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1   Piloting novel multi-centennial palaeoclimate records from mainland

2   southeast Australia

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14 **Abstract**

15 High-resolution palaeoclimate proxies are fundamental to our understanding of the diverse climatic history of the Australian

16 mainland, particularly given the deficiency in instrumental datasets spanning greater than a century. Annually resolved, tree-

17 ring based proxies play a unique role in addressing limitations in our knowledge of interannual to multi-decadal temperature

18 and hydroclimatic variability prior to the instrumental period. Here we present cross-dated ring-width (RW) and minimum

19 blue-intensity (BI) chronologies spanning 70 years (1929 – 1998) for *Podocarpus lawrencei* Hook.f., the Australian

20 mainland's only alpine conifer, based on nine full-disk cross-sections from Mount Loch in the Victorian Alps. Correlations

21 with climate variables from observation stations and gridded data reveal a significant positive relationship between RW and

22 mean monthly maximum temperatures in winter throughout central Victoria (r = 0.62, p < 0.001), and a significant negative

23 correlation to winter precipitation (r = -0.51, p < 0.001). We also found significant negative correlations between RW and

24 monthly snow depth at Spencer Creek in New South Wales (r = -0.60, p < 0.001). Of the assessed BI parameters, delta blue-

25 intensity (ΔBI; the difference between early- and late-wood BI) displayed the greatest sensitivity to climate, with robust spatial

26 correlations with mean October to December maximum and minimum monthly temperatures (r = -0.43, p < 0.001; r = -0.51,

27 p < 0.001) and July precipitation (r = 0.44, p < 0.001), across large areas of northern Victoria. These promising findings

28 highlight the utility of this species for future work. With the very limited availability of suitable long-lived and cross-datable

29 species on the Australian mainland, these results have significant implications for advancing high-resolution palaeoclimate

30 science in southeastern Australia and for improving our understanding of past climate in the region.

31

Plain text summary

Tree-ring records provide a unique window into past climate variability. However, there are few such records from the Australian mainland. We present results from nine cross-sections of an alpine tree species from the Victorian Alps from 1929–1998. The tree ring widths have significant correlations with winter temperature, precipitation and snow depth. The intensity of reflected blue light from the wood surface shows a strong response to growing season temperature and winter precipitation.

1 Introduction

Documentation of climatic variations in the Northern Hemisphere (NH) is notably more comprehensive than that of the Southern Hemisphere (SH). Differences in the distribution of oceans and landmasses, as well as disparities related to cultural and historical development, continue to impair our understanding of SH climate (Villalba, 2000). A complete understanding of the climatic behaviour in a particular hemisphere is not possible without a thorough comprehension of the other (Pittock, 1978). That is, addressing the lack of SH climate knowledge is also a component of understanding NH and global climate.

The Australian continent encompasses a vast geographical extent with a diverse range of climate zones (Pittock, 2003). Instrumental and historical records of climate variables such as temperature and precipitation rarely extend beyond the start of the twentieth century (Bureau of Meteorology, 2001). Palaeoclimate proxies provide an important extension of the instrumental record, and aid in the development of meaningful assessments of the context of recent climate extremes and the fundamental nature of low-frequency climate variability. Dendroclimatology, the study of tree rings as a source of palaeoclimate proxies, has played an increasingly important role in our understanding of long-term climatic changes. Tree-ring studies have been widely applied, particularly in temperate environments, to produce centennial-scale climate information at annual resolution (*eg.* Villalba et al., 1996; Esper et al., 2002; Cook et al., 2006). However, progress in Australian dendroclimatology has been historically challenging due to the sparse availability of suitable materials and sites (Cook et al., 2006). Materials that exhibit annual growth rings are limited (Heinrich and Allen, 2013), and many do not live to sufficient ages for the development of multi-century records (Ogden 1978, 1981). Suitable environments for the preservation of subfossil material are also lacking in most parts of the Australian continent.

The Australian Alps constitute mainland Australia's alpine and subalpine regions. Tree species at their altitudinal threshold, such as those growing in high altitude and/or latitude sites, are typically highly sensitive to variability in climate, and therefore tend to best lend themselves to reconstructions (*e.g.* Villalba et al., 1994; Frank and Esper, 2005; Larocque and Smith, 2005). Dendroclimatological studies within the Australian Alps have focused on the widely distributed genus *Eucalyptus*, which exhibits clear annual rings at high elevations due to the strong growth limitation of winter temperatures (Brookhouse et al., 2008; Brookhouse and Bi, 2009). However, frequent mortality of specimens due to recurring fires in eucalypt habitats limits the availability of individuals of adequate age for long-term study. Given that continuous high-quality

63 climate records throughout the Australian Alps seldom extend beyond several decades, exploration of additional climate-

64 sensitive species with greater longevity and less affected by fire would be beneficial.

65   At high elevation, fire rarely penetrates into rock-scree environments . Due to the protection these environments offer

66 from fire, the age of vegetation growing within scree slopes can greatly exceed that of surrounding communities

67 (Schweingruber, 1992). In the alpine environments of New South Wales, Victoria, rock-scree sites often support pure stands

68 of *Podocarpus lawrencei* Hook f. (Williams et al., 2008). In these locations, *P. lawrencei* occurs as a procumbent shrub and

69 may attain an age of >500 years (Costin et al., 2000). Analysis of *P. lawrencei* revealed well defined, annual growth rings and

70 highly sensitive latewood bands, suggesting a promising opportunity for dendroclimatological study (Schweingruber, 1992).

71 However, attempts to generate chronologies for dendroclimatological analysis have been limited. *Podocarpus lawrencei*

72 exhibits highly eccentric (lobate) radial growth behaviour, with rings frequently affected by, or completely lost to, wedging.

73 These abnormalities make dating of core samples difficult, necessitating the collection of entire stem cross-sections. While the

74 destructive nature of collecting full cross-sections normally prevents their acquisition, sample materials became available

75 following widespread fires in 2002/03 in the Australian Alps. The severity of these fires meant previously protected stands of

76 fire-sensitive *P. lawrencei* were killed, allowing collection of full-disk cross-sections from multiple sites and an initial

77 investigation into their dendroclimatological potential (McDougall et al., 2012).

78   Although dendroclimatology has traditionally relied upon ring-width (RW) data, an array of alternative tree-ring

79 proxies also offer insights to climate histories. Maximum latewood density (MXD), for instance, represents the greatest density

80 incells formed at the latest stage of the growing season (Schweingruber et al., 1988). Maximum latewood density has been

81 widely used as a robust tree-ring proxy for growing-season temperature, particularly in the NH summer (*e.g.* Briffa et al., 1988;

82 D'Arrigo et al., 2000; Davi et al., 2003). However, the considerable cost and effort associated with generating MXD

83 chronologies has hindered their development and utilisation, especially in regions of the world in which dendroclimatology is

84 uncommon. The blue intensity (BI) technique – a recently developed approach that quantifies the intensity of blue light

85 reflected from a wood surface (McCarroll et al., 2002) – offers a cheaper and efficient surrogate for MXD (Björklund et al.,

86 2014; Wilson et al., 2014). Several experimental studies have demonstrated a strong, negative relationship between BI and

87 MXD, and sample preparation and generation of BI data can be performed at comparatively low expense (Campbell et al.,

88 2007, 2011; McCarroll et al., 2002; Björklund et al., 2014).

89   Although application of the BI method has been largely restricted to NH conifers, Brookhouse and Graham (2016)

90 conducted a preliminary assessment on the suitability of the BI method on *P. lawrencei* specimens from Mount Buller in

91 alpine NE Victoria (37.15ºS, 144.44ºE). They reported a highly significant correlation between the resulting BI chronology

92 and mean August-April temperature maxima ($r = -0.79$, $p < 0.0001$). The strength of this relationship greatly exceeded that of

93 RW. The BI method, then, may offer a superior source of climate-sensitive chronologies within the Australian Alps. Applying

94 this technique to Australian species may be the key to significantly improving our understanding of interannual to multi-

95 decadal climate variability prior to the instrumental period (Wilson et al., 2021). Together with existing palaeoclimatological

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96 studies, an expansion of this work could provide a critical baseline for temperature and hydroclimate prior to the industrial era

97 and major land-use changes following European arrival.

98   This study will report a crossdated *P. lawrencei* RW chronology based on sampled material from a previously

99 unexplored site (Mt Loch) in the Victorian Alps (Fig. 1). Chronologies of multiple BI parameters will also be generated.. This

100 study will then investigate the sensitivity of the RW and BI chronologies to climate variability, and discuss the potential

101 contributions of *P. lawrencei* in the advancement towards building reliable, multi-centennial scale reconstructions for

102 southeastern Australia.

