

Assessing Pleistocene–Holocene climatic and environmental change in insular Near Oceania using stable isotope analysis of archaeological fauna

PATRICK ROBERTS,^{1,2,3*} SEAN HIXON,² REBECCA HAMILTON,^{1,4} MARY LUCAS,² JANA ILGNER,² SARA MARZO,² STUART HAWKINS,⁴ SINDY LUU,^{5,6} CHRIS GOSDEN,⁷ MATTHEW SPRIGGS⁸ and GLENN SUMMERHAYES^{3,4,6}

¹isoTROPIC Research Group, Max Planck Institute of Geoanthropology, Jena, Germany

²Department of Archaeology, Max Planck Institute of Geoanthropology, Jena, Germany

³School of Social Science, The University of Queensland, Brisbane, Australia

⁴College of Asia and the Pacific, The Australian National University, Canberra, Australia

⁵Department of Anatomy, School of Biomedical Sciences, University of Otago, Dunedin, New Zealand

⁶Department of Archaeology, University of Otago, Dunedin, New Zealand

⁷School of Archaeology, University of Oxford, Oxford, United Kingdom

⁸School of Archaeology and Anthropology, College of Arts and Social Sciences, The Australian National University, Canberra, Australia

Received 3 November 2022; Revised 24 April 2023; Accepted 11 June 2023

ABSTRACT: In comparison to temperate and arid regions, environmental responses to the Last Glacial Maximum and the Terminal Pleistocene and Holocene boundary remain poorly known for many parts of the tropics, making it challenging to unravel human–landscape interactions across this timeframe. This is particularly the case in insular Near Oceania, where sea-level fluctuations and potential changes in forest cover may have had major impacts on hunter–gatherer populations. Here, we apply stable carbon and oxygen isotope analyses to small-mammal teeth from four Pleistocene–Holocene (spanning from 29 000 years ago to the late Holocene) sequences in the Bismarck Archipelago to reconstruct changes in environments directly exploited by human populations in this part of the world. Our results show a subtle response of tropical habitats in Near Oceania to relatively arid conditions during the late-glacial period, something that has also been observed at sites in South and Southeast Asia, followed by a Terminal Pleistocene–Holocene expansion of tropical forest cover. Nevertheless, site-based variability in environmental responses across this period highlight the need for more multidisciplinary studies of human occupation sequences in a region that is becoming increasingly central to exploring human adaptations, environmental modifications and social network development over the past 20 000 years. © 2023 The Authors *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

KEYWORDS: Archaeology; climate change; Oceania; stable isotope analysis; tropical forests

Introduction

The Last Glacial Maximum (LGM) and the subsequent Terminal Pleistocene to Holocene transition together represent the most significant period of pre-industrial global climate change to have impacted populations of our species following their dispersal to almost all of the world's continents by ~20 000 years ago (Williams *et al.*, 2013; Bourgeon *et al.*, 2017; Roberts and Stewart, 2018). The Last Glacial period (which comprises Marine Isotope Stages from 5d to 2, representing a time-span of 115–11.7 ka; Rasmussen *et al.*, 2006) is generally characterised as a time of cooler and drier conditions which reached their peak during the LGM, when ice sheets were at their greatest extent and sea levels were at their lowest (Rasmussen *et al.*, 2014; Waelbroeck *et al.*, 2002; Wren and Burke, 2019). Based on glacier records, marine oxygen isotope records and records of sea-level change, the timing of the LGM has been constrained to 30–18 ka (Lambeck *et al.*, 2014) or, more precisely, 26.5–20 ka (Clark *et al.*, 2009), and has been linked to a clear decline in tree pollen, grassland expansion,

and cold and dry conditions in mid- and high-latitude Europe (Bartlein *et al.*, 2011; Helmens, 2014; Kageyama *et al.*, 2013). In temperate regions, fluctuations in temperature at the LGM (with estimated temperatures as low as 6°C cooler than today (Tierney *et al.*, 2020)) and the subsequent Terminal Pleistocene–Holocene (~11.7 ka) transition, have been associated with significant changes in human behaviour, including demographic contraction and expansion (Posth *et al.*, 2016; Wren and Burke, 2019), site abandonment, technological change and dietary shifts (Straus, 2016; Burke *et al.*, 2018; Stiner *et al.*, 2022). Meanwhile, in high-latitude regions prone to aridity, late-glacial fluctuations in precipitation (Fuhrmann *et al.*, 2020) have been argued to have led to similar adaptive challenges and human responses (Beuning *et al.*, 2011; Munt *et al.*, 2018).

