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Rainforest response to glacial terminations before and after human arrival in Lutruwita (Tasmania)

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ABSTRACT

Limited understanding of how Indigenous people have created and managed the Australian landscape continues to have repercussions on how landscapes are culturally interpreted and managed today. Addressing this is critically important as climate change is increasing the frequency and intensity of wildfires, whilst challenging the objectives, methods and efficacy of contemporary landscape management practices. Here we compare the palaeoecology of vegetation changes across glacial to interglacial states before (Termination II) and after (Termination I) human occupation of the cool temperate rainforests of western Lutruwita (Tasmania). Sediment from Darwin Crater (Termination II) and Lake Selina (Termination I) were analysed using radiometric dating, fossil pollen, charcoal, geochemical, environmental magnetic and sedimentary methods to produce a comprehensive reconstruction of vegetation and landscape dynamics. Results show marked differences in the rainforest response to the transition from glacial to interglacial climates before and after human arrival at c. 43,000 years ago (ka). In the absence of human disturbance, *Phyllocladus aspleniifolius-Nothofagus cunninghamii* lowland rainforest taxa dominated the last interglacial period (~77% of the pollen sum) but was reduced in the current interglacial (~41%) and largely replaced by *Gymnoschoenus sphaerocephalus* buttongrass moorland (10–23%). This demonstrates the legacy of Indigenous Palawa managed landscapes, primarily using fire to promote landscape openness and prevent the dominance of an ecologically climax rainforest community, until their forced removal via invasion and colonisation ca. 1806.

1. Introduction

Recent human-induced climate change, including more frequent and severe extreme events, has caused extensive adverse impacts and subsequent damages to nature and people, exceeding natural climate variability (IPCC et al., 2022). Rapidly increasing temperature and aridity are shifting baseline conditions, resulting in extreme climatic perturbations (Harris et al., 2018). Terrestrial and oceanic extremes, heavy precipitation events, drought and fire-promoting weather are resulting in pervasive impacts to ecosystems including, but not limited to, deterioration of ecosystem structure and function, resilience and natural adaptive capacity, and increased drought- and fire-related tree mortality (IPCC et al., 2022; Harris et al., 2018).

The timing of the current geological age, controversially coined the 'Anthropocene' epoch (as defined by the *Anthropocene Working Group*; Davis and Todd, 2017), fails to recognise how Indigenous peoples have influenced their environments globally across millennia (Fletcher et al., 2021a, 2021b; Watson et al., 2018; Crabtree et al., 2019; Clement, 2019). Environmental degradation, resulting from the import of European land management (read: exploitation) to Indigenous created and cared for landscapes, can be seen in many colonised regions (Fletcher et al., 2021a; Maezumi et al., 2018). Examples include Indonesia (Henley, 2011) and upland Southeast Asia (Dressler et al., 2017), where sustainable long-fallow swidden systems were replaced by intensive and

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unsustainable farming practices, and in the Amazon basin where the expansion of deforestation and agricultural plantations continue to replace sustainable polyculture agroforestry (Maezumi et al., 2018). Centuries of suppression and removal of Indigenous peoples and their land management practices by European colonisations has had severe social and environmental consequences (Domínguez and Luoma, 2020; Nobre et al., 2016; Maezumi et al., 2018), with pre-colonial narratives and post-colonial practises often stripping Indigenous people's agency from the landscape.

To care for and manage threatened Australian ecosystems effectively in a rapidly warming climate, it is crucial to comprehend the evolution of these landscapes through periods of rapid warming (i.e., Termination events) and the long-term factors that influence and sustain them (Fletcher et al., 2018; Willis and Birks, 2006; Froyd and Willis, 2008). In western Lutruwita (the island of Tasmania, Australia) much of the cool temperate rainforest is part of The Tasmanian Wilderness World Heritage Area (TWWHA), a region both lauded for its wilderness values (Hawes et al., 2015; Sharples, 2003), whilst also being a renowned cultural landscape (Thomas, 1993; Fletcher and Thomas, 2010; Mariani et al., 2017). This paradox is partly the result of a lack of research on the cultural practices of Palawa people and also the adoption of a paradigm which classifies the area as 'wilderness' (Watson et al., 2018; Allan et al., 2017). The latter was invoked to protect it following the Franklin Dam controversy (Lester, 2005; Kellow, 1989; Sewell et al., 1989) and led to the area being placed on the World Heritage List in 1982, under joint arrangements between the federal government of Australia and the Tasmanian government, to 'protect, conserve, present and pass on to future generations one of the world's outstanding wilderness areas' (DPIPWE, 2016). This attribution of 'wilderness' to southwest Lutruwita severely underplays the significance of Palawa people in creating, caring for and shaping the landscapes we experience today and how they should be managed in the future.

Initial human arrival into Australia from southeast Asia occurred >65,000 years ago (ka) (Clarkson et al., 2017). Much of mainland Australia was occupied by ca. 50 ka, with the Palawa arriving in Lutruwita ca. 43 ka (Cosgrove, 1999), when it was connected to mainland Australia via a land-bridge during a period of low glacial eustatic sea level (Allen, 1996; Cosgrove et al., 1990; Cosgrove, 1999). Aboriginal occupation of Lutruwita thus spans the major climatic and environmental changes of the late glacial, last glacial transition (Termination I), and Holocene; a period measured by more than 2000 generations of human occupation and management. The antiquity of Aboriginal occupation of Australia makes understanding the initial impact and ongoing legacy of Aboriginal management on the Australian landscape difficult to ascertain. This difficulty stems from a range of factors, including: (1) uncertainty and large dating uncertainty around the timing of initial arrival of humans (which is beyond radiocarbon dating limits in Lutruwita); (2) the difficulty in ascertaining pre-human environmental baselines under climate regimes that differ markedly from recent times; and (3) the scarcity of natural archives that span the period before, after and the duration of human arrival, particularly in those parts of Australia that are dry and inhospitable to organic preservation. These uncertainties, and deeply embedded colonial myths and narratives of Australia being a '*Terra Nullius*' (i.e., unoccupied land) at the time of European 'discovery' and invasion, fails to recognise that most, if not all, Australian landscapes were the product of careful and intelligent landscape management practices and cultural connection with the land over millennia (Roberts et al., 2021; Clarkson et al., 2017; Cosgrove, 1999; Allen, 1996).

Insight of the legacy of Aboriginal occupation of Lutruwita comes from a range of archaeological deposits (Garvey, 2006; Allen, 1996; Cosgrove, 1999; Cosgrove and Allen, 2001). These include pollen data from Lutruwitan lake sediments (Colhoun et al., 1986; Kirkpatrick, 1986) and age estimates from archaeological cave (Warreen; 39,906 ± 879 cal yr BP) and rock-shelter (Parmerpar Meethaner; 39,310 ± 1151 cal yr BP) sites in southwest and northern Lutruwita, respectively (Allen, 1996; Cosgrove, 1995). These show that the Palawa arrived in Lutruwita when montane landscapes were predominantly treeless during the late Glacial period (~43ka). As the climate warmed throughout Termination I and into the Holocene interglacial, palaeoecological data show that the landscape was dominated by non-arboreal (i.e., treeless) vegetation and abundant fire activity. This was in marked contrast to interglacial periods prior to human occupation, which were dominated by rainforest taxa, with very little evidence of fire (Jackson, 1999; Colhoun et al., 1999; Macphail et al., 1993; Colhoun and Van de Geer, 1988; Van de Geer et al., 1994).

Here we test the hypothesis that this environment is a cultural landscape, rather than a 'wilderness', by comparing the palaeoecology of vegetation changes across glacial to interglacial states before (Termination II) and after (Termination I) human occupation. To date there is no continuous record of changes in vegetation across Terminations I and II from a single site in Lutruwita. Therefore, we compared two separate records from lake sediments in the same climate and vegetation zones (<50 km from each other; Fig. 1a,b): (1) the Darwin Crater Palaeolake archive (this study), which records landscape change during the Termination II, prior to the arrival of humans (MIS6-5e) and; (2) the Lake Selina archive, which records landscape change during Termination I when the Palawa were living in, caring for and curating the landscape of Lutruwita (Fig. 1; Fletcher et al., - in review). This comparison allows us to determine: 1) how the vegetation response to glacial termination events differs when people are present, and managing the landscape, and when they are not present and 2) to critically evaluate the cultural landscape and wilderness paradox.

1.1. *Western Lutruwita (Western Tasmania)*

Western Lutruwita is a cool temperate rainforest region located in the mid-to high latitudes of the Southern Hemisphere (c. 41–43°S' Fig. 1). Mean temperatures range from ~6 to 16 °C and mean annual rainfall is ~2400 mm (Queenstown; 20 km proximity; http://www.bom.gov.au/) and correlated to the intensity of the Southern Hemisphere Westerly Winds (Fig. 1a). Mid-to late-Pleistocene records of vegetation change indicate that, prior to the present Holocene interglacial, the region's vegetation switches between dominance of arboreal rainforest taxa (with little evidence of fire) during interglacial periods to treeless non-arboreal grass, shrub and herb species during glacial periods (with evidence for some fire) (Van de Geer et al., 1994, 1989; Macphail et al., 1993; Colhoun and Van de Geer, 1988). This switching between arboreal and non-arboreal dominance has been interpreted as consistent with the effects of temperature and CO_2 changes during Glacial-Interglacial cycles and is a common feature of these latitudes in the Southern Hemisphere (Vandergoes and Fitzsimons, 2003; Heusser and Van de Geer, 1994; Moreno and León, 2003; De Deckker et al., 2019).

