

1 **Two climate-sensitive tree-ring chronologies from Arnhem Land, monsoonal**
2 **Australia**

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26

27 **Abstract**

28 The ecology of the Australian monsoon tropics is fundamentally shaped by dry
29 conditions between May and October followed by highly variable rainfall over the
30 months of November to April. Due to its crucial ecological importance, a better
31 understanding of past hydroclimate variability in the region is of great interest.
32 Temporally shallow and geographically patchy instrumental record also make highly
33 resolved terrestrial palaeoclimate records for northern Australia prior to 1900 CE of
34 considerable scientific importance. Here we present two new well-replicated *Callitris*
35 *intratropica* ring-width chronologies from Arnhem Land in northern Australia, one of
36 which extends the tree-ring record in the region by another 86 years, back to 1761. Both
37 chronologies have clearly defined regional patterns of correlations with temperature,
38 precipitation, potential evapotranspiration and two drought indices (the self-calibrating
39 Palmer Drought Severity Index (PDSI) and the Standardised Precipitation
40 Evapotranspiration Index (SPEI)) across the lower latitudes of the Northern Territory.
41 Results indicate considerable scope for hydroclimatic reconstructions based on *C.*
42 *intratropica* for transitional periods into and out of the wettest time of the year. This
43 suggests such reconstructions would reflect variability in the duration of the wet period.
44 While precipitation or streamflow reconstructions may be possible for both these
45 transitional periods, drought reconstructions will be best focused on the months of
46 March-May at the end of the wet period. Hydroclimate reconstructions would provide
47 important baseline information for understanding the rate and magnitude of current
48 regional climate change for these ecologically and culturally important transitional
49 periods.

50 **Key words:** *Callitris intratropica*, northern Australia, dendrochronology,
51 hydroclimate, SPEI, ecological processes, Indigenous weather calendars

52 **Introduction**

53 The Australian monsoon tropics is characterised by strongly contrasting
54 seasons, from hot dry and flammable conditions between May and October, and wet
55 conditions between November and April. The hydroecology of the region
56 fundamentally shapes the ecology, distribution and abundance of most flora and fauna
57 as well as indigenous land management practices (Woinarski et al., 2007). While
58 northern Australia is most commonly associated with monsoonal rain, extra-monsoonal
59 rainfall, associated with local convective storms, and its temporal pattern is crucial to
60 these ecological processes (Cook and Heerdegen, 2001), affecting, for example, feeding
61 habits, breeding, flowering and fruiting and species migration. With its very high floral
62 and faunal endemism (Woinarski et al., 2006), the biodiversity of the northern part of
63 the Northern Territory is both nationally and internationally significant (Woinarski et
64 al., 2007). Variability in extra-monsoonal rainfall can have critical impacts on
65 threatened species or species highly dependent on specific conditions (Woinarski et al.,
66 2007) and changes in rainfall seasonality across a number of tropical regions have
67 previously been noted (Feng et al., 2013).

68 A lack of long instrumental record for the region makes it difficult to assess the
69 contribution of past hydroclimate to ecological change in the region. Increased interest
70 in agricultural and regional development in parts of the Northern Territory in recent
71 times (see CSIRO research summary: [https://www.csiro.au/en/Research/Major-](https://www.csiro.au/en/Research/Major-initiatives/Northern-Australia/Current-work/NAWRA)
72 [initiatives/Northern-Australia/Current-work/NAWRA](https://www.csiro.au/en/Research/Major-initiatives/Northern-Australia/Current-work/NAWRA)) also raises the possibility of
73 increased pressures on this highly seasonal environment. This lack of baseline
74 information, potentially increasing land use pressures and general concerns about the
75 impacts of climate change across Australia highlight a need for longer, well-replicated
76 and absolutely dated records of past hydroclimate variability in northern Australia.

77 Dendrochronological records have the potential to provide high-resolution
78 climate records. Historically, the majority of Australian dendroclimatic work has relied
79 upon tree-ring chronologies from the continent's temperate south, with a particular
80 focus on Tasmania in the mid-latitudes. This focus reflects the known reliable
81 production of annual rings in the southern long-lived endemic conifer species (e.g.
82 Cook et al, 2000; Buckley et al., 1997; Allen et al., 2001; 2011; 2017). Conversely,
83 Australia's monsoonal north has received relatively little dendrochronological
84 attention. As the temperate southern and monsoonal northern regions are subject to very
85 different climate regimes, and the roles played by the various ocean-atmosphere
86 processes differ between the two regions, the southern tree-ring chronologies cannot be
87 expected to reflect climatic variability in the north (Allen et al., 2018).

88 Although significant efforts have led to a gradual increase in the number of
89 dendrochronological studies for mainland Australia over the past couple of decades
90 (e.g. Pearson and Searson, 2002; Baker et al., 2008; Heinrich et al., 2008; 2009; Cullen
91 and Grierson, 2007; 2009; O'Donnell et al., 2010; 2015; 2018; Santini et al., 2013;
92 Pearson et al., 2011; Witt et al., 2017; Haines et al., 2018a and b), only four
93 geographically dispersed sites (D'Arrigo et al., 2008; Heinrich et al., 2008; Cullen and
94 Grierson, 2009; O'Donnell et al., 2015; 2018; Palmer et al., 2015) have so far been used
95 to generate annually resolved climate reconstructions. All of these are hydroclimate
96 reconstructions, and three are based on *Callitris* spp.

97 The genus *Callitris* is a widespread, evergreen and taxonomically complex
98 drought-tolerant group of species (Piggins and Bruhl, 2010; Sakaguchi et al., 2013) in
99 the family Cupressaceae. There are around 13 species endemic to Australia (Farjon,
100 2010), and an additional species restricted to New Caledonia. Dendrochronological
101 dating of *Callitris* has been hampered by the formation of frequent false rings,
102 particularly in more arid environments (Pearson et al., 2011). Nevertheless, several

103 studies have demonstrated the potential to develop chronologies from the genus in
104 seasonally dry regions of the continent's north and west (Ogden, 1981; Baker et al.,
105 2008; Cullen and Grierson, 2009; O'Donnell et al., 2010; Pearson et al. 2011). One of
106 the species in this genus, *Callitris intratropica*, distributed across much of monsoonal
107 Australia, is extremely drought tolerant (Brodribb et al., 2010; 2013), resilient to termite
108 attack but sensitive to intense fire (Yates and Russell-Smith 2003; Russell-Smith 2006;
109 Bowman et al., 2014; 2018). The size class distribution of living and dead stems has
110 been the basis for a number of landscape ecology studies (e.g. Bowman and Panton,
111 1993; Prior et al., 2004a; 2010; 2011; Trauernicht, 2012) and the species has commonly
112 been considered an indicator of general ecosystem health, although this has recently
113 been called into question (Radford et al., 2013). Individuals of the species growing in
114 monospecific stands generally reach maturity later than isolated individuals that also
115 have a faster growth rate (Lunt et al., 2011; Lawes et al., 2013). The first details of
116 successfully cross-dated *C. intratropica* chronologies in Australia's far north emerged
117 in 2008, with Baker et al. (2008) reporting annual rings in *C. intratropica* chronologies
118 and the ability to identify false rings in young trees of known age. The same study then
119 produced a successfully crossdated chronology from older non-plantation trees. A
120 continental-scale study subsequently verified, by means of accelerator mass
121 spectrometry to measure ^{14}C content of samples, the annularity of tree-ring formation
122 in *C. intratropica* at some north Australian sites (Pearson et al., 2011).