103

104   [Figure 1 here]

105 **2 Methodology and data**

106 **2.1 Sampling site**

107 The *P. lawrencei* samples employed in this study were collected from Mt. Loch (36.96ºS, 147.16ºE) in 2007. The sample site

108 comprises a steep, south-facing rock-scree slope at ~1800m elevation (Fig 2a). The climate at Mt. Loch, indicated by the

109 nearby (<2 km distance) Mt Hotham meteorological station, exhibits strong seasonality in temperature due to its high altitude

110 (Fig. 3a), and is characterised by cold winter conditions with consistent July to October snow cover (Wahren et al., 2001; Venn

111 and Morgan, 2007). Such environments host numerous *P. lawrencei* communities throughout the Australian Alps (McDougall

112 et al., 2012; Brookhouse and Graham, 2016). A total of nine stem cross-sections of up to 13 cm in diameter were examined in

113 this study.

114

115   [Figure 2 here]

116   [Figure 3 here]

117 **2.2 Sample preparation**

118 A transverse surface of each sample was initially flattened using a belt sander to produce a surface uniformly perpendicular to

119 the tree-ring boundaries. Prior to scanning, resins and other extractives were removed. Because the BI technique relies upon

120 reflected light, staining unrelated to wood formation can alter reflectance and associations with climate data. To overcome

121 these problems, resins and stains that discolour materials are extracted in a process that may exceed 30 hours for each sample.

122 These extraction processes typically rely on soxhlet apparatus and a hazardous extraction solution. Previous analysis of *P.*

123 *lawrencei* (see Brookhouse and Graham, 2016) refluxed radial laths in a soxhlet apparatus and ethanol/toluene solution for up

124 to 42 hours. As an alternative to soxhlet extraction, samples in this study were soaked in pure acetone. This method allows for

125 the preparation of entire disks, which is highly advantageous given the lobate growth behaviour of *P. lawrencei*. Preliminary

126 experiments using acetone treatment for resin removal (Frith, 2009) suggest a minimum required extraction time of 72 hours

127 for partially immersed 5-mm thick *Pinus sylvestris* L. cores. Subsequent applications of the same technique have revealed the

128 majority of extractives are removed from fully immersed samples after just 48 hours of treatment (Rydval et al., 2014).

129 Moreover, as an addition or alternative to standard BI methods, the difference between minimum and maximum BI (ΔBI) may

130 provide a data source that increases the climate sensitivity of BI data and eliminates the need for extraction.

131 A sub-sample of three discs was used in this study to assess the efficacy of acetone treatment on full cross sections

132 of *P. lawrencei*. Three samples, ranging from 7-13 cm in diameter and approximately 1 cm thick, were submerged in 100%

133 acetone in air-tight glass containers at room temperature for an initial 120 hour period, followed by an additional 48 hours of

134 immersion. Each sample was sanded to a 2000-grit (9.5 - 11.1 μm) finish after each extraction stage. When the samples surfaces

135 were free of scratches they were scanned on an Epson Perfection V850 Pro scanner using SilverFast Ai professional software,

136 at a resolution of 4800 dots per inch (dpi). An IT8 Calibration Target (IT8.7/2) was used to calibrate the scanner to ensure the

137 comparable reproduction of colours and brightness between scans (Campbell et al., 2011). After experimentation with different

138 soaking times, the remaining six cross-sections were soaked in acetone for the optimal 120 hour period prior to the development

139 of ΔBI, earlywood (EWBI) and latewood BI (LWBI) chronologies.

140 The highly lobate radial growth of *P. lawrencei* and extensive ring wedging made it necessary to measure multiple

141 axes of measurement from all samples. Ring-width (RW) measurements were produced using the program CooRecorder™

142 and visual crossdating was undertaken on CDendro™, with the additional aid of separate microscope magnification of the

143 wood surface and correlation analysis on the Dendrochronology Program Library in R (dplR: Bunn, 2008, 2009). Blue intensity

144 parameters (delta BI (ΔBI), earlywood BI (EWBI) and latewood BI (LWBI)) were measured along the same paths used for

145 our RW measurement. The Mt. Loch RW chronology was then crossdated against a remotely located *P. lawrencei* RW

146 chronology developed by Brookhouse and Graham (2016) from Mount Buller (67 km southwest of the Mt. Loch study site)

147 over a 79 year overlapping period (1906 - 1985, r = 0.72), to corroborate our dating.

2.3 Chronology development

149 Measured tree-ring series were detrended to remove sample-level noise prior to chronology estimation. Removing age-related

150 trends within RW series often involves the fitting of a negative exponential function (Hughes, 2011). However, growth

151 eccentricities associated with the lobate nature of growth in *P. lawrencei* means that a more flexible data-adaptive approach is

152 required. Smoothing splines equal to 67% of each RW series' length with a 50% frequency cutoff were applied to each

153 individual chronology in dplR (Bunn, 2008, 2010). Ring-width indices were calculated as residuals from the fitted curves. Due

154 to trends specific to each individual BI series, detrending the age-related growth trends of ΔBI, EWBI and LWBI chronologies

155 was undertaken in the same data-adaptive manner as the RW series. The robust bi-weight mean of the detrended residual series

156 were then calculated to produce the standardised RW and BI chronologies (Cook et al., 1990). The robust bi-weight approach

157 produces a chronology that is relatively unaffected by outliers - an important consideration in the study of *P. lawrencei* given

158 the highly eccentric growth behaviour and strong likelihood of outliers otherwise impacting the common signal (McDougall

159 et al., 2012). We further removed autocorrelation from the tree-ring indices within dplR. The pre-whitened (RES) chronologies

160 did not differ significantly from the non-prewhitened chronologies, and we therefore used the RES chronologies to assess
161 climate signals in the chronologies.

162   The quality and reliability of the chronologies were assessed using the expressed population signal (EPS), against the
163 generally accepted threshold of > 0.85 (Wigley et al., 1984). Additionally, due to a prevailing increasing trend apparent in the
164 BI RES chronologies, we produced first-differenced BI and RW RES chronologies for use in subsequent analysis with climate
165 data.

166

167 **2.4 Climate analysis**

168 The final chronologies were evaluated against climate data spanning 70 years (1929 - 1998) due to constraints associated with
169 low sample resolution prior to the early 20th century. The relationship between the RW and BI chronologies and minimum and
170 maximum air temperature, precipitation, snow depth and streamflow data was then explored. Climate-correlation analysis was
171 conducted using observational data from the Bureau of Meteorology (BoM) station in Omeo, 41.8 km southeast of Mt Loch
172 (Fig. 3b). Continuous minimum and maximum monthly mean air temperature data from 1879 to 2009 are available at this site,
173 which correlates strongly with the substantially shorter dataset available in Hotham Heights (mean maximum monthly
174 temperature, r = 0.87; mean minimum monthly temperature, r = 0.71). It is important to note, however, the significant elevation
175 difference between our study location in Hotham Heights (~1800m) and the Omeo station (685m), and therefore the possible
176 variation in correlative strength of individual months. We further evaluated the sensitivity of our chronologies to mean monthly
177 precipitation data at Harrietville (Fig. 4) - the closest station with sufficiently long records (data available from 1884 - 2015).
178 We further examined the relationship between our *P. lawrencei* chronologies and mean monthly snow depth records from
179 1954 - 2001 at Spencers Creek in NSW (~125 km northeast of Mt. Loch). Correlations with total monthly streamflow from
180 BoM hydrologic reference stations at Mitta Mitta River at Hinnomunjie and Livingstone creek at Omeo were also assessed.
181 See Table 1. for metadata pertaining to BoM observation stations used in this study. In addition to individual station data, we
182 explored relationships with the Australian Gridded Climate Data (Evans et al., 2020), which is a recent revision of the
183 Australian Water Availability Project (AWAP) gridded dataset (Jones et al., 2009). We investigated the spatial extent of the
184 relationship between RW and BI chronologies and mean monthly minimum and maximum temperatures and precipitation
185 across the alpine regions of Victoria and southern New South Wales, and further afield across Victoria. To ensure consistency
186 with the detrending approach for the RW and BI chronologies, we explored the links between interannual differences in both,
187 by applying first differencing to the climate data prior to correlation analysis.

188   [Figure 4 here]
189   [Table 1 here]

3 Results and discussion

This study presents nine successfully crossdated *P. lawrencei* specimens (13 individual series). Given the relatively small sample size, a strong common signal (exceeding the 0.85 EPS threshold) throughout a portion of the resulting RW chronology (Fig. 5) is encouraging. The RW chronology reached a mean EPS of 0.86 for the period 1929 - 1998. However, with individual specimen ages ranging from 67 to 327 years, future work with larger sample sizes would allow for the opportunity to utilise this species for climate analysis across multi-centennial time scales. Previous works have developed 114 year (McDougall et al., 2012) and 82 year (Brookhouse and Graham, 2016) RW chronologies from 48 and 13 *P. lawrencei* specimens respectively. Additionally, the ability to crossdate our RW chronology with a remotely located Mt. Buller chronology (Fig. 6a) (Brookhouse and Graham, 2016) demonstrates the spatial coherence in the sensitivity of this species to climate variables throughout southeast Australia. Such findings highlight the possible utility of *P. lawrencei* in the development of a strong dendroclimatic network throughout the Australian Alps.