Lowland western Lutruwita (below ~700 m a.s.l.) receives >1000 mm of precipitation annually, sufficient to promote ecologically climax rainforest of *Nothofagus cunninghamii, Phyllocladus aspleniifolius* and *Lagarostrobos franklinii* (Jackson, 1968; Bowman and Jackson, 1981). However, only 23% of lowland western Lutruwita is currently captured by this climax rainforest (Colhoun and Van de Geer, 1988). Instead, 41% of the region is now dominated by treeless and highly flammable buttongrass (*Gymnoschoenus sphaerocephalus*) moorland communities (Fig. 1) (Kitchener and Harris, 2013; Fletcher and Thomas, 2010). Here, fire is the key determinant of vegetation in this region, with long Fire Return Intervals (FRI; 150–350 years) allowing rainforest to establish, and short FRI (12–25 years) required to maintain open moorland vegetation (Jackson, 1968; Colhoun and Van de Geer, 1988). This dominance by a fire-promoted vegetation type in a high-rainfall cool climate zone, coupled with the failure of rainforest to occupy its potential climatic niche, is considered to be a direct result of burning by Palawa (Jackson, 1968; Hill and Read, 1984; Marsden-Smedley and Kirkpatrick, 2000; Fletcher and Thomas, 2010; di Folco and Kirkpatrick, 2013). This suppression of rainforest by fire has been tracked in the lake

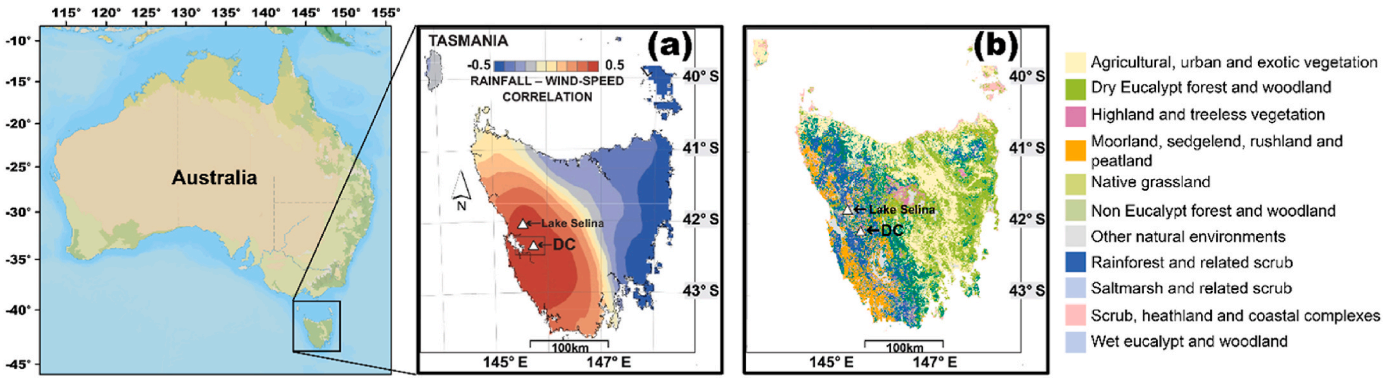

Fig. 1. (a) Map showing the location of Darwin Crater and Lake Selina in western Lutruwita and the correlation between the Southern Westerly Winds and rainfall (modified from Mariani and Fletcher, 2016); (b) Map of Lutruwitan vegetation zones (TasVeg 4.0) showing that Darwin Crater and Lake Selina situated in the same zone of mosaiced vegetation of moorland, rainforest, and related scrub. Note moorland range across western Lutruwita in orange. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

sediment record from Lake Selina (Fletcher et al., - in review; Colhoun et al., 1999) and explains the open moorland landscapes seen today (TasVeg 4.0; Kitchener and Harris, 2013; Thomas, 1993; Cosgrove et al., 1990; Cosgrove, 1999).

2. Methods

While geographically compatible, we first assessed whether the Darwin Crater palaeolake and Lake Selina archives were comparable depositional archives. (i.e., that they were both lacustrine systems through the period of comparison). Below we describe the equivalence of the depositional environments at the two sites. This section will first provide an overview of the Lake Selina site, noting that the proxy record is discussed in Fletcher et al. (in review). The methods applied to the Darwin Crater sequence will then be described to develop the environmental record and discuss the chronology related to the data produced for this study.

2.1. Study sites

2.1.1. Lake Selina

Lake Selina (41°52′41″ S, 145°36′34″ E) is a 190 m^2 open shallow lake (~5 m deep) in the West Coast Range of Lutruwita (516 m a.s.l.), located ~46 km NNW from Darwin Crater Palaeolake (Fig. 1). Lake Selina is situated within superhumid zone of Western Lutruwita, and its vegetation zone includes a mosaic of fire-promoted plant communities and climax rainforest (Fig. 1b). Coring of the uppermost 5.5 m sediments at Lake Selina reveals a continuous lake sediment sequence through Termination I to the present (Fletcher et al., - in review; Lisé-Pronovost et al., 2021; Colhoun et al., 1999). All data were produced according to the methods published in Fletcher et al. (in review). Sediments were sub-sampled at 1.25 cm^3 at 0.25 cm intervals for macroscopic charcoal analysis following standard protocols (Whitlock and Larsen, 2002). Samples were digested in Sodium hypochlorite (bleach, NaClO), sieved using 125 μm and 250 μm diameter mesh and counted under a microscope. Sediments were sub-sampled at 0.5 cm^3 for pollen analysis using standard methods and counted under a microscope to a base sum of 300 terrestrial pollen grains (Faegri and Iverson, 1989).

2.1.2. Darwin Crater

Darwin Crater Palaeolake (42°18.39′S; 145°39.41′E) is a 1.2 km wide infilled meteorite impact-crater (170 m a.s.l.) located ~46 km SSE from Lake Selina, also situated within the superhumid zone of western Lutruwita (Fig. 1) (Gentilli, 1972; Lisé-Pronovost et al., 2019, 2021). The crater was formed at 816 ± 7 ka based on Argon–Argon ($^{40}Ar/^{39}Ar$) dating (Fudali and Ford, 1979; Colhoun and Van de Geer, 1988; Howard and Haines, 2007). Like Lake Selina, the contemporary vegetation zone is a mix of climax rainforest and fire-promoted plant communities, including buttongrass plains, with abundant *G. sphaerocephalus* (Colhoun and Van de Geer, 1988) (Fig. 1b). The impact crater contains a ~70-m-long continuous sequence of Pleistocene lacustrine sediments overlying >100 m of unconsolidated breccia, sands, and mixed muds (Howard and Haines, 2007). Terrestrial infilling of the lake prior to the Last Glacial Maximum (LGM) terminates the lacustrine sediment phase (Colhoun and Van de Geer, 1988; Lisé-Pronovost et al., 2021; Howard and Haines, 2007; Fudali and Ford, 1979). The methods applied for multi-proxy analyses undertaken on the Darwin Crater sequence are described below.

2.2. Coring and sampling

Drilling of Darwin Crater site (TAS1803) in 2018 provided a near-continuous ~70-m-long lacustrine sediment sequence (see Lisé-Pronovost et al., 2019). For this study, five core sections from hole B (TAS1803B: 2TB, 3TM, 3MB, 4TM, 4MB) were targeted. These sections span the uppermost 236.5–818.3 cm of the lacustrine sequence prior to terrestrial infilling. Subsampling was carried out on one half of each core section and environmental magnetic analysis, Micro-XRF (Itrax) core scanning and high-resolution photography were undertaken on the remaining half before archiving.

2.3. Chronology

Four dehydrated bulk sediment (and one organic wood) samples underwent standard ABA pre-treatment at the University of Waikato, New Zealand (Brock et al., 2010). Radiocarbon ages were determined through Accelerator Mass Spectrometry (AMS) and calibrated to the Southern Hemisphere calibration curve (SHCal20) to convert radiocarbon ages to calendar years BP (cal yr BP expressed relative to 1950 CE) (Björck and Wohlfarth, 2002; Hogg et al., 2020). Additional qualitative age control was provided by comparison of trends in total temperature-sensitive tree and shrub species (%) from this study with temperature reconstructions from the Antarctic EPICA Dome C ice core record published by Jouzel et al. (2007) (this analysis is shown later in Fig. 7). This implied likely continuous lacustrine sedimentation from ca. 100–140,000 (kyrs) BP (Lemons and Chan, 1999; Vaasma, 2008; Sperazza et al., 2004).

2.4. Grain size distribution

Seventy-one samples were collected at 10 cm intervals, treated in hydrogen peroxide (H_2O_2) to digest organic material, disaggregated in an ultrasonic bath and sieved (1.7 mm) prior to analysis using a Beckman Coulter's LS 13320 Laser Diffraction Grain Size Analyser (PSA) (to 8–12% obstruction). *GRADISTATv8* software (Blott and Pye, 2001) was utilised to interpret datasets with reference to Folk and Ward (1957).