123 Baker et al. (2008) also provided the initial detailed information concerning the
124 response of ring widths *C. intratropica* to temperature, precipitation and the self-
125 calibrating Palmer Drought Severity Index (sc-PDSI; Wells et al., 2004), thereby laying
126 the first solid foundations for high quality reconstructions from the species. This
127 information provided the essential context for the inclusion of the species in two later
128 broadscale drought reconstructions (September-January; D'Arrigo et al 2008 and

129 December-February; Palmer et al. 2015) based on the sc-PDSI. Further detailed
130 physiological work has noted that although *C. intratropica* is highly drought tolerant
131 (Brodribb et al., 2010; 2013), water availability clearly plays a critical role in the
132 addition of annual increment in this species (Baker et al., 2008; Brodribb et al., 2010;
133 2013; Drew et al., 2011; 2014). Growth typically begins soon after rain begins to
134 reliably fall in November, ceasing in April/May (Prior et al., 2004b; Drew et al., 2014).

135 Although there is increasing impetus to develop long climate reconstructions
136 using this species, there are two immediate challenges to this goal in monsoonal
137 Australia. Firstly, there are very few published chronologies for this region (three), and
138 those that have been published are either short and/or have low sample depths ($n \leq 10$)
139 over much of their length. Higher replication is likely to improve the quality of the
140 climate signal present in the ring widths. Secondly, the variability in tree growth
141 responses to climate variability across the broader region (e.g. Baker et al., 2008; Cullen
142 and Grierson, 2009; O'Donnell et al., 2018) and the different climate regimes at existing
143 and potential sites across northern Australia, highlights a need to better understand the
144 spatial extent over which climate signals are preserved by *C. intratropica*. The
145 relationships shown by Baker et al (2008) were based on single-point climate data and
146 therefore did not explore the geographical extent of the climate signal contained in the
147 ring widths of a single site. Such spatial information is relevant for climate field
148 reconstruction.

149 In this study, our primary objective is to present and describe two well-
150 replicated *C. intratropica* chronologies from Arnhem Land, northern Australia. An
151 important part of this description is an assessment of whether there are coherent
152 regional responses to climate variables such as temperature, precipitation,
153 evapotranspiration and drought across the Australian region from 11-15.25°S and 130-
154 136.5°E. This provides crucial background to assessing the suitability of the sites for

155 future climate field reconstructions of these variables. We also compare the regional
156 responses of our two new sites with those outlined by Baker et al. (2008) for single
157 point data. Specifically, we aim to address the question of whether these two sites will
158 be useful in hydroclimatic reconstructions for this region, and, if so, for what months
159 and what hydroclimatic variables.

160 **Materials and Methods**

161 *Geographic setting*

162 The two new *C. intratropica* sites, Korlobirrahda (KOR) and Murganella
163 (MUR) are located approximately 220 km apart in Arnhem Land (Figure 1) in a
164 landscape with relatively little topographical variability that experiences a strongly
165 seasonal climate. The KOR site builds upon and extends the original KOR chronology
166 shown by Pearson et al (2011).

167 On average, 94% of precipitation falls between November and April (Figure 2a)
168 and average annual rainfall ranges from 1000-1500 mm across the far north of the
169 region, increasing to 2000-3000 mm annually around Darwin. There are typically 50 -
170 75 days with more than 5mm of rainfall (www.bom.gov.au) in the far north, this rapidly
171 decreases as latitude increases. Based on a 20-year period, Cook and Heerdegen (2001)
172 estimated this decrease to be in the order of ~50% over 8 degrees of latitude. Overall,
173 precipitation over the region has increased since the start of records (Figure 2c&d;
174 Mann-Kendall test for trend: Darwin, $p = 0.0128$; Katherine, $p = 0.0807$; Oenpelli, $p =$
175 0.003 ; Waruwi, $p = 0.619$), although the strength of the trend depends upon the period
176 examined (Woinarski et al., 2007; www.bom.gov.au). Increased rainfall appears mainly
177 related to increased intensity of events (Smith et al. 2006).

178 Maximum temperatures across the study region are highest from October - April
179 (34-37°C on average; Figure 2a) compared to a low of 29-30°C in June-July. Minimum

180 temperatures range from ~14°C in July to ~24°C from November-February. There are
181 some subtle differences between the two tree-ring sites with average June – September
182 minimum temperatures at the inland site, KOR, being slighter lower than at the more
183 coastal site, MUR. Evapotranspiration is generally higher at MUR all year round
184 (www.bom.gov.au). Temperatures at Darwin, the closest station in the Bureau of
185 Meteorology’s ACORN-SAT network that provides homogenised temperature records
186 from ground-based stations, illustrate that the increase in both maximum and minimum
187 temperatures since the start of the record in 1910 (Figure 2b) is highly significant
188 (Mann-Kendall test for trend; $p = 2.22e-16$).

189 *Sampling and chronology development*

190 Samples from KOR were collected over successive field trips between 2006 and
191 2016 by Bowman and co-workers as part of a broad scale ecological study (Prior et al.,
192 2011). Sampled trees grew either in small groves or as single trees in open savannah
193 areas. Samples from the region around Murganella were collected from small
194 monospecific stands in the early 1970s for species-level growth modeling (Hammer,
195 1981; 1983). Maps marked with locations of groves at MUR indicate they are scattered
196 across the landscape around Murganella, and this may become relevant when
197 considering the climate-tree-ring width relationship at MUR. Importantly, samples
198 from neither site were collected with dendroclimatological work in mind, but the sheer
199 number of samples for both sites and the temporal depth, makes them of particular
200 interest for climate studies.