[Figure 5 here]

[Figure 6 here]

3.1 Temperature correlations

The RW chronology shows increased variability from the 1900's, with particularly narrow rings observed in the 1950's and 60's. With regard to observation station data, the RW chronology response to mean monthly maximum temperatures from Omeo reveals positive, statistically significant ($p < 0.05$) correlations with the current growth season winter (June, July and August) and October and November in particular, and a strong, negative response to June to November temperature maxima of the previous growth season (Fig. 7a). Additionally, sensitivity of RW to mean minimum monthly temperatures at Omeo is dominated by statistically significant, negative correlations with previous growth season March to May minimum temperatures (Fig. 7b). The ability of the *P. lawrencei* RW chronology developed in this study to capture select months of growing season temperatures is consistent with previous dendroclimatological analysis of this species demonstrating air temperature as a dominant limiting growth factor (McDougall et al., 2012; Brookhouse and Graham, 2016). The influence of temperature throughout the growing season has previously been extensively documented as a primary control on the growth of coniferous species in high altitude and high latitude environments (eg. D'Arrigo et al., 1992; Brookhouse and Bi, 2009; Nishimura and Lovoque, 2011; Rydval et al., 2018). Concerning the strong, inverse relationship of the RW chronology to temperature of the previous growth season, similar response patterns have been found in other species such as lower elevation *Lagarostrobos franklinii* (Buckley et al., 1997) and the widespread *Phyllocladus aspleniifolius* (Allen et al., 2001) in Tasmanian, and high elevation New Zealand *Libocedrus bidwillii* (Palmer and Xiong, 2004). This may be related to a depletion of carbohydrate and nutrients reserves following a favourably warm growing season and accelerated growth rates.

222

223   [Figure 7 here]

224

225   Following the strong, positive correlation between RW and local temperature maxima during winter months, we

226   investigated the spatial signature of this relationship. The RW response to the AGCD was also dominated by a statistically

227   significant, positive correlation with mean June to August maximum temperatures (r = 0.62, p < 0.001), encompassing a broad

228   extent of central Victoria (Fig. 8a). This response is consistent with previously documented alpine *P. lawrencei* chronologies

229   (McDougall et al., 2012; Brookhouse and Graham, 2016). McDougall et al., (2012) reported a strong positive relationship

230   between RW and winter maximum temperatures, and a negative response to mean and maximum monthly snow depth. Given

231   the inverse relationship between winter temperature and snowfall, winter temperatures are suggested to reflect the magnitude

232   of winter snow depth and persistence of spring snow cover, which imposes significant impacts on vegetation growth (Kudo,

233   1991; Halter, 1998; Brookhouse et al., 2008). Snow cover is postulated to be a major determinant of the length of the phenology

234   and growing season of alpine vegetation (Kudo, 1991). With regard to Australian alpine flora, this sensitivity is consistent with

235   documented responses of *E. pauciflora* to winter snow cover (Brookhouse et al., 2008). The timing of growth initiation in

236   boreal and temperate environments is largely defined by temperature (Creber and Chaloner, 1984), with many coniferous and

237   deciduous species experiencing cessation in root growth at soil temperatures below 2 - 4°C (Halter, 1998). Persistent spring

238   snow cover due to cooler winter conditions delays the initiation of cambial activity (essential for the formation of wood cells)

239   and sustains such low soil temperatures, resulting in a shorter growing season and therefore a narrower growth-ring (Vaganov

240   et al., 1999; Kirdyanov et al., 2003). Additionally, considering the acute prostrate growth of *P. lawrencei* communities and the

241   likelihood of stands being buried by snow throughout winter, extended spring snow cover also presents a direct impediment

242   to wood production by delaying the commencement of photosynthesis (McDougall et al., 2012). Conversely, warm winter

243   temperatures are expected to accelerate snowmelt in spring, resulting in an earlier onset of photosynthesis and cambial

244   activation for *P. lawrencei*.

245   The ΔBI chronology developed in this study is most notably negatively correlated (with statistical significance) with

246   mean maximum temperatures in October, November and December of the current growth season (Fig. 7c). Taking the averaged

247   temperature maxima of these months produced a significantly strengthened correlation with the ΔBI chronology (Fig. 6b: r =

248   -0.43, p < 0.001). This response is comparable to the only previously constructed BI chronology for *P. lawrencei* by

249   Brookhouse and Graham (2016), whereby averaged August to April temperature maxima revealed the strongest BI-

250   temperature relationship. Moreover, ΔBI displayed a substantially stronger response to mean monthly minimum temperatures

251   throughout the same period (Fig. 6c: r = -0.51, p < 0.001).

252

253   [Figure 8 here]

254

8

255   The response of the ΔBI chronology to maximum and minimum temperatures throughout October to December is
256   consistent with many previous studies demonstrating that temperature of the growing period is the dominant climate parameter
257   influencing latewood density (eg. D'Arrigo et al., 2000; Davi et al., 2003; Kaczka et al., 2017; Blake et al., 2020). The
258   anatomical basis for wood density lies in the average amount and size of cell wall material within the tracheids (Vaganov et
259   al., 2006). During the growth season, tracheid size reduces, and density thereby increases, between earlywood and latewood
260   formation (Rathgeber et al., 2006; Cuny et al., 2014). An investigation into the interannual variability of wood density and
261   specific contributions of anatomical attributes in NH conifers by Björklund et al., (2017) found earlywood and latewood
262   density to be primarily influenced by tracheid size and cell wall dimensions respectively. Given that BI is an established proxy
263   measure of density, and assuming that it is recording similar variations in these structural anatomical properties (and that such
264   responses are consistent between hemispheres), the BI data in *P. lawrencei* may likewise reflect changes in tracheid size and
265   wall dimensions. Future studies of BI in *P. lawrencei* incorporating the exploration of interannual variations of these
266   anatomical properties could confirm this. Such work could further our understanding of the physiological controls on the BI-
267   density relationship, particularly as it relates to some SH species in which density variations have been noted to behave
268   differently to what is typically observed in NH conifers (Blake et al., 2020).

269

3.2 Precipitation, snow depth and streamflow correlations

271   Correlation analysis with precipitation data revealed a strong negative relationship between RW and June to November and
272   May precipitation of the current growth season, as well as a particularly strong positive response to precipitation in November
273   of the previous season (Fig. 9a). Additional correlations with AGCD most notably exhibited a significant negative relationship
274   between RW and mean June to August precipitation across southern Victoria and high altitude regions (Fig. 10a). Significant
275   negative correlations between the RW chronology and mean snow depth at Spencers Creek are also evident from June to
276   October (Fig. 11). This response is consistent with that observed in *P. lawrencei* RW from Mt. Blue Cow and Schlinks Pass
277   in NSW (McDougall et al., 2012), and reflects the spatial coherence of snow depth throughout the Australian alpine region.
278   Such results further demonstrate the previously discussed impact of temperature maxima on the persistence of spring snow
279   cover, and the consequent limitation on *P. lawrencei* radial growth. Additionally, given the significant contribution of snow
280   melt during winter and spring to the soil moisture balance in the Australian Alps (Costin et al., 1961), we postulate that the
281   positive response of RW to monthly snow depth of the previous growth season (Fig. 9) is related to excess moisture availability
282   providing optimum growth conditions the following growth year.

283   Relationships between BI and snow depth were non-significant (data not shown). However, the ΔBI chronology
284   exhibited particularly strong positive correlations with July mean monthly precipitation (Fig. 9b; Fig. 10c). Assessments of
285   the dendroclimatic potential of ΔBI for hydroclimatic reconstruction have thus far been limited. Notably, however, Seftigen et
286   al., (2020) recently reported an increase in the explained variance of a warm season, ΔBI-based precipitation reconstruction of
287   nearly 20 percentage points (to 55%), relative to the predictive skill of the RW-based reconstruction. The strong response of

288 RW and ΔBI in *P. lawrencei* to precipitation, as demonstrated in this study, hence emphasises the potential to improve the

289 coverage of high resolution, moisture sensitive proxy records in the Australian continent. This would present an opportunity

290 to produce new robust multi-century precipitation reconstructions for southeast Australia.

291 Tree-ring based reconstructions of additional hydrological parameters such as streamflow can provide valuable

292 insights to water resource managers and planners, particularly considering the confined range of observational records. In this

293 study, we therefore also conducted a preliminary evaluation of a potential *P. lawrencei* tree ring-streamflow relationship. The

294 lack of streamflow gauge datasets of comparable length to the *P. lawrencei* chronologies limited overlapping records to 43

295 years (1955 - 1998) for Mitta Mitta River, and just 26 years (1968 - 1994) for Livingstone Creek. Nonetheless, ΔBI exhibited

296 a particularly strong positive response to the current growth season June to March streamflow at Livingstone Creek and with

297 current season July streamflow at Mitta Mitta River (Fig. A1). Correlations between the RW chronology and streamflow data

298 at Livingstone Creek were non-significant. However, significant negative (positive) responses of RW to current (previous)

299 growth season streamflow in June and November at Mitta Mitta River are apparent (Fig. A1). Whilst some strong correlations

300 are present, the inconsistency of results across sites requires further explanation.