2.5. Loss on ignition and Micro-XRF core scanning

Eighty-three sediment samples (1.25 cm^3 at 8 cm intervals) were analysed by Loss on Ignition (LOI) following standard procedures (Heiri et al., 2001; Dean, 1974; Santisteban et al., 2004). Subsequent weight loss was recorded at incremental heating stages (60 °C, 550 °C, 925 °C) to determine moisture and organic carbon content (Bengtsson and Enell, 1986; Heiri et al., 2001). Organic matter was determined by a micro-X-ray fluorescence (μXRF) Itrax core scanner at the Australian Nuclear Science and Technology Organisation (ANSTO) at 2 mm resolution (Croudace et al., 2006). The Itrax scans were conducted using a molybdenum (Mo) tube set at 55 mA and 30 kV with a dwell time of 10s. The μXRF data was normalised to an internal standard (thousand count per spectrum [kcps]), to counteract down core variability in organic and moisture content (Croudace et al., 2006; Boyle, 2002; Croudace and Rothwell, 2015). Ratios of incoherent and coherent scattering measurements (Mo inc:coh) were applied as a proxy for organic matter (e.g., Fletcher et al., 2018), as Mo inc:coh increases with greater concentrations of organic carbon (Saez et al., 2009; Burnett et al., 2011; Liu et al., 2012). Additionally, simple regression analysis was performed on Mo inc:coh and carbon (%) values ascertained through Loss on Ignition (LOI) analysis to assess whether Mo inc:coh may offer the potential to estimate changes in sediment organic content throughout the remaining Darwin Crater sequence (see Woodward and Gadd, 2018; Saez et al., 2009; Chawchai et al., 2016). As Itrax is sampled at a higher resolution than LOI samples, Itrax data was binned using *RStudio* (RStudio Team, 2021) to match the resolution of the LOI data.

2.6. Environmental magnetic analysis

Eighty-one sediment samples (~1 g; 10 cm intervals) were collected, air-dried, gently homogenised using an agate mortar and pestle and encapsulated (size 0) for analyses at the Palaeomagnetic Laboratory of the Australian National University (ANU), Canberra. A 2G Enterprises Cryogenic Magnetometer was used to induce and stepwise demagnetise (0, 5, 10, 20, 30, 40, 60, 80, 100, 120, 140 and 170 mT) an anhysteretic remnant magnetisation (ARM) with peak field of 170 mT and direct current bias field of 0.05 mT. The same series of twelve demagnetisation steps was used to demagnetise and measure an isothermal remanent magnetisation (IRM) acquired in a 1 T saturating field. A Princeton Corp Vibrating Sample Magnetometer was then used to conduct hysteresis and back-curves in fields up to 1 T. The remanent coercive force (*Hcr*) is calculated from the back-curve analysis and corresponds to the required applied backfield value to reach zero magnetisation after initial saturation (Liu et al., 2012; Verosub and Roberts, 1995). The median destructive field (MDF_{IRM}) is calculated from the IRM demagnetisation curve and is the alternating field required to remove half of the remanent magnetisation in a sample.

Hcr and MDF are magnetic coercivity indicators reflecting the magnetic grain size and mineralogy of a sample (Dunlop and Özdemir, 1997). They are site-specific palaeo-environmental proxies. For example, MDF was used as a magnetic grain size proxy in uniform lake sediment mineralogy (e.g., Lisé-Pronovost et al., 2015), as a magnetic mineralogy proxy in marine sediments of the Arctic Ocean (e.g., Brachfeld et al., 2009) and as a proxy for pedogenic hematite in loessite-paleosol couplets (e.g., Western USA - Jia, 2020).

2.7. Fossil pollen and charcoal analysis

Eighty-three samples were collected at 8 cm intervals, increasing to 4 cm intervals across Termination II: 620.5–762.3 cm. These were processed in the University of Melbourne Palynology Laboratory, following (modified) standard procedures (Faegri and Iverson, 1989). A total of 300 terrestrial pollen grains were identified and counted per sample interval under 400× magnification using a ZEISS AX10 light microscope. Pollen data was modified following the protocol outlined in Fletcher et al. (2014), excluding taxa contributing ≤1% to the pollen sum (or <5 occurrence), and percentages were calculated on the remaining 77 terrestrial pollen taxa. The sample at 469 cm contained insufficient pollen grains and was excluded from the dataset.

Eighty-three sediment subsamples (1.25 cm^3 at 8 cm intervals) were processed for macroscopic (>125 μm) charcoal content following standard procedures (Whitlock and Larsen, 2002). Two size fractions (>250 μm and >125 μm) were sieved and dispersed into separate petri dishes and counted under an Olympus SZ51 dissecting microscope (×40 magnification). Macroscopic charcoal counts were summed to ensure consistency between trends of both size divisions. Microscopic (<100 μm) charcoal was processed and counted in conjunction with pollen analysis and presented as a ratio of charcoal pieces versus total terrestrial pollen counts (MC:TP).

2.7.1. Principle component analysis (PCA)

Principal Component Analysis (PCA) was undertaken on the pollen data to identify significant clusters and trends in the datasets in multi-dimensional space (through linear regression) (McCune and Mefford, 2011; Birks, 2012). Ordination biplots were constructed based on CONISS (stratigraphically constrained cluster analysis using the incremental sum of squares method; Grimm, 1987) identified pollen Zones. PCA assumes a normal distribution; therefore, pollen data underwent square-root (0.5) transformation (to counteract skewness) prior to analysis.

3. Results

3.1. Radiocarbon dating (^{14}C)

The wood fragment between 64.5 and 67.5 cm produced a median age of 389 cal yr. BP, and is assumed to be erroneous, representing a young organic intrusion from the upper peat layer. Two bulk sediment samples produced radiocarbon ages of 44,348 ± 870 ^{14}C yr BP (215 cm) and 48,256 ± 1474 ^{14}C yr BP (306.5 cm) that were calibrated to 46,670 and 51,208 cal yr BP, respectively (Table 1). The charcoal sample at 146 cm and the bulk sediment at 481 cm produced ages that were beyond the reliable limit of ^{14}C dating (>~50 kyrs). Optically Stimulated Luminescence (OSL) dating was attempted on sediments within this study by Professor Zenobia Jacobs at the University of Wollongong, Australia, however results were unable to be ascertained due to signal saturation.

3.2. Stratigraphy and sedimentological properties

Three lithostratigraphic zones were present in the core stratigraphy and in the sedimentological analyses (Fig. 3). These include light-olive lacustrine silt (Zone 1) dark-brown lacustrine silt (Zone 2) and silty sand (Zone 3).

3.3. Grain size distribution

Grain size results show that fine silt characterises the lacustrine sediments in Zones 1 and 2 and are replaced by coarser silty sands (90%) in Zone 3 (Figs. 2 and 3A). This suggests greater hydrodynamic energy is associated with Zone 3 sediments which plot at the higher energy end of a D50-D90μm plot (Fig. 2). At 364 cm an abrupt temporary replacement of sand (2%) by lacustrine silt and clay sediments is observed (Fig. 3).

3.4. Organic content from loss on ignition and Micro-XRF core scanning

Lacustrine sediments in Zone 1 have variable water content ranging

Table 1
Radiocarbon dating of samples from Darwin Crater, with median calibrated ages calculated from SHCal20 (Hogg et al., 2020) using *Calib 8.2* (Stuiver and Reimer, 1993). * Denotes that the calibrated age is beyond the reliable limits of radiocarbon analysis (>~50 kyrs).

Lab Code	Sample Depth (cm)	Material dated	Modern fraction		Radiocarbon age		Median age (cal yr BP) 2σ
			pMC	1σ error	Yr. BP	1σ error	
49,929	64.5–67.5	Wood	95.5	0.2	366	16	389
49,930	146	Charcoal	0.0	0.1	>52,818.3	NA	NA*
49,931	215	Bulk sediment	0.4	0.0	44,348	870	46,670
49,932	306.5	Bulk sediment	0.2	0.0	48,256	1474	51,208
49,930	481	Bulk sediment	0.0	0.0	>57,818.3	NA	NA*

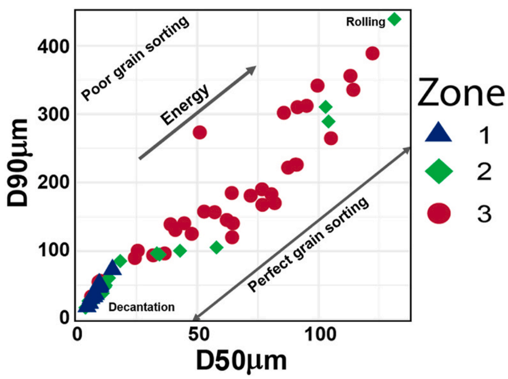

Fig. 2. Grainsize biplot presenting the relationship between coarser (D90 μm) and finer (D50 μm) grain size and hydrodynamic energy (Passega, 1964), in the sediment Zones of Darwin Crater. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

between 30% and 75% (Fig. 3F), carbon via LOI values between 5% and 25% (Fig. 3E), and Itrax Mo inc:coh values of 4–5.5 kcps (Fig. 3D) (Guyard et al., 2007; Burnett et al., 2011). The water content increased across the Zone 1 – Zone 2 boundary to 30–70% (730–480 cm), associated with increases in organic content (LOI peaks at 60% and Mo inc: coh at 8 kcps at 648 cm). The transition to the Zone 3 silty sand is defined by a sharp decline in moisture (10%), and organic content (2% LOI, 4 kcps) values which remain low throughout this period.