201 All samples were prepared in accordance with standard dendrochronological
202 techniques (Stokes and Smiley 1968). Coorecorder in combination with CDendro
203 image analysis software (<http://www.cybis.se/forfun/dendro/>) was used to measure ring
204 widths and the crossdating data quality control COFECHA software (Holmes 1983)

205 used to check visual crossdating (temporal matching of ring widths across samples). In
206 order to examine climate influences on incremental tree growth, it is necessary to first
207 remove nonclimatic variability (Fritts, 1976). Trees at both KOR and MUR typically
208 exhibit declining growth-ring width with age, as commonly observed in many species
209 in relatively open habitats (cf. Fritts 1976). Therefore, a negative exponential/linear
210 regression line detrending regime was used to detrend tree ring-width series at both
211 sites. Site-level skeleton plots that identify particularly narrow rings compared to their
212 neighbours were produced using the dplR package in R (Appendix S1; Bunn 2010). We
213 produced our chronologies in the signal-free environment (Melvin and Briffa, 2007) to
214 avoid or reduce distortion of final chronologies due to the removal of decadal-
215 centennial frequency information common across the site that may well be associated
216 with climate. This variability may be removed with standardisation techniques that fit
217 a growth curve (in this case a negative exponential curve/linear regression line) to the
218 data directly. Signal-free standardisation is an iterative procedure that first removes a
219 common site signal from the data prior to fitting a growth curve to an individual tree-
220 ring series (see Melvin and Briffa 2008 for details).

221 *Climate data and Analyses*

222 To assess the strength of relationships between each of the two chronologies
223 and the climate parameters, we examined Pearson correlations for autoregressively
224 modeled data. This was done over the full period of overlap between each chronology
225 (1902 – 2015 KOR; 1902 – 1973 MUR) and each point contained within the gridded
226 data sets described below for the area bounded by latitudes 11 – 15.25°S and longitudes
227 130 – 137.5°E. This area encapsulates the far north of the Northern Territory (Figure
228 1) and is approximately 291,000km².

229 The temperature data, potential evapotranspiration and SPEI and scPDSI
230 extended from 1902 – 2015 and precipitation data covers the period 1901-2016. All
231 gridded data sets used have a resolution of 0.5 x 0.5°. Climate variables included
232 monthly and seasonal (December-February (DJF), March-May (MAM), June-August
233 (JJA), September-November (SON)) mean, maximum and minimum temperature (107
234 grid cells), total precipitation (118 grid cells), potential evapotranspiration (107 grid
235 cells) and two drought indices (each with 107 grid cells): the sc-PDSI and the
236 Standardised Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al.,
237 2010a&b). The Climate Research Unit (CRU) temperature and potential
238 evapotranspiration were downloaded from <http://doi.org/10/gcmdf7>; Harris et al.,
239 2014), while precipitation data were sourced from the Global Precipitation Climatology
240 Centre (GPCC; <https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html>; Schneider
241 et al., 2011; Becker et al., 2013). Because there is evidence that the number of rainfall
242 events is relevant to growth in this species (Drew et al., 2014), we also compared the
243 chronologies against the number of rain days per year/season at the two closest long-
244 term high quality stations (Oenpelli 1910-2013 and Warruwi 1916-2017). Number of
245 rain days is not available from the gridded monthly data, hence our reliance on these
246 two stations. We used total rainfall and an imposed threshold of ≥ 5 mm/day in
247 accordance with Cook and Heerdegen (2001) who defined a rain day as one with >
248 5mm of rain because evapotranspiration typically exceeds this amount.

249 The two drought indices used in this study incorporate both precipitation and
250 temperature in their calculation. As temperature is an important driver of
251 evapotranspiration, drought indices incorporating it are more appropriate when
252 considering plant drought sensitivity than indices depending only on precipitation. This
253 point is well illustrated by, amongst others, Jeong et al. (2014). Cook et al. (2016) have

254 also demonstrated the crucial role of temperature in drought projections for eastern
255 Australia.

256 The sc-PDSI is a modification of the original PDSI (Palmer 1965) and calibrates
257 behavior of the index at a given location (Wells et al., 2004). It is based on a simple
258 bucket model of soil moisture and essentially measures the excess or lack of moisture
259 at a given point based on certain underlying assumptions and conditions as detailed by
260 Wells et al. (2004). The sc-PDSI is the basis of the tree-ring based drought atlases
261 including the North American Drought Atlas (NADA; Cook et al., 2007), the Monsoon
262 Asia Atlas (MADA; Cook et al., 2010), the Old World Drought Atlas (OWDA; Cook
263 et al., 2015), the Mexican Drought Atlas (MxDA; Stahle et al., 2016) and the Australia
264 New Zealand Drought Atlas (ANZDA; Palmer et al., 2015). The West Australian
265 Drought Atlas (WADA) will also be based on the sc-PDSI (O'Donnell et al., 2018).

266 While this legacy means that the potential to reconstruct the sc-PDSI using
267 *Callitris* from the Arnhem Land region is of considerable interest, limitations of this
268 index include its fixed temporal scale (monthly) and strong autocorrelative structure
269 (Guttman, 1998; Vicente-Serrano et al., 2010a). Drought, on the other hand may occur
270 over time-scales of months to years, and even short-term droughts may negatively affect
271 both plant growth and human societies. In contrast to the sc-PDSI, the SPEI represents
272 an accumulated moisture deficit calculated at different time scales (Vicente-Serrano et
273 al., 2010a&b). Once again, the index is based on moisture deficit, essentially the
274 difference between precipitation and potential evapotranspiration. The calculation
275 process used to scale the index is very similar to that used for the Standardised
276 Precipitation Index (SPI) index. Therefore, like the sc-PDSI it is based on water
277 balance in the soil, but can be calculated based on different time scales. This scaled
278 nature of the index allows the impact of droughts of different durations to be explored,
279 and a comparison with the sc-PDSI to be made. We examined the SPEI at times scales

280 of 1,3,6 and 12 months and the sc-PDSI averaged over the same periods. Data for the
281 sc-PDSI and SPEI were obtained from the CRU data portal
282 (<https://crudata.uea.ac.uk/cru/data/drought/>) and the repository of the Spanish National
283 Research Council (CSIC: <https://digital.csic.es/handle/10261/153475> respectively.
284 Spatial correlations amongst the gridded data are shown and discussed in Appendix S2.

285 As a final hydroclimate comparison, we examined the relationship between the
286 KOR chronology and streamflow at the Australian Bureau of Meteorology's (BOM)
287 East Alligator hydrological reference station (12.72°S, 133.32°E, 460 mASL). There
288 were two reasons to use this streamflow gauge. First, it is the closest station to the KOR
289 site, and secondly, Verdon-Kidd et al. (2017) used this station as the basis for a long
290 streamflow reconstruction that relied exclusively on remote proxies. We did not
291 compare streamflow with MUR because this chronology ends in 1973 and the
292 streamflow data does not commence until late 1971. We compared flows over the same
293 windows identified above.

