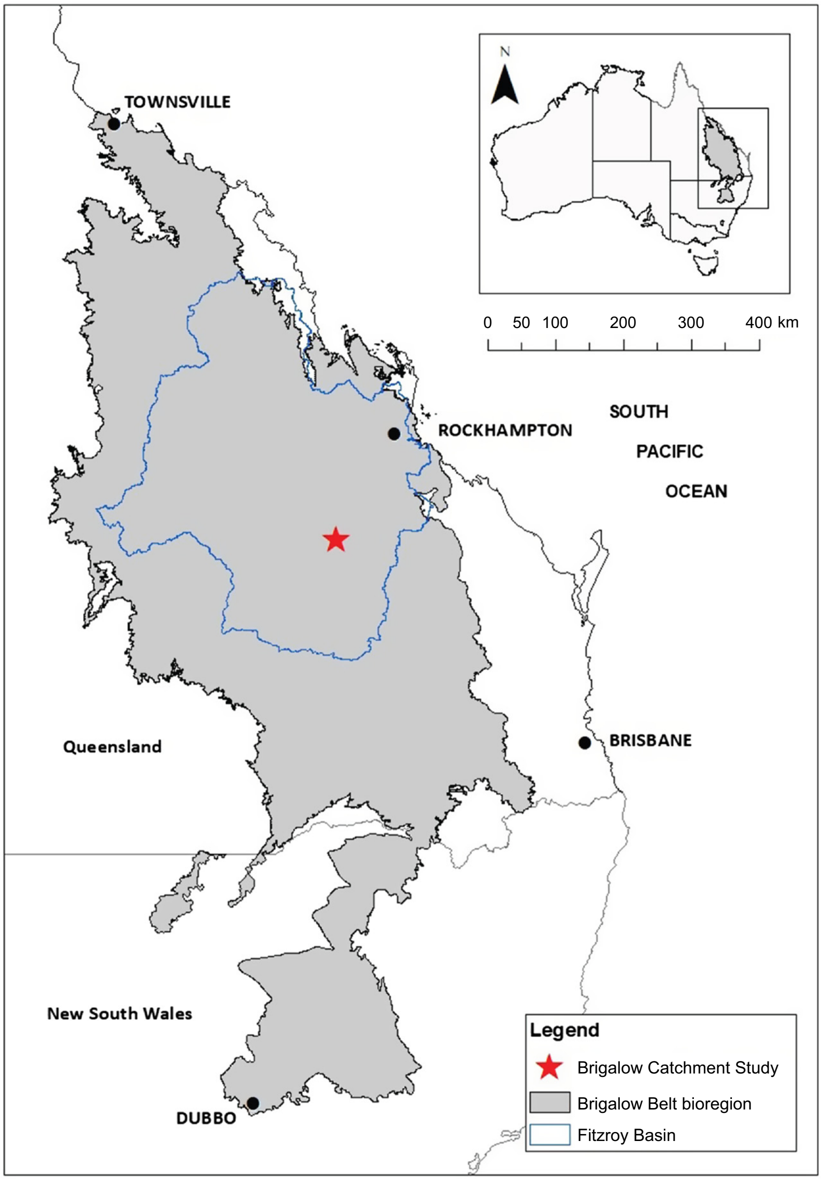

Fig. 1. Location of the Brigalow Catchment Study where samples were collected and the extent of the Brigalow Belt bioregion in central Queensland, Australia.

In the re-analysis of McDonald's (1996) basal area data from the BRA (Table 2; basal area data are from appendix 9 of McDonald 1996), it is unclear during which years the measurements for each tree were taken. To account for the possibility that some trees were measured over a shorter period than others (i.e. 20 years instead of 24 years), we calculated both a minimum and a maximum growth rate ($G_{\min}$ and $G_{\max}$ respectively) by using 24 years (1968–1992) and 20 years (1970–1990) respectively.