3.5. Environmental magnetism

Downcore differences in coercivity-dependent parameters *Hcr* and MDF_{IRM} in the Darwin Crater sediments indicate that the coercivity of magnetic minerals is the highest within light-olive lacustrine silt (Zone 1) and lower in the dark-brown silt (Zone 2) and silty sand (Zone 3) (Fig. 3B; C), with *Hcr* clearly identifying three distinct sediment zones. These coercivity changes in IRM (rather than ARM) analysis suggest these changes are governed by magnetic grains that preferably acquire an IRM (e.g., coarser ferrimagnetic particles and/or higher coercivity minerals such as hematite and goethite). The ARM-derived parameters MDF_{ARM} (average 27 mT) and *k*ARM/IRM (average 0.88 mmA-1) have values matching the typical values for detrital, pedogenic, and aeolian sources (Egli, 2004). Zone 1 is characterised by maximum values in both coercivity-dependent parameters *Hcr* (~38 mT) and MDF_{IRM} (~28 mT). Zone 2 displays an abrupt concomitant decrease in both *Hcr* (28 mT) and MDF_{IRM} (~16 mT) between 648 and 694.3 cm, following the transition into Zone 2. This indicates a shift from higher-coercivity and/or finer particles to lower coercivity and/or coarser particles that are more easily demagnetised (Liu et al., 2012; Verosub and Roberts, 1995). Zone 3 is characterised by generally lower and variable values of coercivity, marked by a notable decrease in coercivity-dependent parameters observed at the sediment transition, with *Hcr* (~20 mT) and MDF_{IRM} (~14 mT), reaching the lowest values and maintaining these throughout this period.

3.6. Fossil pollen and charcoal analysis

A total of 31,389 pollen grains and spores were identified across 135 pollen and spore taxa. Microscopic charcoal is expressed as a ratio between charcoal pieces and total terrestrial pollen count (MC:TP) in each sample, and macroscopic charcoal as pieces per cm^3 (#/cm^3). Both microscopic and macroscopic charcoal display similar trends in Zones 1 and 2 and some opposing trends in Zone 3 (Fig. 4). CONISS analysis identified three main pollen Zones which correspond with the lithostratigraphic zones previously described (Figs. 4 and 5).

Zone 1 (818.3–670 cm depth; correlating with light-olive lacustrine sediments): Poaceae (40–50%) and Asteraceae (20–35%) were the dominant pollen types, with lesser values of Amaranthaceae (3–4%), *Astelia* spp. (4–8%), Caryophyllaceae (2–3%) and *Pherosphaera* spp. (3–5%), and the notable presence of *Tubulifloridites pleistocenicus* (1–3%), a pollen type restricted to glacial and stadial climate zones in southeast Australia (Edney et al., 1990; Kershaw et al., 1991; Harle, 1998; Williams et al., 2006) (Figs. 4 and 7E). The presence of open-water indicator taxa (requiring ~1 m water depth) is restricted to this period, comprising aquatic macrophytes *Isoëtes* spp. (40–70%) and two open water algae taxa, *Pediastrum* spp. (10–30%) and *Botryococcus* spp. (3–6%) (Fig. 5). Herbs and shrubs are replaced by high percentages of Cupressaceae (20–45%) (before declining to <5%) and Myrtaceous taxa, with high relative values of *Eucalyptus* spp. (10–45%) predominantly confined to a single peak across the Zone 1–2 transition. Locally dispersed pollen types, such as *Monotoca* spp. (<1%), *Hibbertia* spp. (0.5–1%), Fabaceae (<1%), *Sprengelia* spp. (1–2%), Apiaceae (1–2%) and *Plantago* spp. (1–5%) are present in low numbers. Microscopic and macroscopic charcoal both indicate a period of increased fire activity throughout Zone 1, displaying distinct peaks (0.8 MC:TP) at 750 cm and 690 cm, and at 818.3 and 720 cm (18–20 #/cm^3), respectively (Fig. 4).

Zone 2 (670-474 cm depth; correlating with dark-brown lacustrine sediments): *P. aspleniifolius* (20–30%) and *N. cunninghamii* (20–35%) dominate the pollen spectra before declining toward the top of the Zone. *L. franklinii* maintains values of 5–10% before an increase (10–20%) at 474 cm. *Eucryphia* spp. (10–20%) and *B. ruboides* (2–4%) are restricted to this zone, and Poaceae maintains low to moderate values (5–30%) throughout. Algal taxa *Pediastrum* spp. remain low (~2%), displaying a slight peak (1–8%) between 550 and 470 cm. Arboreal Myrtaceous taxa display a decline correlating to a decrease in microscopic and macroscopic charcoal activity (Fig. 4). Shallow water/boggy indicator taxa *Potamogeton* spp. becomes more apparent, and an abrupt and synchronous increase in fern species *Gleichenia* spp. (5–10%) and *Histiopteris* spp. (1.5–3%) is observed between 640 and 550 cm (Fig. 5). Locally dispersed pollen types, such as *Hibbertia* spp., Fabaceae, *Sprengelia* spp., Apiaceae and *Plantago* spp. all decline to <1%, while *Monotoca* spp. peaks throughout this zone (1–3%). Minimum values of microscopic (0–0.2 MC:TP) and macroscopic (0–5 #/cm^3) charcoal are generally maintained throughout this zone.

Zone 3 (474–236.5 cm; correlating with silty sand sediments): Herbs and forbs replace trees and shrubs comprising around 50% of the total terrestrial pollen sum. Poaceae (20–50%) and Asteraceae re-establish (10–20%), with Amaranthaceae, *Astelia* spp., Caryophyllaceae, *Pherosphaera* spp. and glacial flora *T. pleistocenicus* (all <5%). A synchronous