294 **Results**

295 *The chronologies*

296 The KOR chronology is comprised of 165 samples, and the MUR chronology
297 of 69 samples (Table 1). Median segment length is 86 for KOR and 74 for MUR.
298 Greatest sample depth for both chronologies occurs in the late 20th Century, only falling
299 below five at 1774 CE (KOR), and 1848 CE (MUR) (Figures 3 and Appendix S1;
300 Figure S2). There is no large discontinuity in sample start dates in the KOR chronology,
301 although the first year of a large proportion of trees sampled in 2006 was between 1930
302 and 1960 (Appendix S1; Figure S2). First and last years in KOR are much more
303 heterogenous than for MUR, reflecting the sampling of dead material at KOR, and the
304 focus on live trees at MUR (Appendix S1; Figure S2). The start of the KOR chronology

305 is weak, but low sample depth at this point means it is not currently possible to assess
306 where problems lie. For the purposes of this study, we have therefore retained all
307 samples representing this time period in the chronology, but recommend that the earliest
308 portion of it be cautiously used until additional samples can help resolve any dating
309 issues.

310 The Expressed Population Signal (EPS; Wigley et al., 1984) for both
311 chronologies is 0.8 or greater for much of their respective lengths, declining as sample
312 depth declines (Figure 3). Overall, average EPS is greater than 0.9 for both
313 chronologies (Table 1) and above the commonly cited 0.85 value at KOR from 1803
314 CE, and at MUR from 1846 CE. The average correlation amongst all possible pairs of
315 samples (RBar) for KOR remains relatively stable between $\sim 0.3 - 0.4$, averaging 0.35
316 (Table 1). Average RBar for MUR is 0.42, exceeding 0.5 during the first two decades
317 when replication is low but decreasing to 0.3 -0.4 as sample depth rapidly climbs from
318 ~ 1880 CE onwards. The two chronologies share nine (1868, 1891, 1896, 1899, 1905,
319 1911, 1925, 1941 and 1945 CE) of 19 possible narrow rings (rings at least 1σ below
320 the mean) identified after removing frequencies lower than 32 years as part of checking
321 crossdating via COFECHA, and 14 of a possible 32 signature rings identified through
322 a comparison of their skeleton plots (Appendix S1; Figure S1). Overall, the narrowest
323 rings are 1951 CE at KOR and 1925 CE at MUR. Average lag 1 autocorrelation is
324 relatively high at both sites (~ 0.57 ; Table 1).

325 With the exception of the start of MUR, inter-annual variability of the two
326 chronologies is relatively consistent (Figure 3). Over the period for which both
327 chronologies have sample depths greater than 10 (1859-1972), the correlation between
328 the two chronologies is 0.55. That relationship breaks down at 1951, the narrowest ring
329 in the KOR chronology (see Section S1 for a brief discussion of a missing ring in
330 MUR). Although there appears to be some decadal variability in KOR, statistically

331 significant ($p < 0.05$) spectral peaks only occur at 64.1, 4.6 and 2.9 years. In the shorter
332 MUR series, statistically significant spectral peaks occur at 64.1 and 4.7 years (Figure
333 3). The limited length of both series means that the 64.1-year periodicity should be
334 treated with caution.

335 *Relationships with climate variables*

336 In this section, we focus on relationships with the data seasonalised across 3-
337 month periods previously identified (DJF, MAM, JJA, SON), while correlations with
338 monthly climate data are shown and discussed in Appendix S2. Monthly results for the
339 variously scaled SPEI- and scPDSI are also shown in Appendix S2. For a single site,
340 the slightly different periods of overlap with the climate data (different by two years for
341 precipitation compared to temperature) are unlikely to have any substantial impact on
342 the correlations shown.

343 There are consistent seasonal patterns in temperature-ring width relationships
344 across the region for the two sites (Figure 4). Strongest significant ($p < 0.05$)
345 correlations typically occur from March-May (Figure 4) when they are negative. The
346 strongest positive and significant ($p \leq 0.05$) grid-point correlations between both
347 chronologies and temperature occur in JJA. The largest difference across the three
348 temperature variables is the positive and significant ($p < 0.05$) correlations with SON
349 minimum temperature (Figure 4). Variability in the response to mean and maximum
350 temperature across the region is low for both sites, but slightly higher for MUR (see
351 also Appendix S2; Figure S3). Overall, there is greater variability in the response to
352 minimum temperatures.

353 For both sites, the variability in the response to precipitation is greater than that
354 to temperature (Figure 4). Overall, strongest positive relationships occur during SON
355 and MAM. The pattern is consistent with the single point precipitation data at Waruwi

356 and Oenpelli (Table 2; $0.18 \leq r \leq 0.43$; Figure S4 in Appendix S2) with marginally
357 stronger relationships with both SON and MAM rainfall. Interestingly, the relationships
358 with the number of rain days at these two rainfall stations, applying the 5mm threshold
359 (0.16 - 0.63), were generally stronger than those with total rainfall amount (0 – 0.48;
360 Table 2). Potential evapotranspiration in MAM is strongly and significantly ($p < 0.05$)
361 negatively correlated with ring width at both sites (Figure 4). For MUR there are
362 positive, but not always significant positive relationships in JJA.

363 The pattern of correlations with the gridded SPEI-3 is similar for the two
364 chronologies (Figure 4) although there is greater spread in correlations for MUR (see
365 also Appendix S2; Figure S5). In broad terms, relationships tend to be positive from
366 July through to May, although there is something of an hiatus for DJF that is more
367 obvious at KOR. Strongest correlations generally occur for April and May (KOR) and
368 May (MUR).

369 Correlation between KOR and August-July streamflow at East Alligator river
370 is negligible at $r = -0.09$, but the relationship becomes positive and marginally
371 significant for SON ($r = 0.276$; $p < 0.1$; Figure 5) and MAM ($r = 0.298$; $p < 0.1$). A
372 relatively strong but negative correlation with DJF streamflow ($r = -0.31$; $p < 0.1$; Figure
373 5), however, cautions against making firm conclusions regarding the strength of these
374 relationships without additional data.

375 **Discussion**

376 *Extending the chronology network in the far north*

377 The central Arnhem Land chronology (KOR) extends back into the 18th
378 Century, exceeding the length of any other north Australian *Callitris* chronologies thus
379 far published by 86 years. Along with the Pine Creek (PC) chronology developed by

380 Baker et al. (2008), our two new chronologies make an important contribution to the
381 development of a network of cross-dated chronologies for this part of the country.