By contrast, the timing and nature of climate-linked environmental changes during the LGM and subsequent transition into the Holocene are relatively poorly understood for many parts of the tropics (Roberts, 2019). Although often considered less extreme than elsewhere, LGM temperature minima of c. 4°C cooler than present have been recorded for tropical Africa, Amazonia and Sahul (Bonnefille *et al.*, 1990; Thompson *et al.*, 1995; van der Kaars, 1998; Kull *et al.*, 2008;

*Correspondence: Patrick Roberts, as above.
Email: roberts@shh.mpg.de

Hope, 2009; Hunt *et al.*, 2012), with fluctuations in glacier extents also documented in high altitude contexts (Bromley *et al.*, 2016). Meanwhile, changes in total annual precipitation and seasonality, as well as CO₂, during the LGM (Mayle *et al.*, 2004) have been associated with altered extents and structures of tropical forest habitats (Haberle, 2003, 2005; Bird *et al.*, 2005; Anhof *et al.*, 2006; Blome *et al.*, 2012). In low latitude island contexts, such as those of Island Southeast Asia, changes in late-glacial sea level likely provided an additional geographical factor which could either buffer or accentuate changes in rainfall (Cannon *et al.*, 2009; Rabett, 2012; Hawkins *et al.*, 2017). For many equatorial regions, there remain significant debates relating to the onset and termination of the environmental effects of the LGM (Baker *et al.*, 2001; Smith *et al.*, 2005) and the nature and degree of ecosystem change (Wurster *et al.*, 2010; Hamilton *et al.*, 2019). The lack of consistent environmental baseline data makes it challenging to develop hypotheses of human responses to climatic changes during this period. For example, Rabett (2012) has proposed that an early expansion of tropical rainforest following the LGM is associated with specialised hunting adaptations in Island Southeast Asia, though others have argued that forests remained fragmented for a significant period following the LGM in the region (Cannon *et al.*, 2009).

The insular setting of Near Oceania presents an important, but relatively neglected, case study of late-glacial human–environment interactions. Since their arrival in highland New Guinea ~45 ka, Late Pleistocene human populations adapted to Near Oceanian tropical forests (Summerhayes *et al.*, 2010, 2017). However, subsequent movement of human populations into the islands beyond the Sahul landmass (i.e. the Bismarck Archipelago) by ~44 ka would have presented additional challenges in the context of insular forests, depauperation of large fauna, and the navigation of oceanic currents and coastal settings (Gosden and Robertson, 1991; Summerhayes and Ford, 2014). Researchers have suggested ‘pulses’ or phases of human subsistence and technological change (Leavesley and Allen, 1998; Allen, 2000; Leavesley, 2006), extending from first arrival through the Holocene period. The perceived difficulty of obtaining animal and plant resources in the interior rainforests of these islands has been used as a basis for models which assume that initial occupation by small groups of hunter–gatherers focused on reef and coastal settings (Enright and Gosden, 1992), although exploitation of bats and reptiles has been documented from Late Pleistocene sequences (Pavlidis, 2004; Leavesley, 2006). The next major ‘pulse’ of activity is then dated to the LGM ~20 ka when the island of Manus was thought to have been occupied, regional social networks intensified (Summerhayes and Allen, 1993), marine resource use intensified, and wild mammals were moved to New Ireland from New Britain (Gosden and Robertson, 1991). There is also increasing evidence at this time for human exploitation of rainforest fauna, including birds (Steadman *et al.*, 1999; Pavlidis, 2004). There then appears to be a hiatus in the occupation of some cave sites until the Terminal Pleistocene, when an expansion of populations and increasingly intense utilisation of the landscape has been suggested (Shaw *et al.*, 2020; Shaw, 2021).