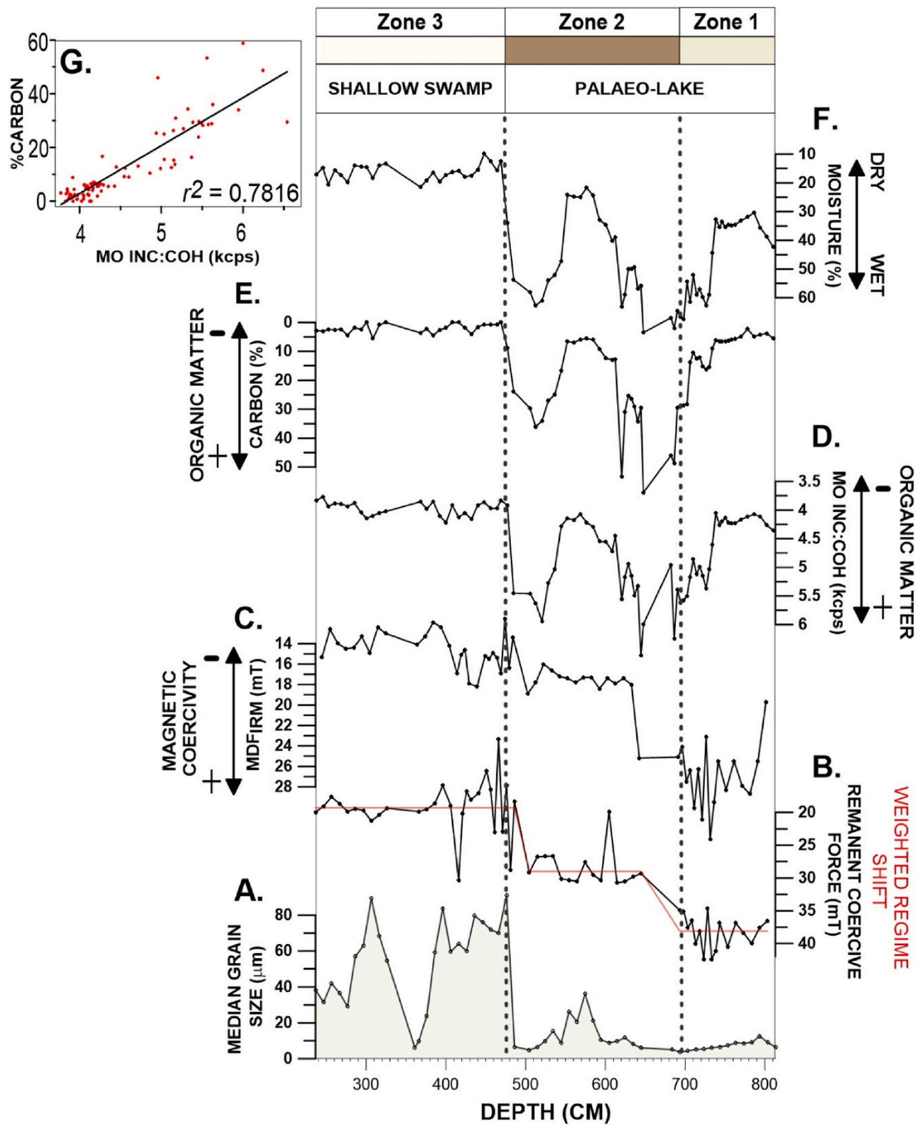

Fig. 3. Lithostratigraphic zones and sedimentary properties of the Darwin Crater sediment core. Lithostratigraphic zones, labelled and colour-coded at top of graph: light-olive lacustrine silts (Zone 1, 694.3–818.3 cm), dark-brown lacustrine silts (Zone 2, 474–694.3 cm), silty sands (Zone 3, 236.5–474 cm). (A) median grain size (μm), coercivity-dependent magnetic parameters (B) remanent coercive force (H_{cr}) and (C) median destructive field of IRM (MDF_{IRM}); (D) Itrax organic matter proxy Mo inc:coh, normalised to an internal standard (thousand count per spectrum [kcps]); (E) carbon content via Loss on Ignition (%); (F) water content (%); and (G) Regression analysis results of Mo inc:coh and carbon (%) ($r^2 = 0.7816$) (Woodward and Gadd, 2018). Note the inverted axes on some graphs. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

increase in locally dispersed scrub species Ericaceae (20–30%) and *Allocasuarina* spp. (5–20%) is observed. This correlates with the shift in sediment along with an increase in locally dispersed pollen types: *Hibbertia* spp. (1–2%), Fabaceae (2–10%), *Sprengelia* spp. (2–6%), Apiaceae (2–3%) and *Plantago* spp. (2–18%), while *Monotoca* spp. decline to <1% (Fig. 4). A rapid increase in shallow water/boggy indicator taxa is observed. Relative values of Haloragaceae (1–4%), *Potamogeton* spp. (2–3%) and *Hydrocotyle* spp. (1–4%) increase synchronously at the start of this zone (Fig. 5). This zone is also marked by a peak in macroscopic charcoal (5–15 #/cm^3) between 470 and 430 cm, and microscopic charcoal maintains relatively low values (0.1–0.3 MC:TP) before increasing (0.3–0.7 MC:TP) at the top of the sequence.

3.6.1. *Principal Component Analysis (PCA)*

Relationships between pollen taxa in Zones 1–3 and the two most significant ordination axes are presented as a biplot (Fig. 6). PCA Axis 1 (PC1) explains 46% and Axis 2 (PC2) explains 18% of variance within the dataset. Pollen taxa that display a positive correlation with PC1 include typical warm interglacial climate species *Eucryphia* spp. (r^2 0.849), *P. aspleniifolius* ($r^2 = 0.902$), and *N. cunninghamii* ($r^2 = 0.783$). Taxa that display a negative correlation with PC1 include typical cold climate species Poaceae ($r^2 = 0.579$), Asteraceae ($r^2 = 0.767$) and *Pherosphaera* spp. ($r^2 = 0.599$) which also displays a positive correlation with PC2. Those displaying a negative correlation with PC2 include scrub heathland species Ericaceae ($r^2 = 0.428$), and shallow water/boggy indicator taxa *Plantago* spp. ($r^2 = 0.478$), *Hibbertia* spp. ($r^2 = 0.556$), Haloragaceae ($r^2 = 0.646$), and *Allocasuarina* spp. ($r^2 = 0.719$). PC1 rapidly shifts from low and consistent axis scores (~-4) in Zone 1 to high and consistent axis scores (~6) in Zone 2, before maintaining moderate and variable negative axis scores (-3-0) in Zone 3 (Fig. 4). PC2 displays a stepwise decrease from relatively stable peak high positive axis scores (~2) throughout Zone 1 to moderately high and stable positive axis scores (~1) throughout Zone 2. An abrupt shift to highly variable negative axis scores (~-5-0) occurs in Zone 3 (Fig. 5).

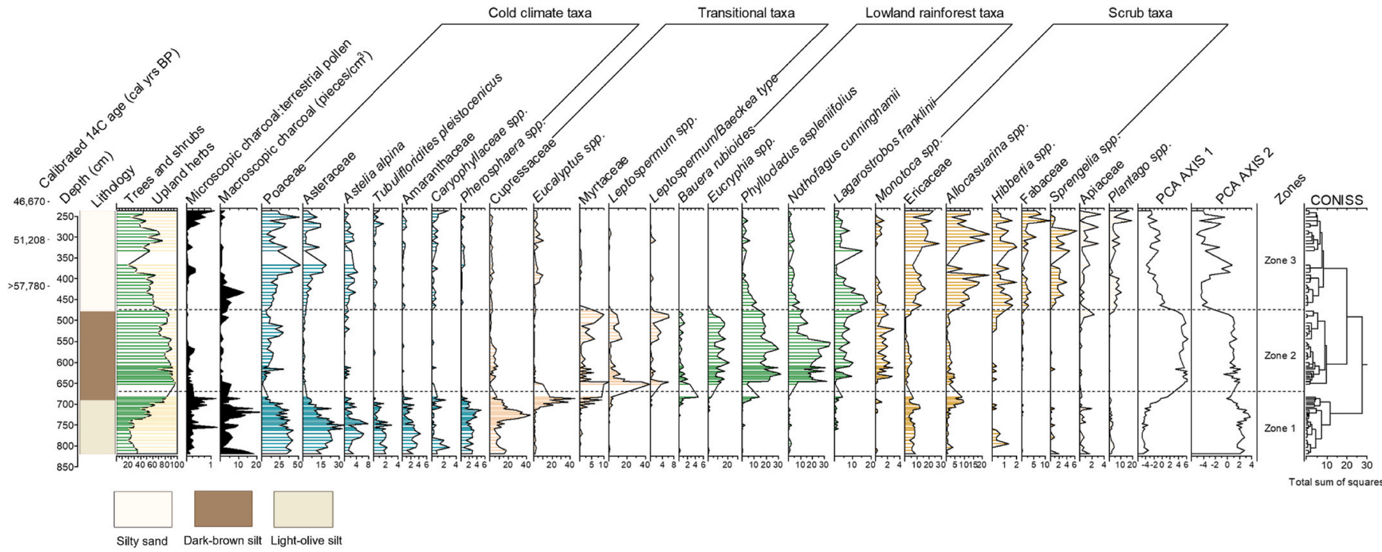

Fig. 4. Darwin Crater pollen and charcoal record including pollen, with >1% abundance. Axis Y represents depth (cm) with corresponding calibrated ^{14}C ages. Note % scale changes in X axes. The three lithostratigraphic Zones (left) are mirrored by the CONISS defined pollen Zones (right). Total terrestrial pollen is represented by trees and shrubs in green and herbs and upland herbs in yellow. Cold climate taxa are expressed in teal, transitional species in tan, lowland rainforest taxa in green, and scrub taxa in brown. Microscopic and macroscopic charcoal are presented as a ratio of charcoal:terrestrial pollen counts (MC:TP) and pieces/cm^3 (#/cm^3), respectively. PCA axis 1 (PC1) represents the primary trend within the dataset, responding to shift in temperature and explaining 46% of the variance. PCA axis 2 (PC2) represents the secondary trend within the dataset, responding to change in site type and explaining 18% of variance (see Fig. 6). Note: Gaps in sampling intervals are due to sediment lost in extraction process. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