382 Importantly, KOR is comprised of naturally occurring trees and includes long-
383 dead trees, relatively young (~50 years) and old (> 100 years) trees, thus avoiding
384 possible bias in climate relationships associated with tree age (e.g. Hanna et al., 2018).
385 All previously published chronologies (PC; 1847-2006 and Howard Springs HS; 1965-
386 2006) shown in Baker et al. (2008), and the early version of the KOR chronology
387 (Pearson et al., 2011) rely exclusively on live trees. Additionally, all previously
388 published chronologies of the species are considerably less well replicated in the early
389 part of the 20th Century in particular (Baker et al. 2008; Pearson et al., 2011; Palmer et
390 al., 2015), and include samples from far fewer trees (Table 1). The greater length of the
391 new KOR chronology and the much improved replication of both MUR and KOR are
392 the chief improvements offered by our chronologies for this region. Average EPS
393 values for the longer Baker et al. (2008) and our new chronologies are almost the same
394 although RBar is much higher in the PC chronology. This higher RBar is also reflected
395 in a very high mean inter-series correlation (MISC) at PC (Table 1). Mean sensitivity
396 of the three longer chronologies is again comparable while that for HS is relatively low
397 (Table 1). The very high MISC and RBar for PC is likely associated with improvements
398 made for climate reconstruction purposes (D'Arrigo et al., 2008). Originally, cores from
399 26 trees were collected, but only those from 14 trees have been included in the final
400 chronology.

401 The Pearson et al. (2011) study identified additional collections of the species
402 in the region (Figure 1), indicating considerable potential exists for additional sites.

403

404 *Consistency with previous work*

405 Although gridded data in regions with a low-density network of climate stations
406 such as this one must be treated with caution (Fu et al., 2015), the strength of our results
407 lies with the ability to identify general patterns across the region as well as their
408 consistency with the point comparisons made by Baker et al. (2008), particularly for
409 their PC chronology (Figure 4; Appendix S2). There is less consistency with the shorter
410 HS chronology, but Baker et al. (2008) found that patterns of correlations with climate
411 were not well defined for HS relative to PC. The relative youth of HS – deliberately
412 sourced from plantation trees of a known age (~40 years) to validate the annual nature
413 of rings in the species – is a likely reason for this difference. The general pattern of
414 response of our two sites to the monthly sc-PDSI and SPEI again indicates a regionally
415 consistent response (Appendix S2; Figures S5-S6) and is also consistent with results
416 for PC (Baker et al., 2008). Some differences between the two sites and potential
417 reasons for these are explored in the Supplementary material (Appendix S2, Figures
418 S8-9).

419 Our work also expands upon the results of Baker et al. (2008) by demonstrating
420 consistency in these climate relationships across the region (Figures 3, S3-5) and
421 showing that these relationships are more geographically coherent for temperature,
422 evapotranspiration and drought as defined by the SPEI and sc-PDSI than for
423 precipitation. Our investigation of multi-month windows also helps to further
424 consolidate foundations for future climate reconstructions.

425 It is also important that our statistical results accord with previous physiological
426 work on the species and ecological knowledge of the region. As described in the
427 Introduction, increment growth in the species is tied to the wet period of the year. In
428 relation to precipitation, Brodribb (2010; 2013) and Drew et al. (2011; 2014) have
429 found that larger growth increments are less related to total precipitation over the wet
430 season than to the frequency of rainfall events. Additional wet days over the SON and

431 MAM periods may be associated with wider growth rings; fewer wet days during these
432 periods are likely to result in narrower rings. Indeed, Drew et al. (2014) observed that
433 the short-term record-breaking rainfall associated with tropical cyclone Carlos in 2011
434 had little impact on growth increment of *C. intratropica* for that year, and our results in
435 Table 2 show notionally stronger relationships with rain days (once a threshold is
436 applied) than with rainfall amount. Drew et al. (2014) also suggested that narrow rings
437 may usefully identify dry years. Our results that show higher moisture sensitivity of *C.*
438 *intratropica* in SON and MAM (Figures 4, Appendix S2) with a DJF hiatus when
439 moisture is unlikely to be limiting (Figures 4, Appendix S2), concur with this detailed
440 monitoring work. Additionally, we note that the narrowest rings for both chronologies
441 (1925 (MUR) and 1951 (KOR)) are associated with both low rainfall and a low number
442 of rain days at one or both rainfall stations (Table S2). There also appears to be some
443 correspondence between narrow rings (more than 1σ below mean ring width), and dry
444 years (more than 1σ below the mean), or years that had relatively few (more than 1σ
445 below the mean) rain days, for the first part of the 20th Century, but this pattern does
446 not clearly persist for the latter part of the century (Table S2). This relationship with
447 moisture conforms with the ecology of flora and fauna in this region that is intimately
448 linked to the timing and pattern of rain (Woinarski et al., 2007).

449 Strong correlations with temperature (~July-October, MAM; Figure 4),
450 evapotranspiration (MAM; Figure 4) and drought (Figure 4; Appendix S2) also concur
451 with previous findings that temperature plays an important role in the moisture budget
452 for the species (Drew et al. 2014). Stronger and more spatially consistent relationships
453 between increment growth and the SPEI (and sc-PDSI; Figures 4; Appendix S2; Figures
454 S5, S6) compared to precipitation (Figure 4, Appendix S2; Figure S3) could be
455 associated with greater geographic variability in the incidence of precipitation and the
456 presence of ground water.

457 The consistency of our statistical results with detailed physiological work
458 supports selection of months at the start and end of the wet period of the year for
459 hydroclimate reconstructions.

460

461 *The potential of C. intratropica for hydrological reconstructions*

462 Our analyses point to the importance of hydroclimate to ring widths in this
463 species during the transition into (SON) and out of (MAM) the wettest months of the
464 year in northern Australia. This in turn strongly points to the relevance of early/late
465 starts and ends of the wet period of the year for incremental growth, in line with Drew
466 et al. (2014). Based on our results, both total precipitation and streamflow in the region
467 may be suitable targets for reconstruction at these times. Although not a variable
468 commonly reconstructed, its potential link to the El Niño Southern Oscillation (ENSO;
469 Smith et al., 2006; Cook and Heerdegen, 2001), means further investigation of the
470 possibility for reconstructions of days of precipitation (> 5mm) over MAM would be
471 worthwhile. We note that narrow rings in both chronologies often coincide with El Niño
472 but not La Niña events (Table S2), although unfortunately, there is inadequate
473 information to statistically test this.