Results

The modelled age of each sample is consistent with prior information about order of each sample (sequence) within each tree (i.e. that the wood near the pith is older than wood near the bark). For the modelled ages derived from radiocarbon measurements, the agreement index of the OxCal Sequence model (A_{model}) for each tree ranged from 74% to 84%, which is higher than the accepted level of 60% (Bronk Ramsey 2008). The agreement index of each date in each model (A) was also higher than 60%, indicating that there were no outliers in each model.

It is likely that three of the four sampled trees (Table 1, Fig. 2) began growing in the last quarter of the 19th century (1841–1881 CE), with one tree (Tree 2) being likely to have begun growth in the mid-20th century (1938 CE). All trees are likely to have died in the early 21st century. The trees span in age from ~64 to ~163 years old; the oldest tree (Tree 3) has a DBH of ~27 cm.

On average, the total growth rate of all four trees was 1.3 mm year^{-1} over their lifetime (Fig. 3, Table 1). Trees 3 and 4 grew between 0.6 and 1.6 mm year^{-1} over their

Table 1. Brigalow tree location, calculated radii, sample depths, radiocarbon content (pMC), modelled ages and growth characteristics along each radii.

Tree and location	Radius (mm)[A]	Sample distance from bark (mm)	pMC (% modern carbon)		Modelled calibrated age (CE)[B]					Distance from 'pith' (mm)[C]	Age of tree (year)	Growth (mm)	Growth period (year, mean ± 1σ)	Growth rate ($\mathrm{mm\ year^{-1}}$, mean± 1σ)[D]	Total growth rate ($\mathrm{mm\ year^{-1}}$, mean ± 1σ)[D]
			Mean	1σ	68% CI		95% CI		Mean ± 1σ						
Tree 1, 24.81697°S, 149.79533°E	106	117	97.92	0.30	1857	1943	1804	1946	1881 ± 41	0	0	–	–	–	
		94	99.06	0.29	1895	1946	1825	1955	1910 ± 23	23	29	23	29 ± 47	0.8 ± 1.3	
		70	97.86	0.19	1928	1954	1921	1956	1937 ± 16	47	56	24	27 ± 28	0.9 ± 0.9	
		47	135.96	0.32	1975	1977	1962	1977	1974 ± 4	70	93	23	37 ± 17	0.6 ± 0.3	
		23	128.34	0.30	1980	1981	1979	1982	1980 ± 1	94	99	24	6 ± 4	4 ± 2.7	
		0	110.34	0.26	1998	1999	1997	2001	1999 ± 1	117	118	23	19 ± 1	1.2 ± 0.1	1.0 ± 0.3
Tree 2, 24.81705°S, 149.79599°E	124	145	98.22	0.26	1937	1950	1909	1954	1938 ± 16	0	0	–	–	–	
		121	97.12	0.27	1950	1953	1949	1955	1951 ± 8	24	13	24	13 ± 18	1.8 ± 2.5	
		97	158.73	0.41	1966	1968	1963	1969	1967 ± 1	48	29	24	16 ± 8	1.5 ± 0.8	
		73	151.68	0.43	1969	1971	1969	1972	1970 ± 1	72	32	24	3 ± 1	8 ± 3.8	
		48	137.23	0.35	1975	1976	1974	1977	1975 ± 1	97	37	25	5 ± 1	5 ± 1.4	
		24	118.71	0.32	1986	1988	1986	1989	1987 ± 1	121	49	24	12 ± 1	2 ± 0.2	
		0	108.55	0.29	2002	2003	2000	2004	2002 ± 1	145	64	24	15 ± 1	1.6 ± 0.2	2.3 ± 0.6
Tree 3, 24.81749°S, 149.79655°E	138	163	97.87	0.26	1803	1892	1684	1935	1841 ± 53	0	0	–	–	–	
		136	98.61	0.29	1817	1916	1810	1931	1870 ± 42	27	29	27	29 ± 68	0.9 ± 2.2	
		109	98.16	0.29	1865	1934	1829	1944	1892 ± 34	54	51	27	22 ± 54	1.2 ± 3	
		82	98.30	0.20	1906	1947	1852	1949	1913 ± 26	81	72	27	21 ± 43	1.3 ± 2.6	
		54	97.86	0.26	1930	1954	1870	1956	1935 ± 18	109	94	28	22 ± 32	1.3 ± 1.8	
		27	141.64	0.29	1973	1975	1962	1975	1972 ± 4	136	131	27	37 ± 18	0.7 ± 0.4	
		0	103.15	0.21	2014	2016	2013	2017	2015 ± 1	163	174	27	43 ± 4	0.6 ± 0.1	0.9 ± 0.3
Tree 4, 24.81748°S, 149.79671°E	146	146	98.07	0.19	1854	1911	1808	1942	1875 ± 32	0	0	–	–	–	
		122	98.88	0.27	1893	1919	1823	1947	1902 ± 21	24	27	24	27 ± 38	0.9 ± 1.3	
		97	98.43	0.25	1904	1947	1893	1949	1919 ± 17	49	44	25	17 ± 27	1.5 ± 2.3	
		73	97.69	0.21	1930	1955	1926	1955	1942 ± 12	73	67	24	23 ± 21	1 ± 0.9	
		49	120.50	0.25	1960	1962	1959	1963	1961 ± 1	97	86	24	19 ± 12	1.3 ± 0.8	
		24	130.69	0.34	1978	1980	1962	1980	1977 ± 5	122	102	25	16 ± 5	1.6 ± 0.5	
		0	105.72	0.30	2008	2010	2007	2011	2009 ± 1	146	134	24	32 ± 5	0.8 ± 0.1	1.1 ± 0.3
														Mean total growth rate	1.3