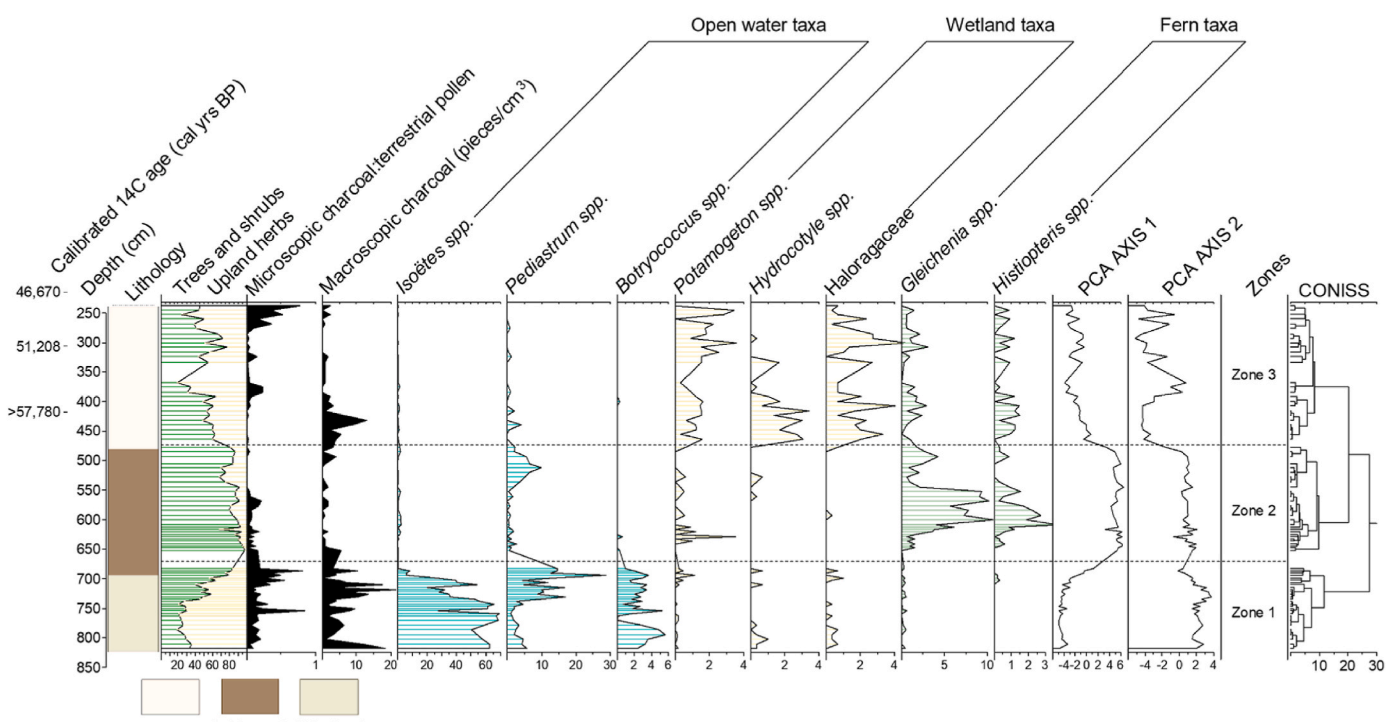

Fig. 5. Darwin Crater pollen and charcoal record (continued) showing aquatic, shallow water/boggy indicator and fern species (>1%). Aquatic open water indicator species are expressed in blue, shallow water/boggy indicator species in yellow, and vascular cryptogams in green. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

4. Discussion

4.1. Darwin Crater palaeolake

Our results clearly identify three distinct sedimentary facies within the Darwin Crater sediment sequence: two lacustrine silt dominated facies between 818.3 and 474 cm (Zones 1 and 2) and coarser sandy-silt facies between 474 and 236.5 cm (Zone 3). The lacustrine facies have two distinct units: (1) a light-olive lacustrine phase between 818.3 and 694.3 cm (Zone 1) dominated by cold climate glacial stage pollen types

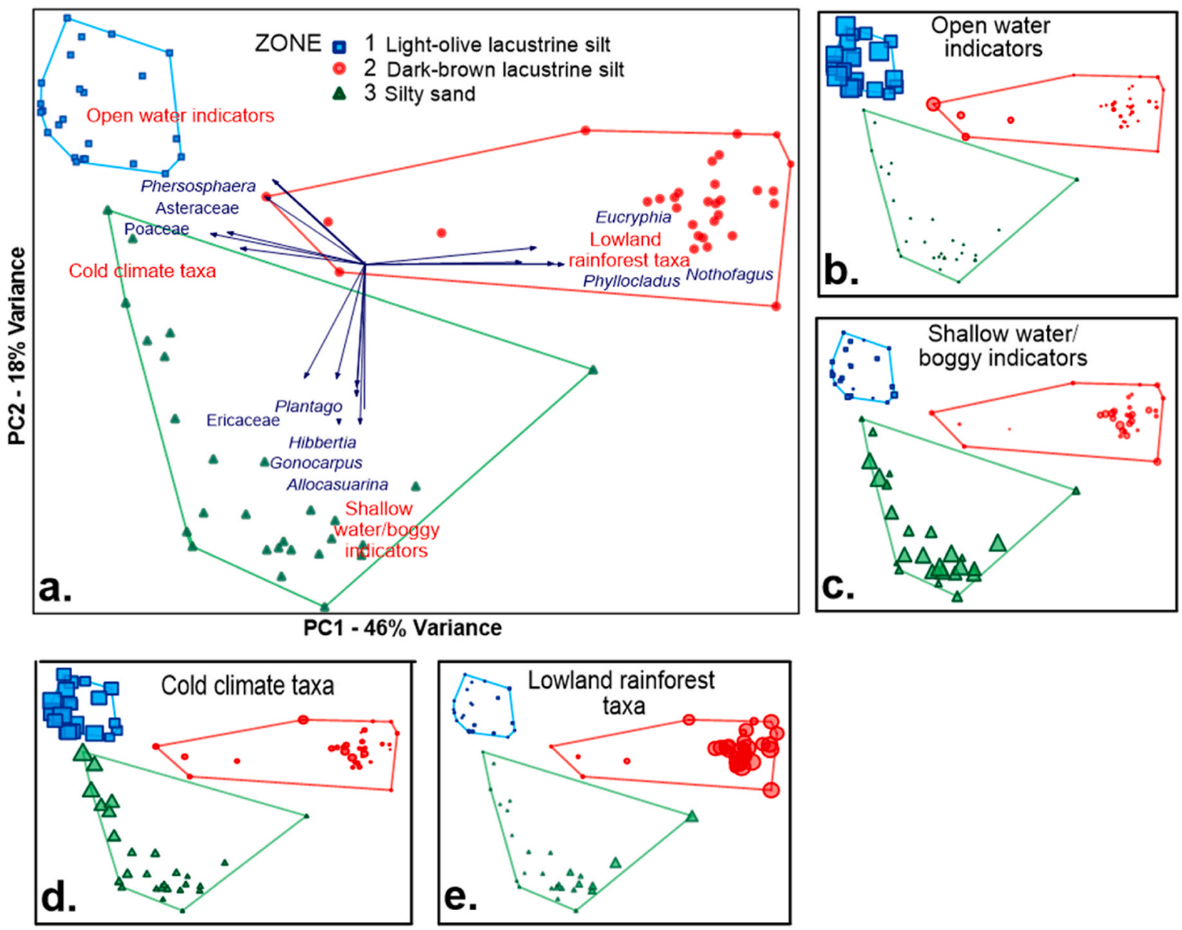

Fig. 6. | Principal component analysis biplot of the terrestrial pollen dataset from Darwin Crater. CONISS-identified pollen Zones are outlined in different coloured bounding lines and individual pollen samples as coloured shapes (as defined in the legend): PC1 explains 46% and PC2 explains 18% of variance in the dataset. (a) The contribution of individual taxa to the axis scores is indicated by arrow orientation and length, (b) cluster of open water indicator taxa samples, displaying a strong correlation with high PC2 scores; (c) cluster of shallow water/boggy indicator species, displaying a strong correlation with PC2 scores; (d) cluster of glacial indicator species, displaying strong correlations with low PC1 scores; (e) cluster of interglacial indicator species, displaying a strong correlation with high PC1 scores. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

(80%) (Fig. 7A), containing high-coercivity magnetic particles (Fig. 3B; C), indicating a cold and relatively dry glacial climate; and (2) a dark-brown lacustrine phase between 694.3 and 474 cm (Zone 2) dominated by thermophilus rainforest pollen types (77%) indicating an interglacial climate (Fig. 7A). Based on these pollen shifts (Fig. 7A), and the correlation between PC1 (which is based on the pollen data; Fig. 7B) and the EPICA Dome C temperature record (Fig. 7D), we propose that the chronology of the core spans from ca. 100–140 kyrs BP (Jouzel et al., 2007). We acknowledge that the apparent correlations between these plots require a stable sediment accumulation rate throughout the core, an assumption that which we cannot independently test. Nevertheless, reliable ^{14}C results indicate the sediment sequence represents a pre-Palawa interval. We discuss our interpretations of the glacial phases and vegetation shifts in more detail below.

Glacial periods are generally considered to be relatively dry in southeast Australia and Lutruwita (Colhoun, 2000; Cadd et al., 2021; De Deckker et al., 2019). The presence of high-coercivity magnetic particles within Zone 1 (represented by H_{cr} and MDF_{IRM}; Fig. 3B,C) supports this interpretation since the highest coercivity minerals (hematite and goethite), as well as the preservation of finer particles, are often associated with dust and aridity (e.g., Jia, 2020; Maher, 2011; Kohfeld and Harrison, 2001, 2003; Harrison et al., 2001). The abundance of cold climate taxa in this zone, primarily Asteraceae, Poaceae (Fig. 7A) and the presence of *T. pleistocenicus* (Fig. 7E) – a pollen type restricted to glacial (and stadial) stages during the Pleistocene in Lutruwita – supports the interpretation that Zone 1 represents a glacial climate phase (Edney et al., 1990; Kershaw et al., 1991; Harle, 1998; Williams et al., 2006). The vegetation changes within the lacustrine sediment clearly indicate a glacial termination event between Zone 1 and Zone 2. While we tentatively ascribe this event to Termination II, it is clear from the ^{14}C data that this termination event is pre-Palawa. Indeed, the oscillations in the pollen sequence are entirely consistent with temperature changes through Marine Isotope Stages (MIS) 5e (interglacial), 5d (stadial) and 5c (interstadial) (Fig. 7D), with similar trends observed at Lake Selina (Lutruwita; Colhoun et al., 1999), Chatham Rise (east of the south island of New Zealand; Heusser and Van de Geer, 1994) and Cape Bridgewater (offshore Portland in western Victoria, southeast Australia; Harle, 1997) throughout the same time period. This further corroborates our ascription of this shift to Termination II.