474 Although interest is often focused on total precipitation received over the entire
475 wet period, the significance of hydroclimate reconstructions for the transitional months
476 should not be underestimated. These are key periods both for Indigenous peoples and
477 ecological processes and are defined by particular activities, events, availability of
478 foods and the presence of particular fauna (Table 3). Variability in the timing of
479 monsoonal rain, especially at the start and end of the wet period (i.e. the duration of the
480 wet period) will have critical impacts on land management and on ecological processes
481 that in turn affect the availability of certain foods such as sugarbag honey or bush yams,

482 or breeding and migration cycles of some species (Redhead 1979; Vardon et al., 2001;
483 Cook and Heerdegen 2001; Woinarski et al., 2007). Reconstructed climate variability
484 at this time may therefore provide vital clues to some aspects of regional environmental
485 history, providing baseline information about duration of the wet period prior to
486 instrumental records. Daily information available from Australian Water Availability
487 Project (Jones et al., 2009) data may help facilitate gridded reconstructions of duration
488 of the wet period and this potential requires further investigation.

489 In general, the apparent correspondence between very narrow rings and dry
490 conditions and our correlative results suggest that hydrological reconstructions from *C.*
491 *intratropica* may be possible for either of the transitional periods here, (SON or MAM),
492 but that care will need to be taken in selecting the target variable. While the potential
493 of the species to reconstruct precipitation for either of these windows requires further
494 investigation, results suggest that for drought – as defined by the SPEI or sc-PDSI –
495 only reconstructions for MAM drought make sense (Figures 4, Appendix 2; Figures
496 S5-S6). This is because the formulation of the drought indices used here is premised on
497 the negative impact of increased temperature on moisture availability (see Vicente-
498 Serrano et al., 2010 and references therein). This means that for a positive relationship
499 with the SPEI to make sense, we would expect a positive relationship with precipitation
500 and a simultaneously negative association with temperature. While MAM period meets
501 this condition, JJA does not (Figure 4; Appendix S2; Figures S5-6). The association
502 with evapotranspiration is also strongly negative for MAM, this being consistent with
503 opposite relationships with temperature and precipitation at this time. Therefore, *C.*
504 *intratropica* in this region appears ideally placed to reconstruct MAM drought.
505 Nevertheless, the ability to reconstruct any hydrological variable needs to be properly
506 considered in the context of a reconstruction model, and this is well beyond the scope
507 of this paper.

508 A further important consideration will be the required sampling strategy. Based
509 on the greater spatial coherence of correlations with the drought indices compared to
510 precipitation shown in this study, drought index reconstruction is likely to require a
511 lower site density than reconstructions of precipitation for which there is greater
512 variability across the region. Importantly, neither of the sites presented in this study
513 were sampled with dendroclimatology in mind and relatively weak relationships found
514 with streamflow in particular, may reflect this.

515 **Conclusions**

516 In this paper we have presented two well-replicated and crossdated Australian
517 *Callitris* tree-ring chronologies, and demonstrated the potential for dead *C. intratropica*
518 trees that remain sufficiently intact over long periods of time to be included in
519 chronologies. This demonstrates the potential to temporally and spatially extend the *C.*
520 *intratropica* tree-ring network across northern Australia suitable for hydroclimate
521 reconstructions over the past 250-300 years. An expanded network of well-replicated
522 tree-ring chronologies for this region increases the potential for high-quality
523 hydroclimate reconstructions in a region where there currently exist very few annually
524 resolved multi-centennial palaeoclimate records. The KOR chronology extends the
525 tree-ring based climate record back 86 years, and its response to climate is consistent
526 with previous work.

527 For the first time, we demonstrate clear consistent and seasonal patterns in
528 relationships between the chronologies and climate across the far north of Australia.
529 This is an important basis for future hydroclimate reconstructions, although our results
530 suggest that perhaps a broader region should be further tested. Overall, results indicate
531 that reconstruction efforts should focus on hydroclimate variability for months that
532 transition into and out of the wet period of the year. This strongly points to the

533 importance of the duration of the wet time of the year to wood formation in this species.
534 Crucial ecological processes that support Indigenous land management and cultural
535 practices occur during both these transitional periods and previous work has
536 commented on the importance of duration of the wet period to regional flora and fauna.
537 Given that variability in the length of the wet period may also be linked to ENSO,
538 hydrological reconstructions from this species in this region may be particularly
539 valuable for assessing past variability in this climate mode with an almost global reach.
540

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764 *Journal of Wildland Fire* 12: 349-358

765

766 **Figures and Tables in Supplementary Appendices**

767 **Figure S1.** Skeleton plots for the two sites

768 **Figure S2.** Correlation of all tree-ring series at a site to master series for each
769 chronology

770 **Figure S3.** Boxplots of regional monthly correlations of chronologies with climate
771 variables

772 **Figure S4.** Correlations between chronologies and site temperature and precipitation

773 **Figure S5.** Boxplots of Pearson correlations of KOR and MUR with variously scaled
774 SPEI indices

775 **Figure S6.** As for Figure S3, but for PDSI

776 **Figure S7.** Regional correlations, chronologies with drought indices (1903 – 1973)

777 **Figure S8.** Regional correlations, chronologies with drought indices (1903-1973 MUR;
778 1903-2015 KOR)

779 **Table S1.** Narrow rings in chronologies, years total precipitation total and days low, El
780 Nino events

781 **Table S2.** Average intercorrelations amongst all gridded climate data for climate
782 variables

783 **Figure captions**

784 **Figure 1:** Top: Map showing location of Top End and area for which climate
785 correlations calculated. Bottom: tree-ring site locations, location of East Alligator River
786 streamflow gauge, and location of the four high quality precipitation stations used to
787 show trends over the 20th Century. Temperature data series also from the Darwin
788 meteorological station. The white square denoting the Litchfield National Park shows
789 the existence of two other small collections of *C. intratropica* (for details, see Pearson
790 et al., 2011). The ggmap package in R was used to produce the map showing sites
791 (Kahle and Wickham 2013).

792 **Figure 2:** Average monthly temperature and precipitation for the study region,
793 averaged from the CRU temperature data and GPCC precipitation for the identified
794 region (Figure 1). Blue bars are precipitation, solid black line is maximum temperature
795 and dashed line is minimum temperature. B. Average annual temperature at Darwin
796 (August-September year; station 014015) shown as z-scores. Solid line is maximum
797 temperature and dashed line minimum temperature; C. Time series of precipitation z-
798 scores for two of four high quality precipitation stations in region shown in Figure 1
799 (Darwin airport 014015 solid line; Waruwi 014042 dotted line); D Time series of
800 precipitation z-scores for two of four high quality precipitation stations in region shown
801 in Figure 1 (Oenpelli 014042 solid line, Katherine 014902 dotted line). Note the
802 differing scales on the x-axes for temperature and precipitation series. Meteorological
803 data for these stations was obtained from the Bureau of Meteorology
804 (www.bom.gov.au).