[A] Mean tree radius calculated from measured circumference.

[B] The chronology of each tree was constructed using the Sequence model in the OxCal program (Bronk Ramsey 2008), with constraint in the chronological ordering of dates (outer samples are younger than inner samples).

[C] Distance from the innermost sample, within <5 mm of the pith.

[D] Uncertainty associated with mean growth rate is based on derivative estimation.

lifetime, whereas Trees 1 and 2 displayed short periods of rapid growth rates (4–8 mm $\mathrm{year^{-1}}$).

A re-analysis of DBH data collected by McDonald (1996) showed that the average growth rate for the 23 trees in the BRA over two decades was ~1.3 mm $\mathrm{year^{-1}}$ (Table 2). Using our data and the McDonald (1996) data, the largest dead tree in the McDonald data (with a DBH of 46.1 cm) was likely to be >165 years old when it died. These estimates of growth are likely to be less accurate, as each tree's DBH measured in 1968/1970 was assigned to 1-inch size classes, whereas the actual DBH of each tree was measured and recorded in 1990/1992. For example, there is a strong positive relationship between $G_{\min}$ and $G_{\max}$ and the radius measured in 1990/1992. However, the assumption here is that actual tree DBH spanned the 1-inch size classes in a normal distribution, and therefore the derived growth rates reflected a normal distribution as most bias would have been removed with 23 samples.