This ‘pulse’ or phase model of occupation of insular Near Oceania has been debated and reworked in a number of ways (e.g. in terms of chronology and the nomenclature used to define different ‘phases’) (Specht, 2005). For example, recent data suggest that Pamwak on Manus may have been occupied long before the LGM (Roberts *et al.*, 2022). Nonetheless, such models encapsulate the potential significance of changing subsistence and settlement patterns in the region and raise the question as to their relationship with late-glacial climate and

environmental change. On nearby New Guinea, for example, vegetation changes across the Pleistocene to Holocene transition have been associated with the onset of more intensive human forest management and changing settlement patterns (Haberle, 2005). A lack of well-dated palaeoenvironmental records for insular Near Oceania has hindered such discussions, however. Here, we apply stable carbon and oxygen isotope analysis to faunal tooth enamel from the Pleistocene–Holocene sites of Matenkupkum, Buang Merabak and Matenkupkum on New Ireland, combined with an evaluation of the published data from Pamwak on Manus Island (Roberts *et al.*, 2022), to explore climate-linked environmental changes in the Bismarck Archipelago from ~29 ka to the present. Stable isotope analysis of fauna, particularly small mammals, which are sensitive to local environmental change, has been shown to provide direct insights into forest extent in the tropics (Roberts *et al.*, 2015, 2017, 2020a, 2020b). Importantly, as this proxy comes from ‘on-site’, the results can be directly linked to records of human subsistence (e.g. zooarchaeology, archaeobotany) and cultural behavioural (e.g. lithic technology) change. We compare our results with the available site-based records of human occupation, as well as regional climate change proxy records, which span the LGM and Terminal Pleistocene–Holocene, to assess the degree to which observed environmental changes may have placed novel pressures on human populations relative to other parts of the world.

Background

Archaeological and environmental context of Pleistocene–Holocene island Near Oceania

Situated northeast of New Guinea, the Bismarck Archipelago comprises hundreds of small islands as well as three larger islands, New Britain, New Ireland and Manus (Leavesley, 2006). Bathymetric data show that the archipelago was never joined to New Guinea in the Pleistocene, nor were any of the three larger islands ever connected to each other (Leavesley, 2006). The islands of both the Bismarck and neighbouring Solomon Archipelago primarily consist of a volcanic basement overlain by varying amounts of limestone and sandstone (Leavesley, 2006). All of these islands today are dominated by dense tropical rainforest vegetation and experience a wet, warm climate (Leavesley, 2006) (Fig. 1). Movement out from the Sahul landmass into the Bismarck Archipelago is currently dated to 44–39 ka based on archaeological excavation of the sites of Matenkupkum and Buang Merabak on New Ireland (Leavesley and Chappell, 2004; Summerhayes and Ford, 2014). Meanwhile, archaeological research at Yombon and Kupona Na Dari provides evidence for a similarly early occupation of New Britain (Pavlidis, 2004; Torrence *et al.*, 2004). Although these early movements would have taken place during a sea-level low stand, sea crossings of at least 50 km would have been required. The distance from mainland New Guinea to New Britain is between 90 and 100 km, though an island in between, Umboi, would have provided a staging point. The period ~30–20 ka currently appears to be one of expanded settlement of this island region. Occupation of Kilu in the northern Solomon Islands dates to 33–31 ka (Wickler, 2001), while occupation of the sites of Balof 2 and Panakiwuk on New Ireland date to 22–20 ka (Leavesley, 2006). New chronological modelling of Pamwak on Manus Island places the onset of occupation of this island at ~29–24 ka (Roberts *et al.*, 2022). Nevertheless, documentation of a considerable cultural deposit below the dated levels hints at the possibility