Zone 3 in the Darwin crater sequence represents the stage of palaeolake infilling with coarse sand sediments and magnetic particles with the lowest coercivity (Figs. 3 and 7G). This shift in site type, represented by PC2 (Fig. 7I), is typical of ephemeral lake termination, whereby open lake environments transform to boggy reducing wetlands with limited open water surface and dissolution of the smaller magnetic particles (Strahler and Foresman, 2012; Roberts, 2015). The change in aquatic environment saw a shift from open water taxa (*Isoëtes* spp., *Pediastrum* spp. *Botryococcus* spp.) (Fig. 7F) to wetland taxa (*Hydrocotyle* spp., Haloragaceae, *Potamogeton* spp.) (Prahalad et al., 2018; Kirkpatrick and Harwood, 1983; Kirkpatrick and Wells, 1987) (Figs. 5 and 7H).

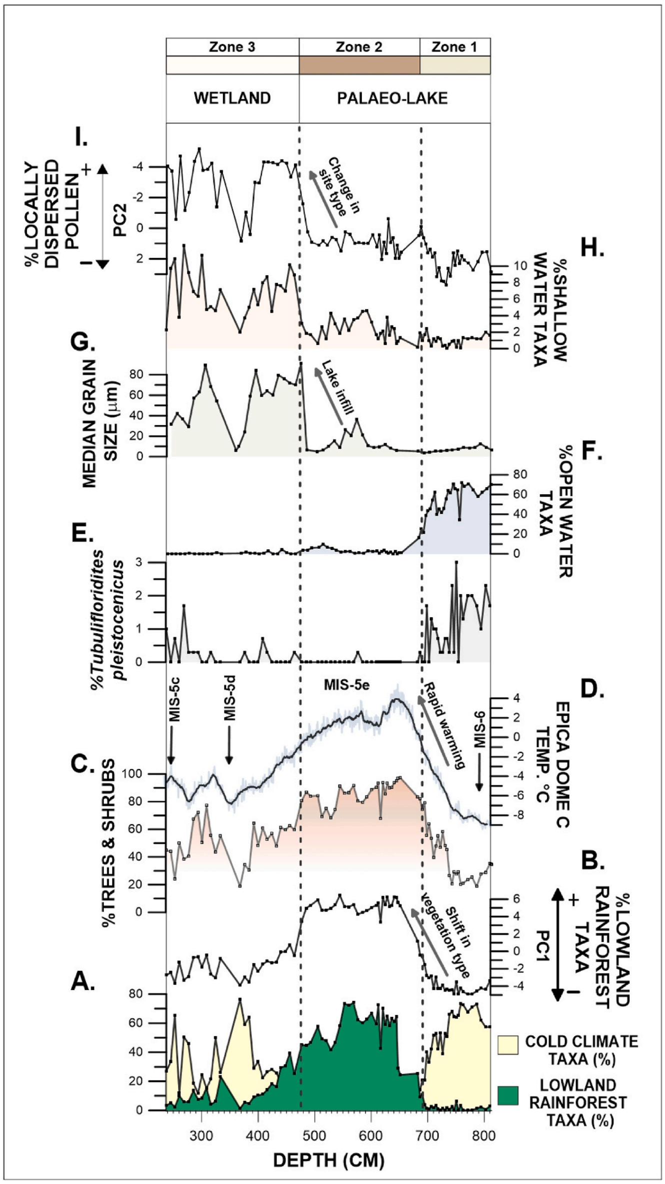

Fig. 7. | Summary plot of sedimentological and pollen data from Darwin Crater tied to the EPICA Dome C ice core temperature record. (A) relative percentages of cold climate (yellow) and lowland rainforest taxa (green), displaying abrupt climate driven shifts at 694.3 cm and 474 cm. Note: light green represents taxa which occur in both groups; (B) PC1 (explaining 46% of variance in the pollen dataset; data underwent square root transformation prior to analysis); (C) percent of total pollen represented by tree and shrub taxa; (D) EPICA Dome C temperature reconstruction spanning Termination II, ca. 100–140 kyrs BP (Jouzel et al., 2007); E) *Tubulifloridites pleistocenicus*, a pollen type restricted to glacial (and stadial) stages during the Pleistocene in Lutruwita (Edney et al., 1990; Kershaw et al., 1991; Harle, 1998; Williams et al., 2006); (D) percentage open water indicator taxa, which require a depth of ~1 m to establish; (E) median grain size (μm), (F) percentage shallow water/boggy indicator pollen taxa; (G) PC2 (explaining 18% of variance in the dataset; data underwent square root transformation prior to analysis). Note some axes are inverted. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Collectively, our data record the infilling of the Darwin Crater palaeolake after Termination II and in the latter stages of the MIS5 interglacial, following an open lacustrine phase throughout the MIS6 glacial period.

4.2. Western Lutruwita: a cultural landscape in a warming world

Our data demonstrate that glacial phases at both Darwin Crater and Lake Selina were near-identical (Fig. 8). This is particularly evident with macroscopic charcoal presence (ranging between 2 and 20 #/cm^3) and cold climate taxa (maximum 80%), suggesting that baseline fire regime and climate conditions are suitable for inter-site comparison (Fig. 8). Following the warming at Darwin Crater during Termination II (ca. 100–140 kyrs BP), fire activity rapidly decreased and, as interglacial climate conditions prevailed, rainforest returned (Fig. 8). In contrast, the warming observed at Lake Selina during Termination I (ca. 18–11.7 kyrs BP) demonstrates that, while during MIS5 the site was dominated by rainforest, both fire and fire promoted plant communities expanded instead of rainforest (Fig. 8). By comparing the deep time records of

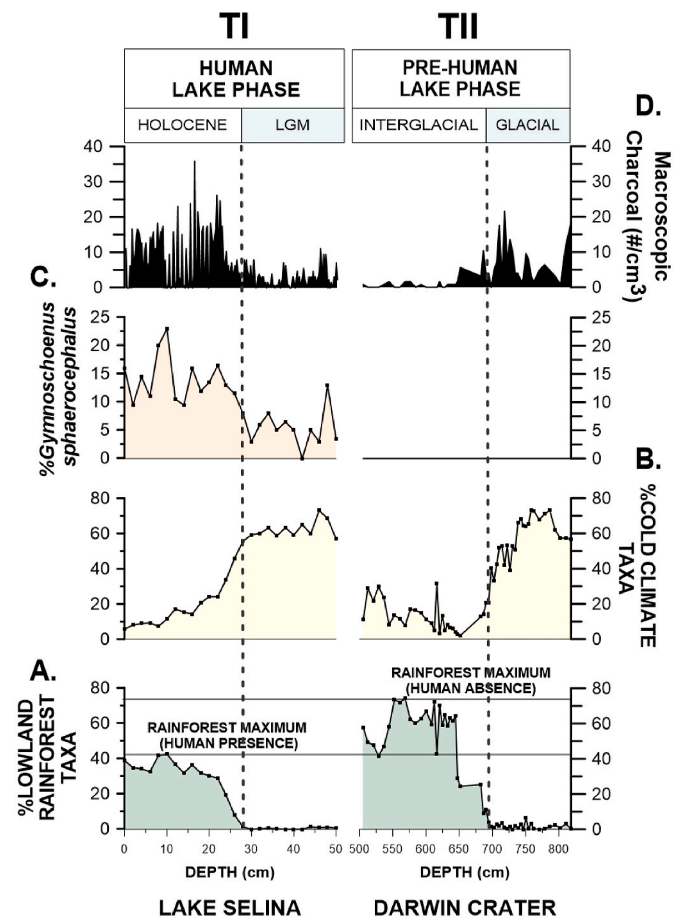

Fig. 8. | Summary plot comparing key charcoal and pollen data at Lake Selina (left), spanning Termination I (Fletcher et al., - in review), and Darwin Crater (right), spanning Termination II (or older). (A) Percentage pollen values for lowland rainforest taxa show 36% difference in pollen count following the Glacial Terminations at Darwin Crater (77%) in the absence of human influence, and Lake Selina (41%) when the Palawa were managing the landscape with fire. Horizontal lines represent maximum lowland rainforest percentage values in both pollen records throughout respective interglacial periods; (B) Cold climate glacial taxa comprised ~80% of the pollen count at both Darwin Crater and Lake Selina, indicating that both glacial climate stages had comparable species assemblages; (C) Anthropogenic indicator species *Gymnoschoenus sphaerocephalus* is absent from the pollen spectra at Darwin Crater across Termination II, but well-established in Lake Selina across Termination I and through the Holocene; (D) Macroscopic charcoal concentration (#/cm^3) showing low levels of fire activity after the Termination II in Darwin Crater and high levels of fire activity throughout Termination I and into the Holocene at Lake Selina. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Darwin Crater and Lake Selina, and the ecological responses to glacial-interglacial conditions, it is possible to assess the timing (and magnitude) of when Palawa cultural burning shaped the landscape.