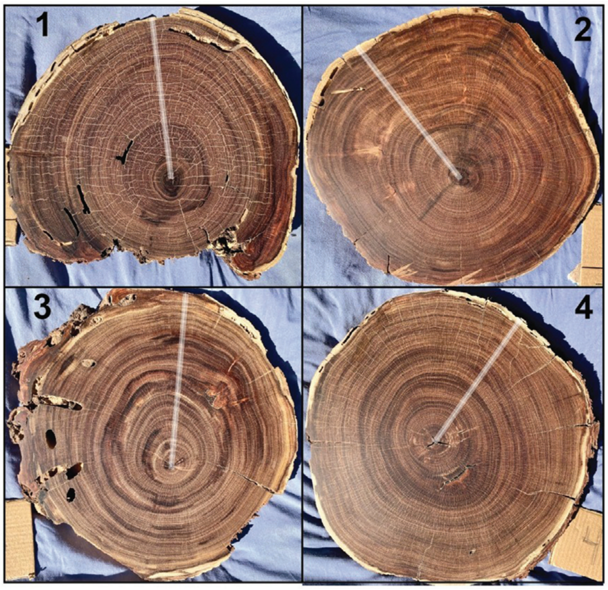

Fig. 2. The four brigalow wood discs from standing-dead trees used in this study. Tree ID is in the top corner, and the white line is the radius along which radiocarbon samples were taken.

Discussion

The growth rates and maximum age estimates obtained from the four BCS trees are internally consistent. The mean growth rate of the trees measured by radiocarbon (1.3 mm year^{-1}) is also consistent with the growth rate derived from basal area measurements collected over 20 years from trees of a similar size and in the same location (1.3 mm year^{-1}; McDonald 1996). The growth rates yielded by radiocarbon are also consistent with those of Towers and Dwyer (2021), although in a very different context (closed canopy forest versus regrowth in a pasture respectively). Similar to other trees in general, brigalow radial growth rates in this study decline slightly (~0.4 mm year^{-1} less than maximum growth rates) as the trees age and the circumference increases.

The anomalous growth rates found in Tree 1 and Tree 2 (Fig. 3) may be a result of canopy openings nearby that released the trees from light, water and/or nutrient limitations. The rapid rise in growth rate of Tree 2–8.0 mm year^{-1} followed by a gradual return to just above the mean growth rate of 1.3 mm year^{-1} is consistent with this hypothesis. Clearing occurred adjacent to the location of Trees 1 and 2 in approximately 1965 to facilitate the installation of hydrological monitoring equipment, and resulted in total canopy removal across 0.3 ha. Although tree height is not necessarily well correlated with root spread, a conservative estimate of radial root spread equivalent to tree height (Day *et al.* 2010) suggests that the roots of Tree 1 and Tree 2 would have extended substantially into the cleared area. Nearby clearing would have given these trees access to additional soil water

Table 2. Growth rates derived from individual *Acacia harpophylla* measured over two decades in central Queensland (basal area data are from appendix 9 of McDonald 1996).

Plot	Basal area (cm^2)		Radius (mm)		Growth (mm year^{-1})	
	1968/1970	1990/1992	1968/1970	1990/1992	G_{min}	G_{max}
39	1145.9	1406.6	191.0	211.6	0.9	1.0
38	993.3	1265.6	177.8	200.7	1.0	1.1
60	993.3	1107.3	177.8	187.7	0.4	0.5
39	961.9	1574.8	175.0	223.9	2.0	2.4
59	851.6	881.6	164.6	167.5	0.1	0.1
30	720.8	1058.9	151.5	183.6	1.3	1.6
30	720.8	843.8	151.5	163.9	0.5	0.6
59	600.9	653.1	138.3	144.2	0.2	0.3
13	491.9	909.1	125.1	170.1	1.9	2.2
60	491.9	735.4	125.1	153.0	1.2	1.4
37	491.9	672.0	125.1	146.3	0.9	1.1
40	393.8	672.0	112.0	146.3	1.4	1.7
61	393.8	507.2	112.0	127.1	0.6	0.8
59	306.6	532.4	98.8	130.2	1.3	1.6
39	306.6	519.7	98.8	128.6	1.2	1.5
61	306.6	318.0	98.8	100.6	0.1	0.1
39	230.3	503.1	85.6	126.5	1.7	2.0
12	230.3	482.7	85.6	124.0	1.6	1.9
14	164.9	390.6	72.4	111.5	1.6	2.0
40	164.9	344.8	72.4	104.8	1.3	1.6
60	66.8	111.8	46.1	59.6	0.6	0.7
61	66.8	100.4	46.1	56.5	0.4	0.5
40	34.1	321.3	32.9	101.1	2.8	3.4
37[A]	**12.3**	**192.7**	**19.8**	**78.3**	**2.4**	**2.9**
37	**12.3**	**132.0**	**19.8**	**64.8**	**1.9**	**2.3**
37	**12.3**	**121.7**	**19.8**	**62.2**	**1.8**	**2.1**
37	**12.3**	**89.7**	**19.8**	**53.4**	**1.4**	**1.7**
61	**12.3**	**87.9**	**19.8**	**52.9**	**1.4**	**1.7**
30	**12.3**	**62.5**	**19.8**	**44.6**	**1.0**	**1.2**
37	**12.3**	**62.5**	**19.8**	**44.6**	**1.0**	**1.2**
37	**12.3**	**58.2**	**19.8**	**43.0**	**1.0**	**1.2**
38	**12.3**	**39.1**	**19.8**	**35.3**	**0.6**	**0.8**
38	1669.1	DEAD	230.5			
13	1343.4	DEAD	206.8			
61	993.3	DEAD	177.8			
61	851.6	DEAD	164.6			
14	851.6	DEAD	164.6			
12	491.9	DEAD	125.1			
38	393.8	DEAD	112.0			
61	306.6	DEAD	98.8			