301

302 [Figure 9 here]

303 [Figure 10 here]

304 [Figure 11 here]

305

3.3 Limitations and future prospects

307 It is important to first note the necessity of full stem cross-sections for accurate dating of *P. lawrencei* due to highly eccentric

308 growth behaviour and frequent ring-wedging. Whilst the destructive sampling method required to obtain such cross-sections

309 may not always be justified or permissible (February and Stock, 1998; McDougall et al., 2012), ample opportunity exists for

310 further collection of fire-killed *P. lawrencei* stands throughout the Australian Alps, given the frequency of large-scale fire

311 activity in recent decades.

312 Both RW and BI chronologies in this study were inherently challenged by a limited sample size of just nine stem

313 cross-sections. Whilst the ΔBI data produced in this study presented a relatively strong common climate signal, multiple BI

314 chronologies reported in previous works have highlighted the requirement of a greater sample size to achieve comparable

315 interseries correlations to MXD (eg. Wilson et al., 2014; Blake et al., 2020). It is therefore likely that the common signal

316 strength of the *P. lawrencei* BI chronologies would increase substantially with the incorporation of additional series,

317 particularly on longer time scales.

318 Tree-ring parameters are known to comprise a considerable degree of non-climatic variance at lower frequencies

319 (Cook, 1985; Esper et al., 2005; Fonti et al., 2009; Björklund et al., 2020). Blue intensity chronologies in particular have

320 displayed stronger responses to temperature at high frequencies, yet generally poorer portrayals of low-frequency trends when

321   compared to RW (eg. Rydval et al., 2014; Wilson et al. 2021). Samples in this study consist of a vast range of ages. Whilst the

322   smoothing spline method of detrending aims to preserve the majority of the resolvable low frequency variance (Cook et al.,

323   1995), the extent to which this approach impacts the expression of low frequency variance requires further exploration with

324   longer *P. lawrencei* chronologies.

325   Whilst correlation analysis between RW and BI chronologies and climate variables in this study has empirically

326   highlighted the strength of the *P. lawrencei* growth response to climate, a more detailed understanding of physiological

327   mechanisms is required to further establish the causality of these relationships. Given the limited study of the

328   dendroclimatological properties of *P. lawrencei* thus far, and our relatively rudimentary understanding of the BI-density link,

329   further sampling and physiological investigation is warranted. This would allow for better interpretation of RW and BI data,

330   and improve upon an already encouraging expression of the climate signal.

331   Despite earlier quite pessimistic assessments of the Podocarpus genus for dendroclimatological purposes (Dunwiddie,

332   1979; February and Stock, 1998), due in part to limited sample availability (in the absence of fire-killed specimens) the strength

333   of the observed correlations presented in this study of just nine samples are promising with regard to the future analysis of this

334   species. The BI method appears to offer a promising additional proxy to RW for *P. lawrencei*, as in other SH species in which

335   the climate signal of BI parameters has been explored (Blake et al., 2020; Wilson et al., 2021). The ongoing development and

336   application of the BI method in *P. lawrencei*, particularly for longer, multi-centennial scale chronologies may help significantly

337   improve our understanding of past climatic changes in the SH, given the valuable position annually resolved, tree ring-based

338   proxies hold in palaeoclimatology.

4 Conclusion

340   Despite inherent challenges due to growth abnormalities, this study has presented crossdated *P. lawrencei* RW and BI

341   chronologies on the order of 70 years for climate analysis (with individual (non-crossdated) series dating back to 1676), based

342   on nine fire-killed specimens from Mt. Loch in the Victorian Alps. Ring-width measurements displayed the strongest responses

343   to mean winter temperature maxima and snow depth, analogous to that demonstrated by high altitude *E. pauciflora*

344   communities. The ΔBI parameter exhibited a greater sensitivity to climate than earlywood or latewood BI, presenting a

345   particularly strong relationship with temperature and precipitation in the current growing season. This study offers encouraging

346   results, particularly those pertaining to RW, for the increased utilisation of *P. lawrencei* in Australian dendroclimatology. With

347   ongoing efforts to further reduce the limitations of the BI parameter and develop the most appropriate detrending methods, as

348   well as the incorporation of anatomical analysis, the BI method also offers an important opportunity in Australian

349   dendroclimatology. Given the known longevity of individual *P. lawrencei* specimens, the temporal extension and increased

350   utilisation of *P. lawrencei* chronologies from the Australian Alps may help to provide an important perspective on climate

351   change in the region. A detailed dendroclimatological network of this species could contribute meaningfully towards

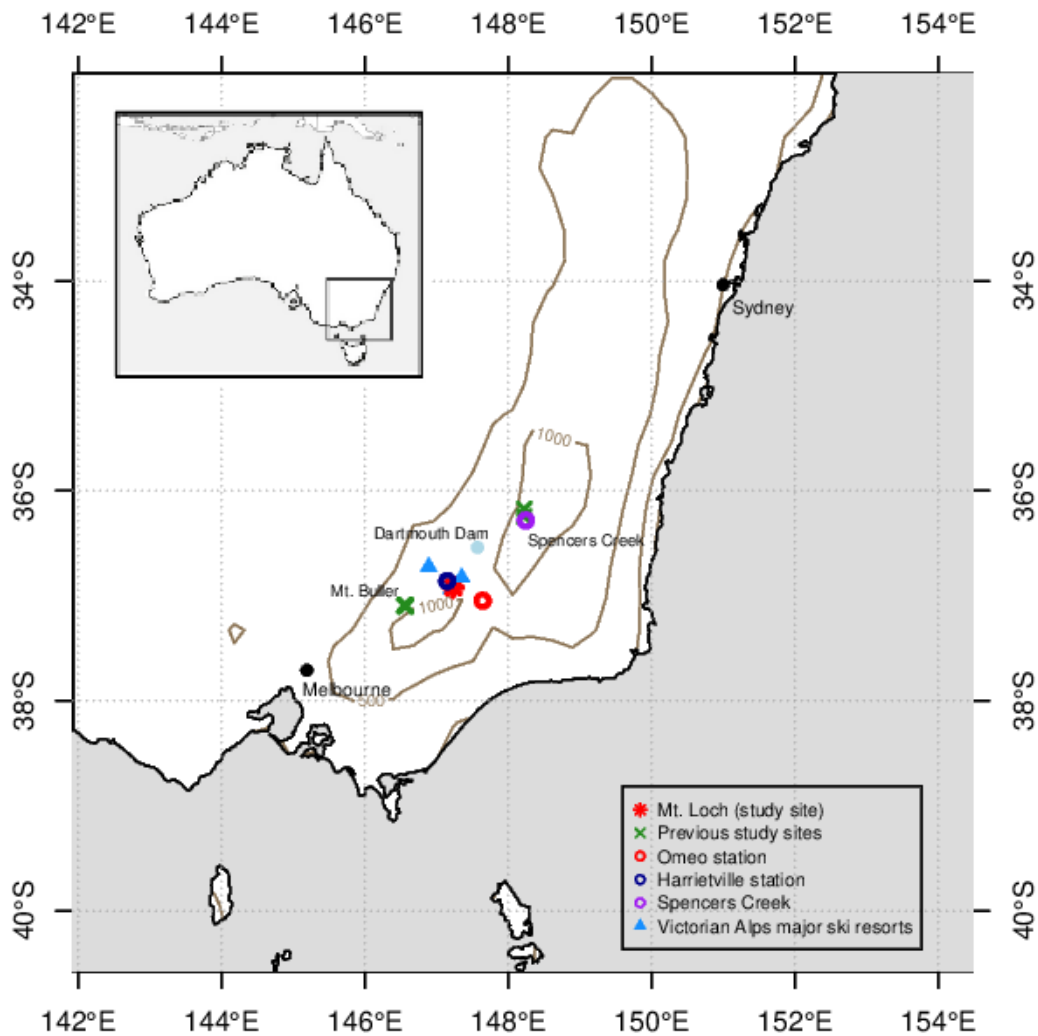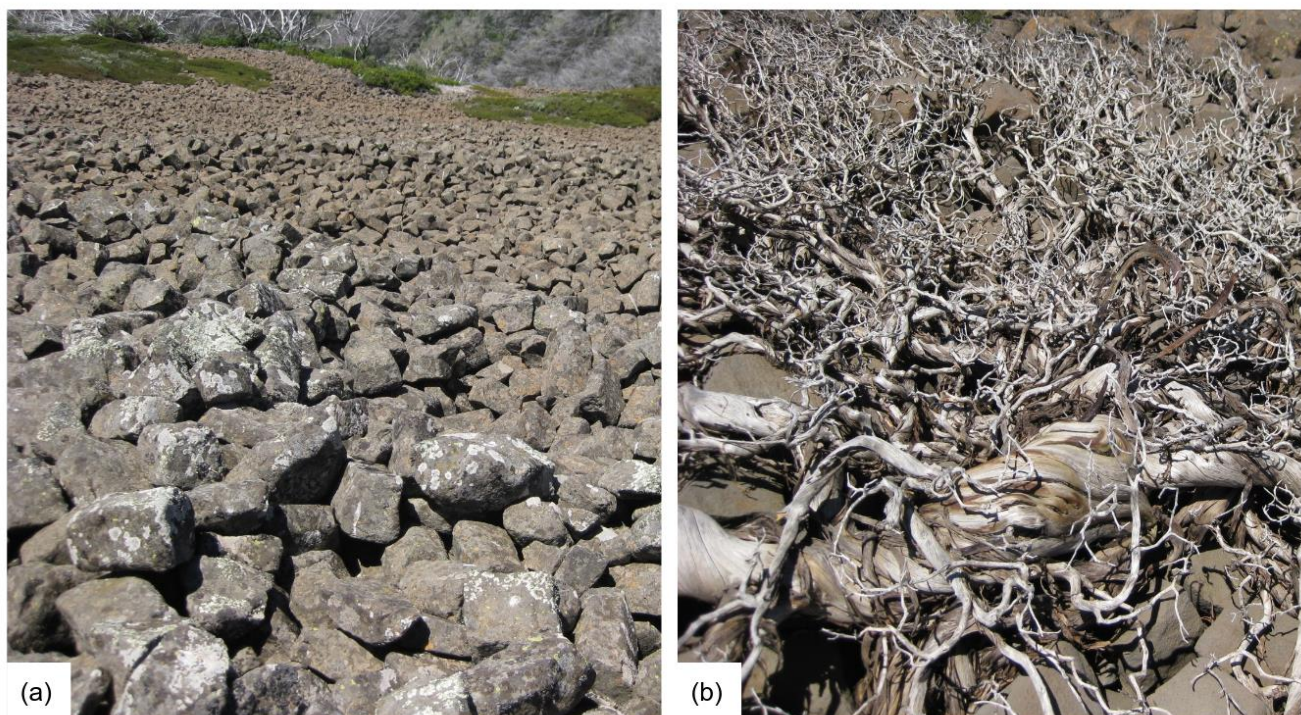352   improving palaeoclimate data coverage in the Southern Hemisphere.