805 **Figure 3:** A. The two chronologies and sample depths. B. Running EPS and RBar for
806 the two sites, calculated for successive 50-year windows. C. Spectra of the two sites.
807 Statistically significant ($p < 0.05$) periodicities include 64.1, 4.57, 2.91 years (KOR)

808 and 64.1 and 4.74 years (MUR). The dotted line represents the 95% significance
809 level and the dashed line, the 99% significance level.

810 **Figure 4:** Boxplots of correlations between the two chronologies and gridded climate
811 data averaged over 3-monthly periods for the period 1902 – 2015 (KOR temperature
812 and drought indices), 1901-2015 (KOR; precipitation) and 1902 – 1973 (MUR;
813 temperature and drought indices) and 1901 – 1973 (MUR; precipitation). The SPEI
814 plots are for the SPEI-3, for the same months as the other climate variables. A - B
815 mean temperature (107 grid cells); C-D maximum temperature (107 grid cells); E-F
816 minimum temperature (2017 grid cells); G-H precipitation (118 grid cells); I-J
817 potential evapotranspiration (107 grid cells), K-L SPEI-3 (107 grid cells). The left
818 column shows correlations for KOR and the right, for MUR. The box represents the
819 interquartile range and the whiskers for each box extend out to the maximum and
820 minimum values. Coloured boxes are shown for those periods in which correlations
821 for all grid cells are positive (negative) while grey boxes are used for periods in which
822 there are both positive and negative values. Dashed lines represent the 95%
823 significance limits. A 'p' in front of the x-axis label denotes the year prior to growth.

824 **Figure 5.** KOR chronology plotted against streamflow at East Alligator River gauge
825 for (A) Aug-Jul, (B) Sep-Nov, (C) Dec-Feb and (D) Mar-May. Black line is KOR
826 chronology, red line with points is streamflow. Note the visually strong relationships
827 with MAM streamflow over the past ~15 years.

828

| Statistic | KOR | MUR | PC | HS |
|-----------------------------|-------------|-------------|------------------------|-------------|
| Chronology period | 1761 - 2015 | 1845 - 1973 | 1847 - 2006 | 1964 - 2004 |
| n (N ⁺) | 165 (129) | 69 (43) | 30 (14) | 64 (20) |
| Average EPS | 0.92 | 0.95 | 0.94 | - |
| Period for which EPS > 0.85 | 1803-2015 | 1846-1973 | 1857-2006 [‡] | - |
| Average RBar | 0.35 | 0.42 | 0.67 | - |
| Median segment length | 86 (43,188) | 74 (39,127) | 96 (56,160) | 40 |
| Average autocorrelation | 0.585 | 0.556 | 0.56 | - |
| MS | 0.4 | 0.4 | 0.35 | 0.26 |
| MISC | 0.55 | 0.46 | 0.74 | 0.69 |

830 **Table 1:** Chronology statistics for the KOR and MUR chronologies presented here as
831 well as the previously published Pine Creek (PS) and Howard Springs (HS) sites (Baker
832 et al., 2008) where data/information available. n (N) is the number of samples (trees)
833 making up the chronology. ⁺Note that N is an estimate. Due to labelling of samples –
834 particularly for old MUR samples - it was not always possible to identify whether two
835 separate cores came from a single tree. [‡] indicates that this is not provided in the original
836 paper, but has been recalculated here using the signal-free version of the chronology
837 (see methods). This will result in small differences with the original chronology.
838 Median segment length refers to the median length of an individual sample in the

839 chronology. Figures in brackets are the minimum and maximum lengths respectively.
840 Average RBar and EPS are calculated for the entire chronologies; for year –to-year
841 variation, see Figure 4B. Average autocorrelation reports the average lag 1
842 autocorrelation. Figures shown in the table for PC relate to the samples used in the
843 final chronology rather than all samples collected (as shown in Baker et al. 2008).

| | Oenpelli | | Warruwi | | |
|--|----------------------|--------------------|----------------------|----------------------|----------------|
| <i>Amount of precipitation</i> | | | | | |
| | KOR (1910-2013) | MUR (1910-1973) | KOR (1916-2015) | MUR (1916-1973) | Average |
| Aug– Jul | 0.31 | 0.22 | 0.38 | 0.33 | 0.31 |
| Dec-Feb | -0.07 | 0.00 | 0.03 | 0.12 | 0.08 |
| Sept – Nov | 0.30 | 0.27 | 0.37 | 0.21 | 0.29 |
| Mar- May | 0.43 | 0.27 | 0.42 | 0.35 | 0.37 |
| <i>Number of days of precipitation</i> | | | | | |
| Aug– Jul | 0.25 (0.53) | 0.39 (0.41) | 0.18 (0.44) | 0.24 (0.40) | 0.27 (0.45) |
| Dec-Feb | 0.15 (0.23) | 0.21 (0.21) | 0.06 (0.16) | 0.03 (0.18) | 0.11 (0.20) |
| Sep – Nov | 0.14 (0.39) | 0.25 (0.24) | 0.00 (0.27) | 0.05 (0.22) | 0.11 (0.28) |
| Mar - May | 0.41 (0.63) | 0.48 (0.49) | 0.17 (0.52) | 0.17 (0.51) | 0.31 (0.54) |

845 **Table 2:** Correlations between the two chronologies and rainfall at the two nearest high
846 quality rainfall stations. Periods available for each analysis are noted next to the site
847 names). Figures in brackets for number of rain days are correlations for days when rain
848 exceeded 5mm. Correlations with both the amount of precipitation and the number of
849 days of rain are nominally highest for March-May, and correlations with the number of
850 days of rain are generally nominally higher than those with the absolute amount of rain
851 in each case. Italicised correlations for individual sites are significant at 0.05 level and
852 bold italics indicate significance at the 0.01 level.