(*Continued on next page*)

Table 2. (*Continued*).

Plot	Basal area (cm^2)		Radius (mm)		Growth ($mm\ year^{-1}$)	
	1968/1970	1990/1992	1968/1970	1990/1992	G_{min}	G_{max}
14	306.6	DEAD	98.8			
39	164.9	DEAD	72.4			
Mean[B]	351.2	523.7	88.8	117.1	1.2	1.4

[A] Bold denotes data from one 1968/1970 size class (McDonald 1996). The effect of comparing DBH class data to numerical DBH data taken in 1990/1992 can be seen in the direct positive relationship of G_{max} and G_{min} to the 1990/1992 DBH measurements.

[B] DEAD trees are excluded from the 1968/1970 basal area and radius means.

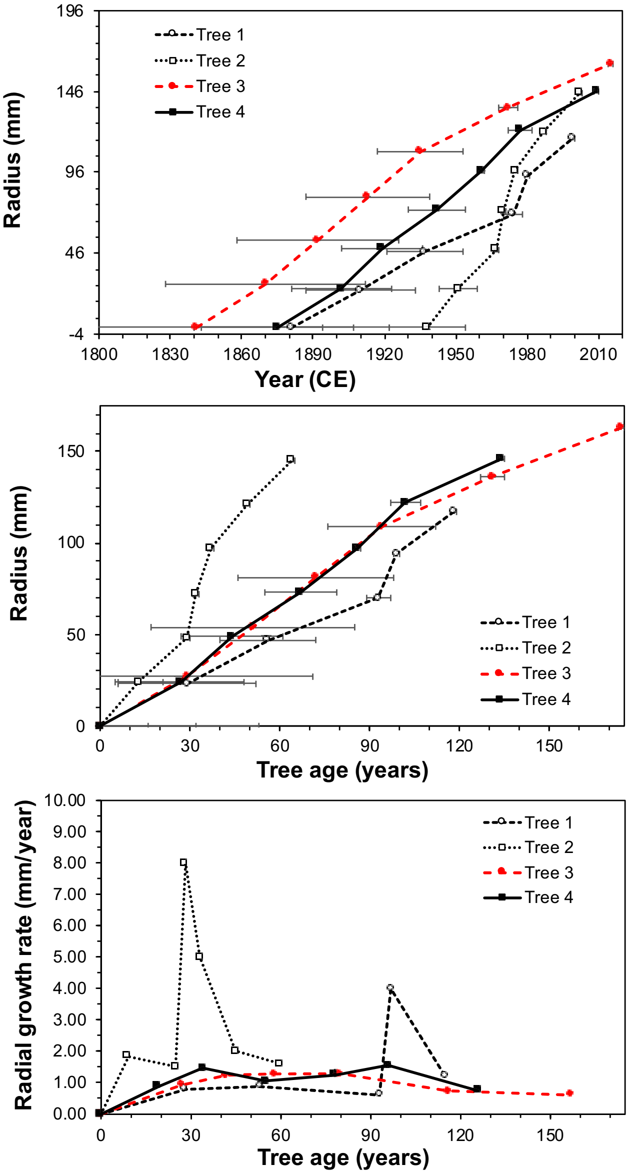

Fig. 3. Modelled calibrated mean age of brigalow trees and their radius (top, with 1σ error bars), the radii of the trees at the modelled age (middle, with 1σ error bars), and the calculated growth rates of each tree (bottom).

accumulated in the cleared area as a result of vegetation removal. The period of accelerated growth of Trees 1 and 2 corresponds to the 15-year period following adjacent clearing. Although Tree 2 grew more quickly than did the other three trees, it was also the youngest when it died. We do not know what caused the death of the tree and so cannot speculate whether its death was related to its rapid growth. Likewise, all the trees sampled were dead, and so may not represent healthy, longer-lived brigalow trees and it is likely that our limited sample does not reflect the full range of growth rates or ages across the range of brigalow trees. A geographically diverse sampling of large, living trees by using tree cores would provide better evidence that the ages and growth rates shown here are the means and not the minimum ages and growth rates.

When examining the growth model data, it is most likely that Trees 1, 3 and 4 began growing in the early 19th century and are therefore ≥150 years old. Tree 2 was likely to be relatively young given the presence of bomb-spike radiocarbon (>100 pMC; Hua *et al.* 2022) almost two-thirds of the way into the trunk (~100 mm below the bark). Primary growth of brigalow trees growing in closed forests with a DBH between 23 and 29 cm are likely to be 100–150 years old, up to ≥150 years old, and are possibly older (≥165 years old).