Figure 1: Location of Mt. Loch sample site and main meteorological stations, and *P. lawrencei* study sites from previous works (Mt. Blue Cow and Schlinks Pass: McDougall et al., 2012, Mt. Buller: Brookhouse and Graham, 2016).
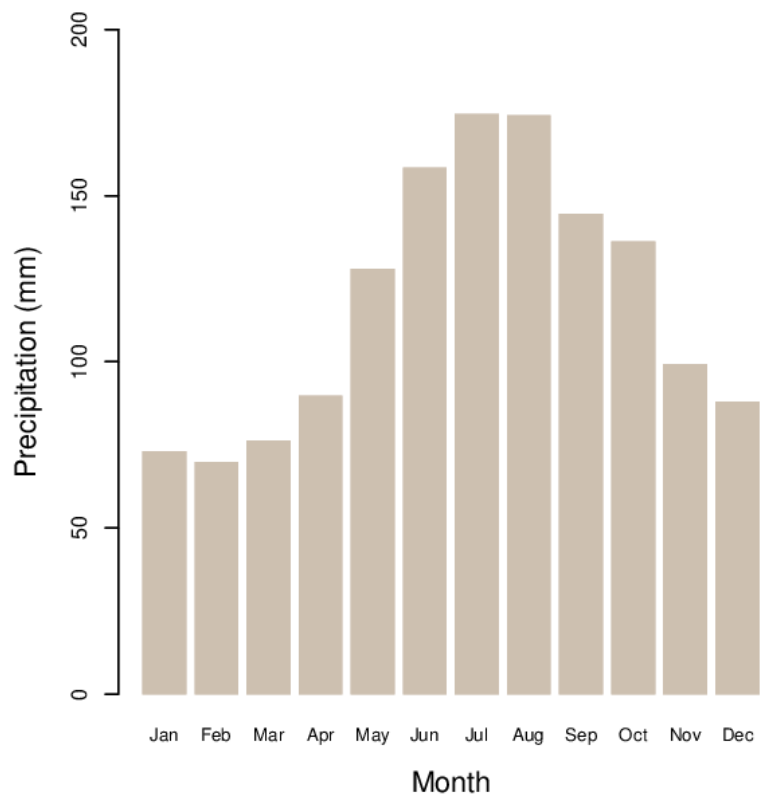
Figure 2: (a) Mt. Loch boulder field on rock scree slope, from which samples for this study were collected. (b) Highly prostrate growth of fire-killed *P. lawrencei* stands from the same locality. Images taken by Matthew Brookhouse (ANU).
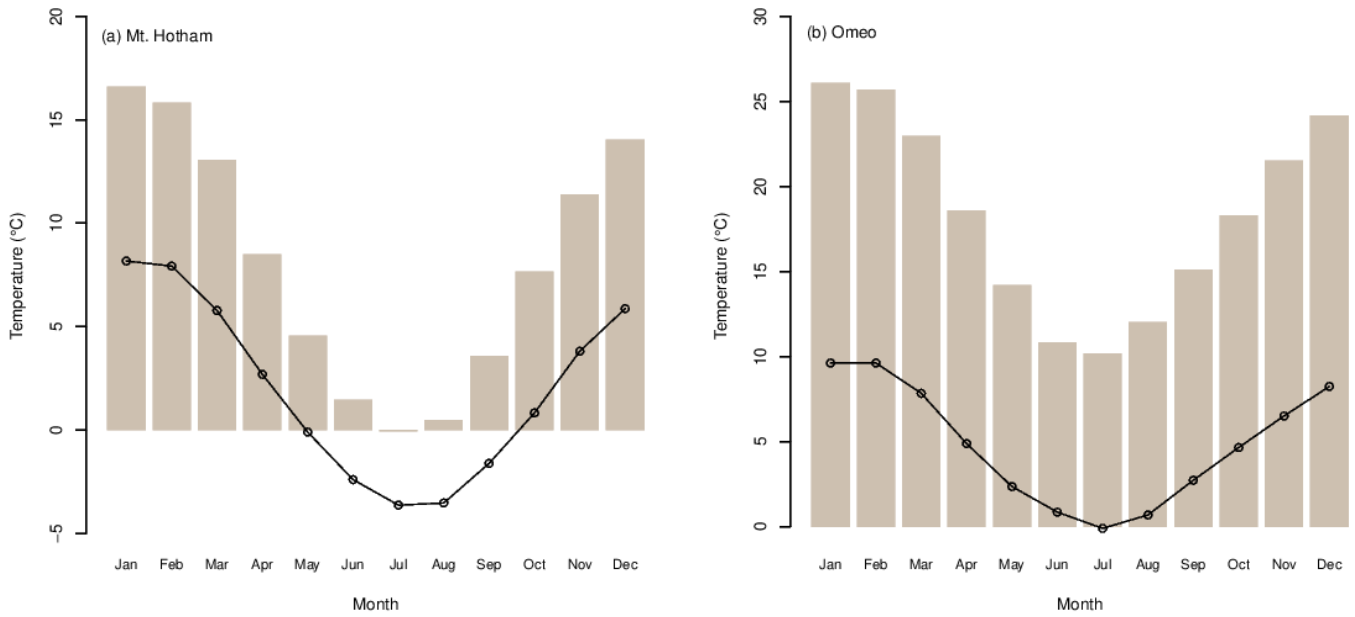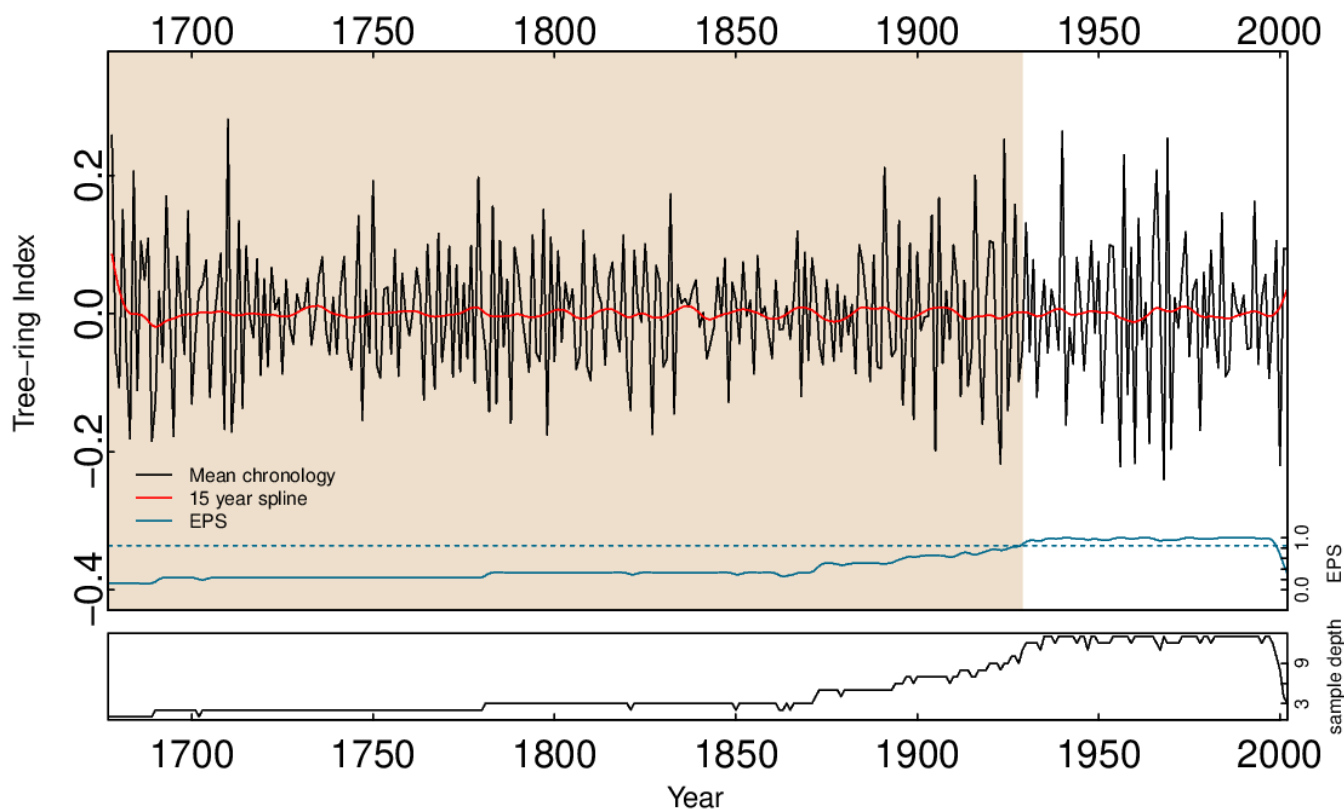
Figure 3: Mean monthly maximum (shaded bars) and minimum (open circles) air temperature at (a) Mt. Hotham and (b) Omeo meteorological stations.