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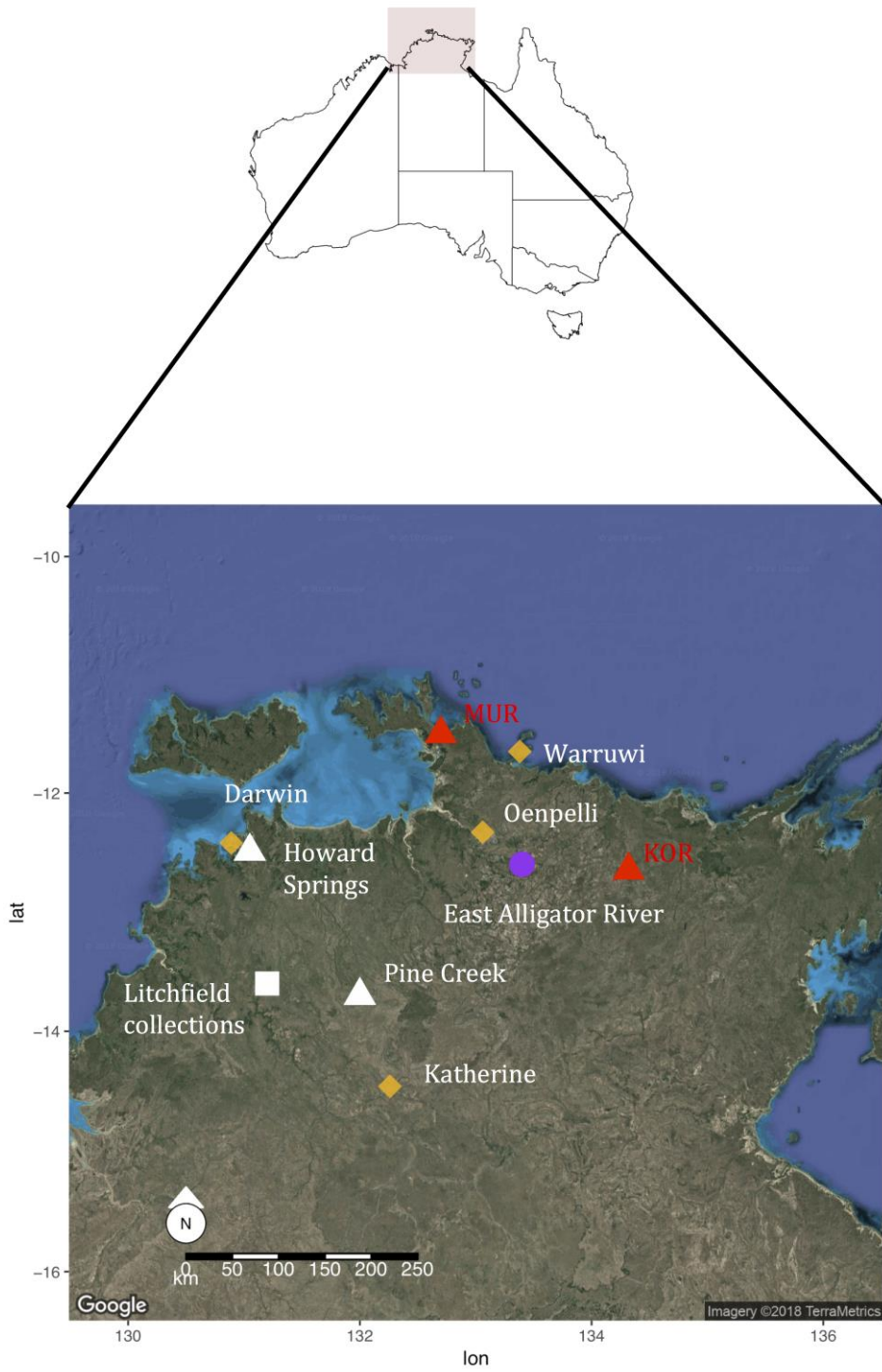
| Window | Indigenous calendar | Season name/part | Characteristics | Impt foods/others...from Indigenous calendars |
|--------|---------------------|--|---|--|
| JJA | Maung | Wumulukuk (March-July) | SE trade winds (Jun-Jul) | 'Knock'em down winds', tamarind, wattle and eucalypt flowers, sugarbag harvesting,, grass and trees dry out, time to burn off |
| | Tiwi | Kununupari (Mar-Aug) | Dry, fire and smoke | Plants and animals: yams, water lily, bush pumpkin, long yam, mud mussel, bush turkey, carpet python, turtles |
| | Jawoyn | Malaparr (Jun-Aug) | Cooler | |
| SON | Maung | Walmatpalmat (Nov-Feb), Kinyjapurr (Sep-Oct) | Heavy rain (Nov) Hot and humid, strong SE winds (Aug) SE and NW winds (Sep-Oct) | Kinyjapurr: rougher seas, thicker clouds, storms begin, wild apple, billy goat plums, bush potato sprouting Walmatpalmat : Bushfires, cyclones, new plant shoots, tamarind flowers, mangoes, wild |

| | | | | |
|-----|--------|---|--|--|
| | | | | apple, green plums, yam shoots, crab moulting |
| | Tiwi | Tiyari | Hot weather, high humidity | Plants and animals: cycad, peanut tree, magpie geese, dugong, whistling duck, mangrove worms |
| | Jawoyn | Worrwopmi (Sep-Oct) Wakaringding (Nov-Dec) | Monsoonal buildup (Sep-Dec), first rains (Nov-Dec) | |
| DJF | Maung | Walmatpalmat | Heavy rain | Bushfires, cyclones, new plant shoots, tamarind flowers, mangoes, wild apple, green plums, yam shoots, crab moulting |
| | Tiwi | Jamutakari | Wet season, consistent rain, NW winds, storms | Plants and animals: Green plums, pink bush apple, bush potato, northern brush tail possum, saltwater crocodile, barramundi, crested tern eggs, cocky apple |

| | | | | |
|-----|--------|---|--|---|
| | Jawoyn | Wakaringding (Nov-Dec), Jiorrk (Jan-Feb) | First rains (Nov-Dec) Main part of wet season 9Jan-Feb) | |
| MAM | Maung | Wumulukuk (March-July) | Cold weather NW-SE winds (Mar-Apr; 'knock-'em down winds) | Tamarind, wattle and eucalypt flowers, sugarbag harvesting,, grass and trees dry out, time to burn off |
| | Tiwi | Kumunupari (Mar-Aug) | Dry, fire and smoke | Plants and animals: yams, water lily, bush pumpkin, long yam, mud mussel, bush turkey, carpet python, turtles |
| | Jawoyn | Bungarung (Mar-Apr) Jungalk (Apr-May) | Last of the rains, drying Hot/dry | |

857

858 **Table 3:** Monthly windows used in the text and their correspondence to three local
859 Indigenous weather calendars for northern Australia available at :
860 <http://www.bom.gov.au/iwk/> . Information summarised from the website. Note that
861 there is not a perfect correspondence to the windows used in this study. For minor
862 seasons and additional details regarding flora and fauna of importance during these
863 seasons, see the website above.
864



865
 866
 867 Fig. 1