Understanding the age of mature trees in primary forest provides an estimation of the lag time between suckering of brigalow regrowth and maturity. Previous studies adjacent to this study site showed that 45-year-old brigalow regrowth had substantially higher stem densities than does remnant primary forest, and modelled that it would take 95 years to self-thin to its pre-clearing state (Ngugi *et al.* 2011; Johnson *et al.* 2016). Note that this is again a different site from the BCS and the BRA, known as the Brigalow Regrowth Plots, which were in K-block of the former Brigalow Research Station. The tree ages determined in this study support their hypothesis without the need to monitor for another five decades to confirm it.

Restoration activities directly benefit from a better understanding of forest demography. Tree planting is not always an effective restoration technique in the semiarid subtropics because of extreme variability in both inter- and intra-annual rainfall. Knowing that the lag time between tree establishment and maturity is in the order of 100 years likely favours restoration that is based around assisting naturally regenerating brigalow through management rather than undertaking tree planting activities because of the inherent risk of failure owing to climate. This is essential information for proponents of restoration projects such as those likely to occur under market-based mechanisms, such as the Nature Repair Market (Australian Government 2025).

Conclusions

This work found that the maximum age of brigalow trees in primary forest stands of central Queensland is likely to be close to 150 years. Their radial growth rate of ~1.3 mm year^{-1} is in line with other Australian hardwoods but may vary up to 8 mm year^{-1}. These estimates are supported by previous work and repeat measurements of brigalow trees in the BRA, which is adjacent to the BCS. Brigalow trees are likely to experience increased growth rates of up to five times their normal growth rate when they are released from water, light or nutrient limitation (although this is inferred rather than measured in this study). As in other studies, the use of sequential samples is critical in dating these trees, because their true age is beyond the bomb-spike period and is likely to exist within the radiocarbon plateau from ~1650 to 1950 CE, a period where single radiocarbon dates have a large range of probable dates (Hua 2009).

Supplementary material

Supplementary material is available online.

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