The arrival of humans into Lutruwita (ca. 43ka; Cosgrove, 1999), introduced an ignition source independent of climate, which had profound implications for typical (expected) successional trends in post-glacial and interglacial vegetation (Jordan et al.,1991; McWethy et al., 2013). In the Darwin Crater sequence, floristically simple *P. aspleniifolius-N. cunninghamii* lowland rainforest has demonstrated its potential to dominate under relatively undisturbed conditions (FRI 150–350 years; Jackson, 1968) (Fig. 8). In some instances, for example across Surrey Hills (Lutruwita), following the removal of fire-based land management by the Palawa, *P. aspleniifolius-N. cunninghamii* lowland rainforest has replaced grassy Eucalypt-savanna, which was the dominant vegetation only 200 years prior (Fletcher et al., 2021b; Thomas, 2011). In the absence of human disturbance, lowland rainforest dominated interglacial vegetation at Darwin Crater (rainforest maximum = 77%). Whereas, with increased fire activity, lowland rainforest failed to recapture its potential range from the last interglacial (MIS5) at Lake Selina (rainforest maximum = 41%) (Fletcher et. al., – in review). Multiple factors influence the over- and under-representation of vegetation in pollen records (e.g., pollen productivity and preservation, dispersal capabilities) (Fletcher and Thomas, 2007; Mariani et al., 2017; de Nascimento et al., 2015). The model proposed by Mariani et al. (2017) further highlights the extent of pollen biases, revealing that over-represented rainforest species registering ~80% in the percent pollen sum may reflect only 30–40% of landscape cover, while under-represented species such as *G. sphaerocephalus* may cover 40–50% of the landscape yet only register ~5% in the pollen sum (Mariani et al., 2017). This suggests that pollen percent values overserved in the Lake Selina record likely over- and under-estimates the corresponding land-cover of lowland rainforest and *G. sphaerocephalus* in the landscape (i.e., 40% rainforest = ~15% landcover and 10% *G. sphaerocephalus* = ~35–40% landcover) (Mariani et al., 2017). Interestingly, the contemporary landscape of western Lutruwita is dominated by fire promoted vegetation, with ~17% occupied by anthropogenic indicator taxon *G. sphaerocephalus* (buttongrass moorland) (Fig. 1b) (requiring 12–25 yrs. FRI to sustain; Jackson, 1968; Colhoun and Van de Geer, 1988; Marsden-Smedley, 2009). *G. sphaerocephalus*, a severely under-represented local pollen type (Mariani et al., 2017; Fletcher and Thomas, 2007), significantly increased in the Lake Selina pollen record following T1 (ca. 18–11.7 kyrs BP) (Fig. 8). However, while abundant in the contemporary catchment, it is notably absent throughout the Darwin Crater record, suggesting that moorland vegetation failed to establish prior to human occupation. This may result from increased human-fire activity throughout the Holocene shifting soil hydrology from fertile, wet forest promoting, to less fertile, poorly drained soils, which promote flammable moorland vegetation maintained by frequent fire-based management (Adeleye et al., 2023; Bowman and Perry, 2017; Wood and Bowman, 2012; McIntosh et al., 2005; Fletcher et al., 2014).

Despite rainforest dominating all pre-human interglacials in Lutruwita (e.g., this study; Fletcher et al., - in review; Jackson, 1999; Colhoun et al., 1999; Macphail et al., 1993; Colhoun and Van de Geer, 1988; Van de Geer et al., 1994), the shift into the Holocene (the current interglacial) is marked by a failure of rainforest to recapture its predicted range across western Lutruwita. This contradicts what is observed at similar latitudes and landscapes across New Zealand where rainforest dominates early Holocene pollen records prior to Polynesian settlement ca. 800 years ago (i.e., prior to human influence) (Newnham et al., 2007; McIntosh et al., 2005; Ogden et al., 1998; Augustinus et al., 2008; Perry et al., 2014). It should be acknowledged that historically, Southern Hemisphere glacial and interglacial periods have varied in expression, and more specifically, forest composition due to fluctuations in southern ice volume, insolation and precipitation variability (Daniau et al., 2023; Rodríguez-Zorro et al., 2020; Kershaw et al., 2007). As such, the differences in the 'natural' response of rainforest to climate warming observed across both Termination I and II in western Lutruwita have been considered. However, there is a raft of scientific evidence supporting that the Palawa maintained glacial landscape 'openness' in a rapidly warming Holocene (interglacial) climate in Lutruwita via the targeted application of fire (e.g., this study; Fletcher et al., - in review; Adeleye et al.,2023; Mariani et al., 2017; Jackson, 1999; Thomas, 1993; Bowman and Jackson, 1981; Fletcher and Thomas, 2010). Moreover, studies from New Zealand indicate that rainforest dominated early Holocene pollen records, persisting until their decline in the late Holocene (Newnham et al., 2007; Augustinus et al., 2008). This observed decline correlates with human arrival to the New Zealand landscape (ca. 800 yrs. BP) and subsequent increase in anthropogenic fire activity (McIntosh et al., 2005; McGlone et al., 1995; McGlone, 2001; Ogden et al., 1998; Perry et al., 2014). This highlights that: 1) rainforest would likely dominate Holocene pollen records at the mid-latitudes of the Southern Hemisphere under 'natural' conditions; and 2) anthropogenic burning has an observable impact on rainforest vegetation – notably reducing and converting densely forested areas to open grasslands, and promoting fire-adapted vegetation (McIntosh et al., 2005; McGlone et al., 1995; McGlone, 2001; Jackson, 1999; Fletcher and Thomas, 2010). Thus, suppressed rainforest capture across western Lutruwita throughout the Holocene is regarded as an anomaly (Fletcher and Thomas, 2010). As such, the presence of open fire promoted vegetation (e.g., buttongrass moorland), which has persisted throughout the Holocene, rather than expected rainforest vegetation, is considered the result of planned and sophisticated application of fire to the landscape by the Palawa (Mariani et al., 2017; Pascoe, 2018; Gammage, 2011; Thomas, 2011).

Our results highlight the effectiveness of such timed ignitions by the Palawa, and further support the hypothesis that western Lutruwita is now a neglected cultural landscape, not a 'wilderness' (DCCEEW, 2023; UNESCO World Heritage Centre, 2021). A failure to recognise Indigenous agency in landscape creation results in misguided management paradigms, such as 'wilderness', that can actively degrade ecosystem and landscape integrity, further leading to increased catastrophic wildfires and biodiversity loss (Fletcher et al., 2021a, 2021b; Crabtree et al., 2019; Watson et al., 2018). Fires across western Lutruwita are predicted to intensify in both frequency and magnitude as temperature and aridity rapidly increase across southeast Australia (IPCC et al., 2022; Harris et al., 2018). As such, failing to recognise western Lutruwita as a cultural (and cared for, curated, managed) landscape in the current 'fire crisis' may have extreme negative ramifications for the future of this juxtaposed mosaiced landscape of flammable buttongrass moorland and highly fire sensitive taxa, e.g., *Athrotaxis cupressoides* (Pencil Pine) and *A. selaginoides* (King Billy Pine) (IPCC et al., 2022; Fletcher et al., 2021a; AFAC, 2016, 2019). By comparing the analogues of Darwin Crater and Lake Selina (that encompass pre-human and human presence in Lutruwita), it is apparent that, until their forced removal (and cessation of cultural practices including application of fire), western Lutruwita was being actively managed by the Palawa, who suppressed forest expansion mitigating biomass accumulation (read: fuel) thus reducing flammability (and promoting biodiversity) (Fletcher et al., - in review; Fletcher et al., 2021c; Adeleye et al., 2021, 2022; Mariani et al., 2022; Bowman, 1998). This study provides baseline evidence and highlights the need for appropriate and ongoing land management of western Lutruwita under climate warming scenarios.

5. Conclusion

The arrival of humans to Lutruwita (ca. 43ka; Cosgrove, 1999) and the systematic application of fire to the landscape, that was and remains one of the principal means through which people engage with the natural world, fundamentally altered the landscape of Lutruwita. Our data demonstrate that, rather than a 'wilderness', the TWWHA is in fact a cultural landscape. It also refutes the colonial myth that Australia was *'Terra Nullius'* at the time of British invasion. Our data present a way forward for those who attempt to understand the evolution of the

Australian landscape. Understanding the impact of Aboriginal arrival on this continent requires understanding of what the continent was like prior to human arrival and during equivalent climatic envelopes.

Author contributions

Conceptualisation, S.C., M-S.F., A.L-P and J-H.M.; methodology, S.C., M-S.F., A.L-P., M.M., J-H.M., and P.S.G.; investigation, S.C.; formal analysis, S.C., M-S.F., A.L-P., J-H.M, M.M., and P.S.G.; writing-original draft, S.C., M-S.F. and A.L-P.; writing – review and editing, S.C., M-S.F., A.L-P., P.S.G., J-H.M., H.H., D.A.H., M.M.; visualisation, S.C., M-S.F. and A.L-P; supervision, M-S.F., A.L-P., and J-H.M.; project administration, M-S.F. and A.L-P.; funding acquisition, M-S.F., A.L-P. and S.C. All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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