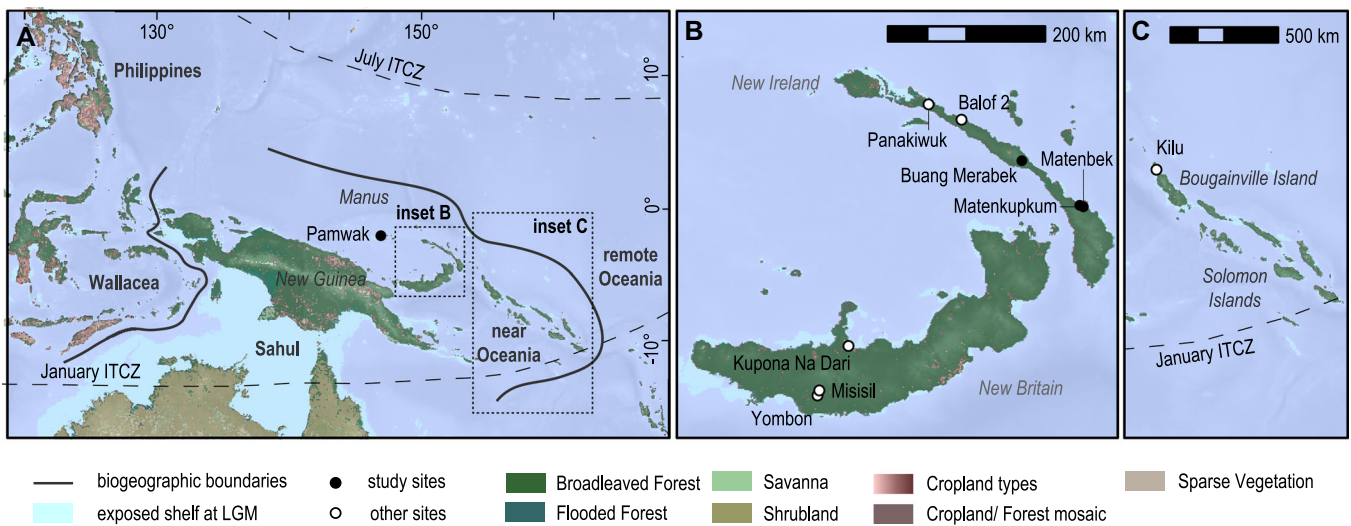


Figure 1. Map of the sites sampled (black circles) and discussed (white circles) in the text within the wider context of Island Southeast Asia and Near Oceania. Panels B and C show close-ups of the Bismarck and Solomon Archipelagos, respectively. 300 m global land cover data from 2019 (ESA, 2017) are shown, highlighting the domination of tropical forest on these archipelagos today. The average position of the Inter-Tropical Convergence Zone in July and January (dashed lined) are adapted from Liu *et al.* (2015), and mean sea-level data from the Last Glacial Maximum, are mapped from Spratt and Lisiecki (2016). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/jqs.3555)]

that Manus may have been colonised considerably earlier (Fredericksen *et al.*, 1993).

A reduction in human activity has been identified on New Ireland and New Britain from ~20 ka based on a reduction of the number of occupied sites and archaeological materials (Leavesley, 2006). However, the exact timing of the hiatus seems to vary, with occupation persisting longer in the interior rainforests of New Britain than in coastal settings (Pavlidis, 1999). There is then a clear intensification of human activity at sites across the Bismarck and Solomon Archipelagos between 15 and 10 ka (Pavlidis and Gosden, 1994; Pavlidis 2004; Wickler, 2001; Leavesley, 2006). Renewed settlement is dated to 16 ka and 14 ka at Matenkupkum and Buang Merabak, respectively (Leavesley, 2006), and Panakiwuk on New Ireland was first occupied between 15 and 13 ka (Leavesley, 2006). Meanwhile, Yombon, Kilu and Misilil Cave were all occupied, or re-occupied, between 12 and 10 ka (Specht *et al.*, 1981; Pavlidis, 1999; Wickler, 2001). At 12 ka, the New Ireland sites also show the highest intensity of artefact deposition (Spriggs, 1993; Allen and Gosden, 1996). Whether these changes in settlement pattern are climatically and environmentally driven, and whether they reflect real abandonment versus a shift in landscape use, remains debated (Specht, 2005; Leavesley, 2006).