Figure 4: Mean monthly precipitation at Harrietville meteorological station.

Figure 5. Full mean ring width chronology (1676 - 2002) based on 13 Mt. Loch *P. lawrencei* series from 9 samples (13 individual series), with 30 year spline and two standard errors (top panel), and concurrent sample resolution (bottom panel). Expressed Population Signal (EPS) denoted by green line, with 0.85 threshold (dashed green horizontal line).
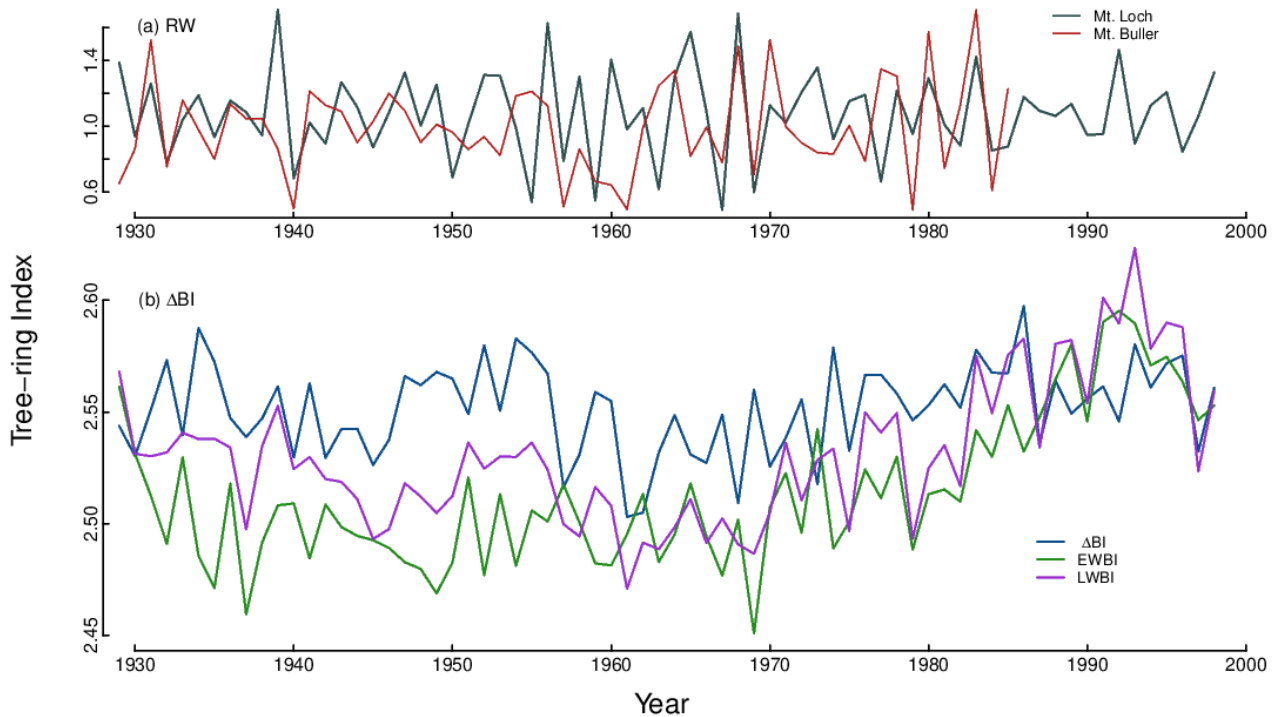
Figure 6. (a) Detrended *P. lawrencei* ring width (RES) chronologies for Mt. Loch (this study) and Mt. Buller (Brookhouse and Graham 2016) and (b) earlywood and latewood BI chronologies, with the derived ΔBI parameter, for the 1929 - 1998 period.
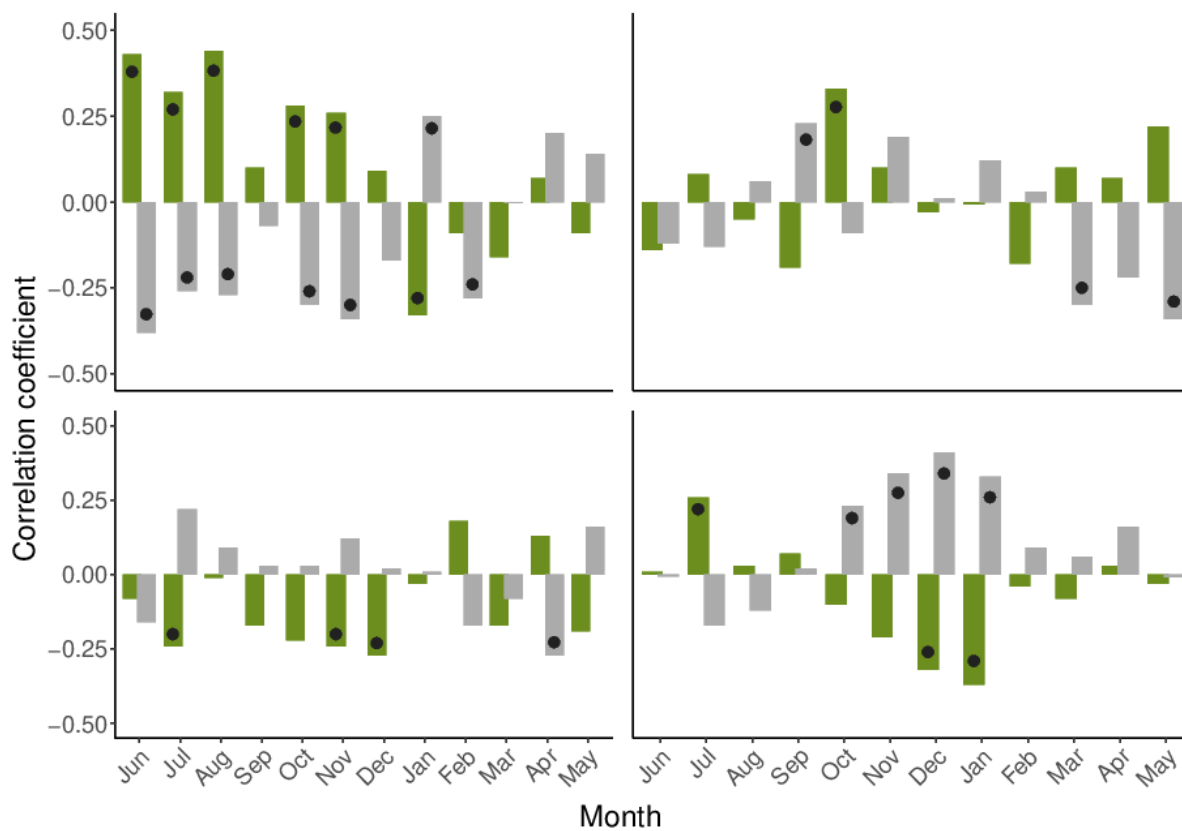
Figure 7. Correlations between RW and ΔBI chronologies and mean minimum and maximum monthly temperature data from Omeo observation station across the period 1929-1998, for both the current and previous growth season. Black dots indicate statistical significance (p < 0.05).