A review of palaeoenvironmental proxy records from neighbouring New Guinea and Island Southeast Asia indicates that the LGM was likely cooler (-5°C), more seasonal and drier than the present due to a weaker, variable Indonesian–Australian summer monsoon and increased continentality driven by low sea levels (Fig. 1) (Haberle *et al.*, 2001). Variable monsoon conditions persisted after the LGM, with negative Northern Hemisphere to Southern Hemisphere temperature gradients between 18 and 12 ka driving a southwards displacement of the Inter-Tropical Convergence Zone (McGee *et al.*, 2014). The relatively dry, seasonal climates of the LGM have been associated with more open grassland and seasonal forest habitats in lowland Wallacea (Dam *et al.*, 2001; Hamilton *et al.*, 2019; Hope, 2001; Russell *et al.*, 2014; Stevenson, 2018; Wicaksono *et al.*, 2015; Wicaksono *et al.*, 2017), and the downslope expansion of montane forest in lowland New Guinea and on the Sahul Shelf (Hope and Tulip, 1994; Kaars *et al.*, 2000). Increased temperatures (Haberle *et al.*, 2001) and effective moisture are

then documented from 17–16 ka to the Holocene boundary and are attributed to the expansion of closed forest across the region's lowlands (Hamilton *et al.*, 2019; Russell *et al.*, 2014). Despite these general trends, regional and local palaeoclimatic and palaeoecological reconstructions have shown that they may not apply everywhere. Notably, deglacial monsoon precipitation remained variable, with some records indicating a cool, dry period ~12.9–11.7 ka (Haberle *et al.*, 2001; Hamilton *et al.*, 2019) and others showing relative stability across this period (Russell *et al.*, 2014). Even within Near Oceania, the exact timing and impact of late-glacial cooling, drying and heightened seasonality on different human populations across the region remains disputed (Hope, 2001, 2005; O'Connor and Aplin, 2007).

Archaeological and zooarchaeological evidence from the Bismarck Archipelago and Solomon Islands suggests some changes in landscape use in island Near Oceania over time. Early occupations from ~45 to 29 ka appear to be associated with coastal exploitation (Gosden and Robertson, 1991). Meanwhile, from 25 to 20 ka there appears to have been an intensification of both marine resource use and interior rainforest exploitation, with zooarchaeological records from Yombon, Buang Merabak and Matenkupkum highlighting the human use of forest birds and bats (Pavlidis, 2004; Leavesley, 2006). Stable carbon isotope data from humans from Pamwak and Matenkupkum further support the intensive use of tropical forest resources during the Terminal Pleistocene (Roberts *et al.*, 2022). Significantly, first at 20 ka and then at 15–12 ka, there appears to be an intensification in social networks in the region, with contacts between the Bismarck Archipelago and New Guinea evidenced by obsidian exchange (Leavesley, 2006). Meanwhile, the northern common cuscus *Phalanger orientalis* and, later, a bandicoot (*Echymipera cf. kalubu*) and spotted cuscus (*Spiloscus kraemeri*) were moved between islands, presumably as a source of protein (Gosden and Robertson, 1991; Spriggs, 1997). It is also during the Terminal Pleistocene and Early Holocene that records of deliberate human modification of tropical forests have been presented for New Ireland and the Solomon Islands on the basis of archaeobotanical evidence (Gosden, 1995; Spriggs, 1997; Barton and Torrence, 2015), with similar patterns suggested for New Guinea (Haberle, 2003).