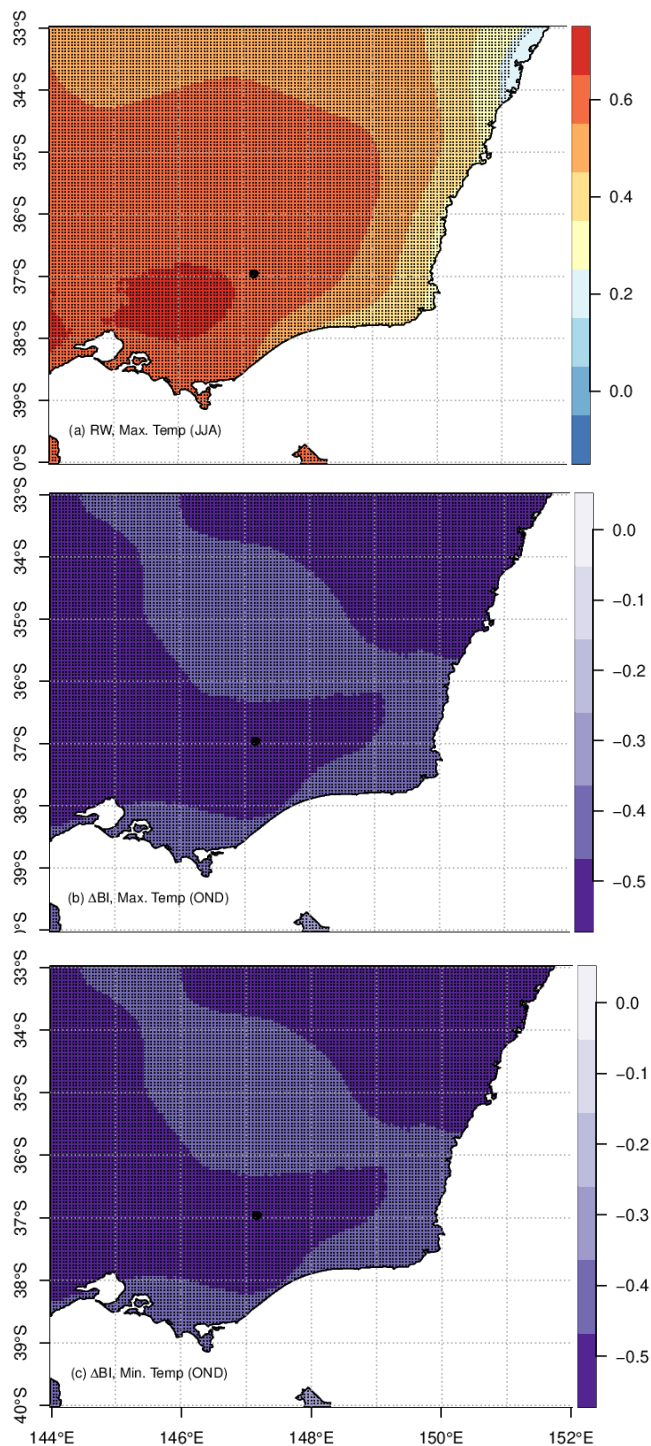
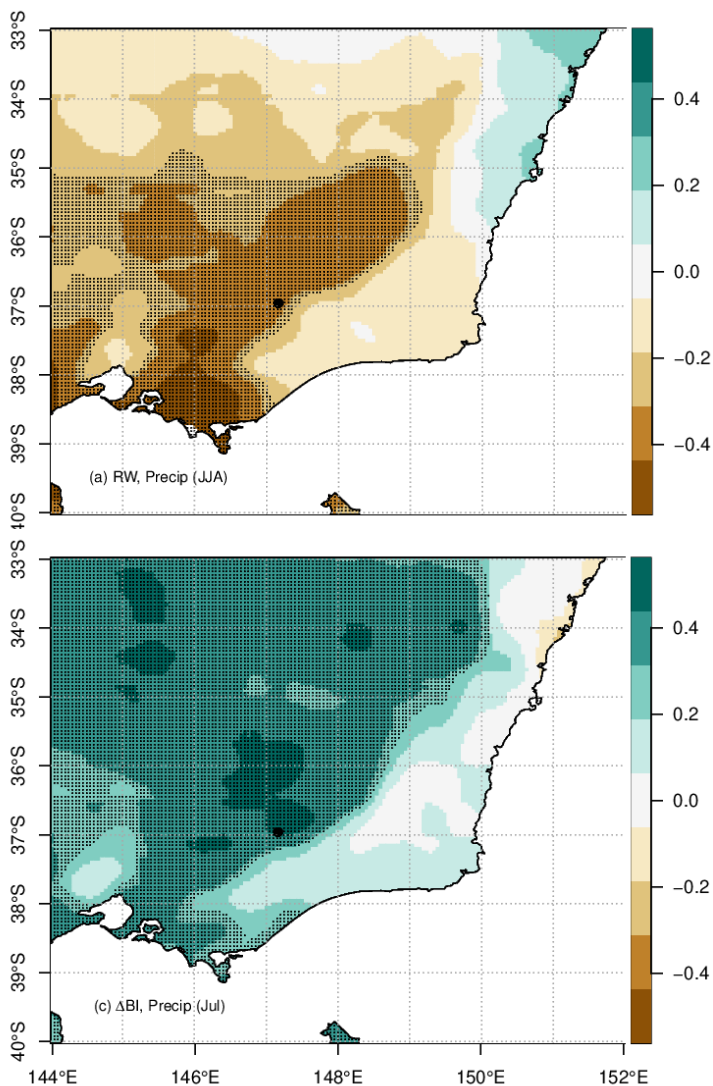**Figure 8: RW and ΔBI chronology correlations with AGCD mean monthly temperatures data for 1929 - 1998 period. (a) RW correlation with mean June, July and August (winter) maximum temperatures, (b) ΔBI correlation with mean October, November and December maximum temperatures and (c) ΔBI correlation with mean December minimum temperature. Shaded areas represent statistically significant correlations (p < 0.05) and study site location is marked by black dot.**
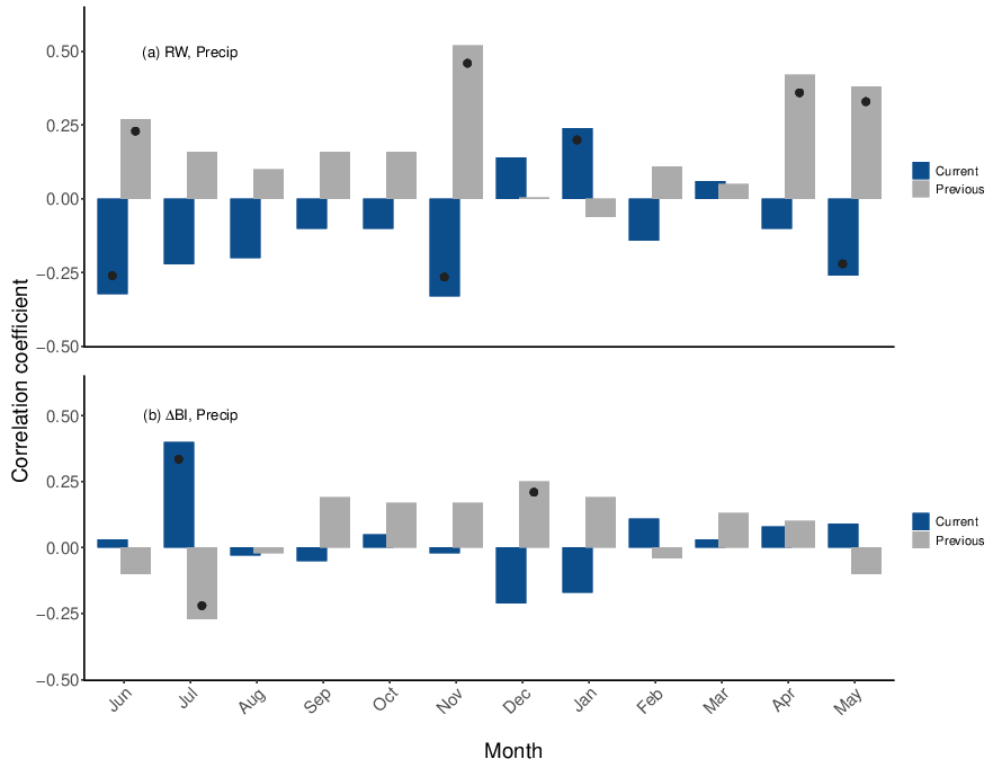
Figure 9: Correlations between RW and ΔBI chronologies and mean monthly precipitation data from Harrietville observation station across the period 1929-1998, for both the current and previous growth season. Black dots indicate statistical significance (p < 0.05).

Figure 10: RW and ΔBI chronology correlations with AGCD mean monthly precipitation data for 1929 - 1998 period. (a) RW correlation with mean June, July and August (winter) precipitation, (b) ΔBI correlation with mean July precipitation. Shaded areas represent statistically significant correlations (p < 0.05) and study site location is marked by black dot.
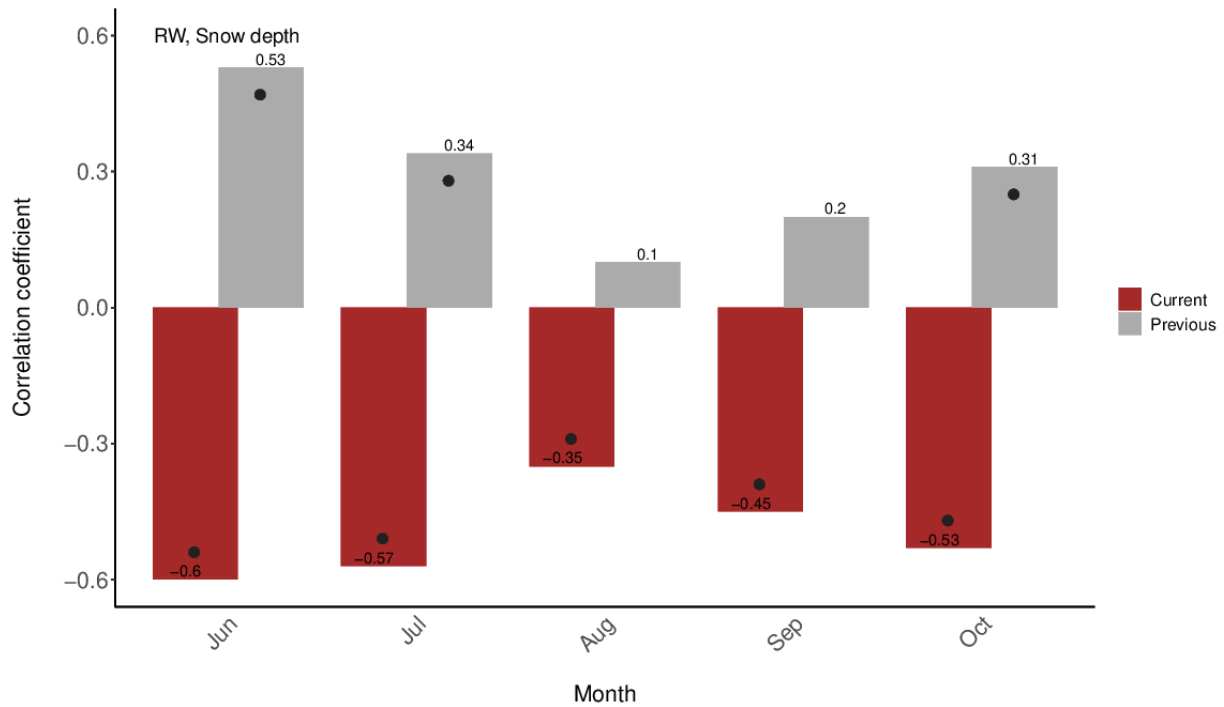
Figure 11: Correlations between the Mt. Loch RW chronology and mean monthly snow depth at Spencers Creek, for the period 1954 - 1998. Black dots indicate statistical significance.

Station name	Station number	Latitude	Longitude	Elevation	Period of record	Variable(s)
Omeo Comparison VIC	083025	37.10ºS	147.60ºE	685 m	1879 - 2009 (130 years)	Mean monthly maximum and minimum temperature (ºC)
Mount Hotham VIC	083085	36.98ºS	147.13ºE	1849m	1990 - 2021 (31 years)	Mean monthly maximum and minimum temperature (ºC)
Harrietville VIC	083012	36.89ºS	147.06ºE	396m	1884 - 2015 (131 years)	Total monthly precipitation (mm)
Livingstone Creek at Omeo	401209	37.11ºS	147.57ºE	691 m	1968 - 1994 (26 years)	Total monthly streamflow (m^3/s)
Mitta Mitta River at Hinnomunjie	401203	36.95ºS	147.61ºE	544 m	1931 - 2021 (90 years)	Total monthly streamflow (ML)

Table 1. Bureau of Meteorology instrumental station metadata.

Appendix
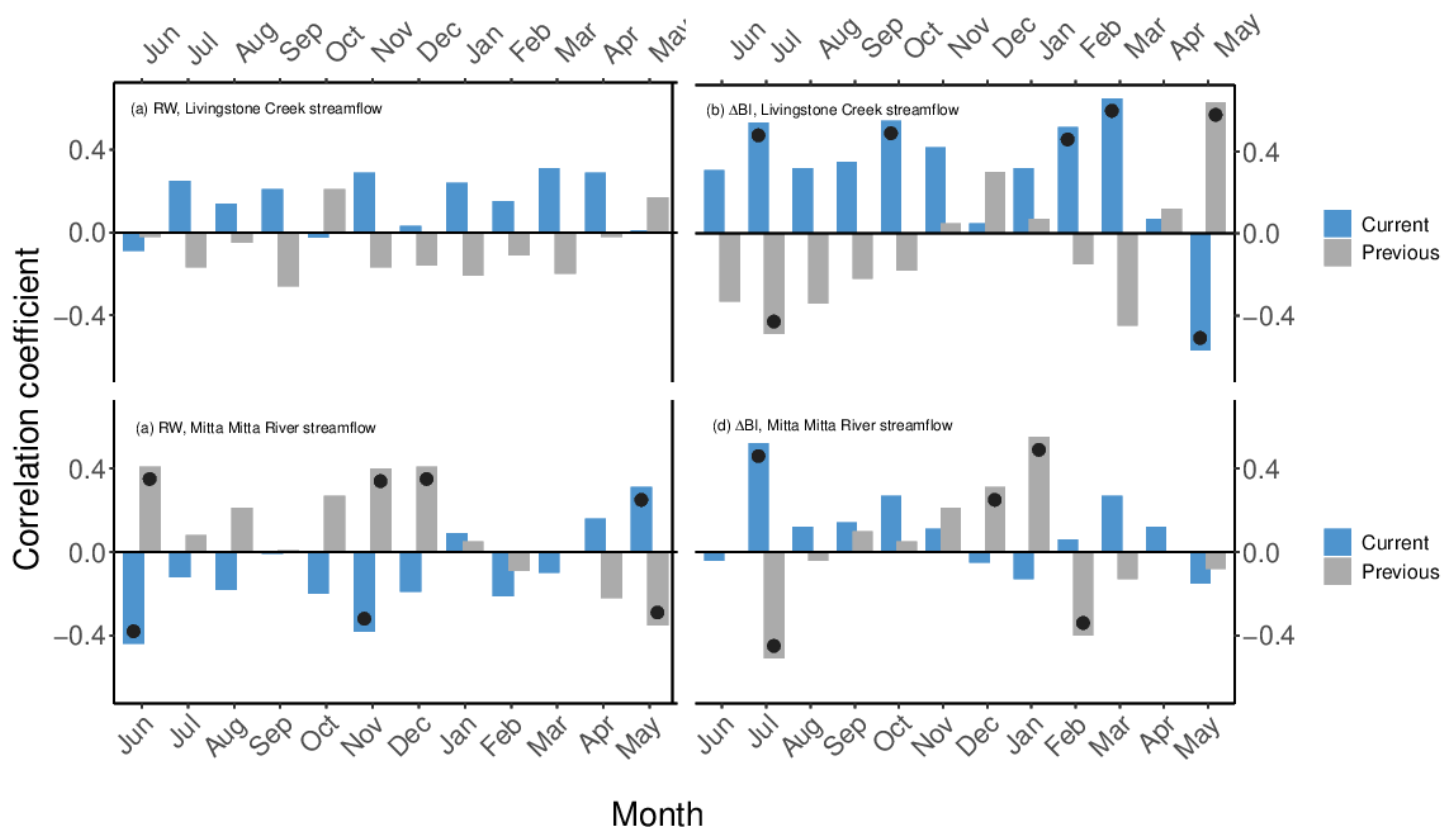
Figure A1: Correlations between RW and ΔBI chronologies and total monthly streamflow (m³/s) at Livingstone Creek at Omeo for 1968 - 1994 period, and total monthly streamflow (ML) at Mitta Mitta River at Hinnomunjie across 1955 - 1998 period. Black dots indicate statistical significance ($p < 0.05$).

Competing interests

The authors declare that they have no conflict of interest.

Author contribution

J.O undertook all of the cross dating, measurements, and climate analysis, and took the lead role in writing the manuscript. B.H. conceived and developed the project, provided supervision, mentoring and equipment, and guided the climate analysis. M.B. provided the samples, conceived the study of the location and species and advised on the interpretation of the analysis. K.A. guided the dendrochronological analysis and interpretation. All authors contributed significantly to the manuscript.

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