Stable isotope approaches to zooarchaeological assemblages in Near Oceania

Stable carbon and oxygen isotope analysis of the tooth enamel of fauna recovered from archaeological sites has long been utilised as a palaeoenvironmental proxy, including specifically within the context of human dispersals and adaptations to variable Pleistocene environments (e.g. Roberts *et al.*, 2017a, 2020b). In the tropics, stable carbon isotope analysis of mammalian faunal enamel primarily documents the amount of C₃ and C₄ biomass in the diet. Low faunal $\delta^{13}\text{C}$ suggests reliance on C₃ resources, which dominate in forest settings, relative to C₄ resources available in open areas including tropical grasslands (Lee-Thorp and van der Merwe, 1987; Cerling *et al.*, 2004; Levin *et al.*, 2008). These environmental factors are predictably observed in mammalian tooth enamel (Lee-Thorp and van der Merwe, 1987; Cerling and Harris 1999), leading to values of approximately c. -12‰ and c. -4–0‰ for terrestrial fauna relying on C₃ resources and C₄ resources in pre-industrial contexts, respectively (Lee-Thorp *et al.*, 1989; Levin *et al.*, 2008). In dense tropical forest settings, faunal enamel for animals feeding on C₃ vegetation have even lower $\delta^{13}\text{C}$ values as a consequence of the influences of low light exposure (Farquhar *et al.*, 1989) and recycled CO₂ on photosynthesis (Van der Merwe, Medina, 1991). The stable oxygen isotope values of animal tissues can provide additional palaeoecological information about water and food. In tropical ecosystems it has been shown that vegetation $\delta^{18}\text{O}$ reflects evaporative potential or the source-effect of rainfall (Buchmann *et al.*, 1997; Buchmann and Ehleringer, 1998), with dense, humid canopies yielding lower $\delta^{18}\text{O}$ values than more evaporative areas. Animals which obtain the majority of their water requirements from plants will particularly strongly reflect those environmental factors that influence plant transpiration and plant $\delta^{18}\text{O}$ (Kohn *et al.*, 1996; Levin *et al.*, 2006; Carter and Bradbury, 2015).

Small mammals are becoming an increasingly popular focus for stable isotope applications thanks to their abundance, small feeding and drinking ranges, and high fidelity to habitat types (Grimes *et al.*, 2008; Jeffrey *et al.*, 2015; Roberts *et al.*, 2017b). Based on the above-discussed climatic context for Southeast Asia and New Guinea, we hypothesise that lowland tropical forests retreated during cooler, drier glacial periods, when pCO₂ was also low, making way for the expansion of tropical grasslands and shrublands (Bird *et al.*, 2005; Jolly and Haxeltine, 1997; Mayle *et al.*, 2004) or seasonal forest (Hamilton *et al.*, 2019). These climatic and environmental changes would be expected to have corresponding impacts on faunal diets and ingested water, with $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values increasing with more open habitats and greater aridity, respectively. Based on existing palaeoenvironmental reviews (Haberle *et al.*, 2001; O'Connor and Aplin, 2007), it might also be expected that such changes would be 'dampened' on the coast relative to interior and upland contexts, with local heterogeneity. Nevertheless, Roberts *et al.* (2020b) found environmental changes, notably more humid conditions and the expansion of tropical forest in the Terminal Pleistocene based on the isotopic analysis of small terrestrial fauna on Alor and Timor in Wallacea. Within the context of Sahul, Roberts *et al.* (2017b) documented relative stability in closed montane forest habitats across the Terminal Pleistocene–Holocene transition based on stable carbon and oxygen isotope analyses of fruit bats (*Aproteles bulmerae*), cuscus (Phalangeridae), ring-tailed possums (Pseudocheiridae) and macropods (Macropodidae) from the site of Kiowa in Highland New Guinea. This supports observations of forest stability during the LGM from lowland New Guinea pollen records (Hope and Tulip, 1994).

In late-glacial archaeological contexts such as those studied here, it is important to take into account the human selectivity of fauna, faunal feeding and drinking strategies (Roberts *et al.*, 2017b), and the potential for changes in the $\delta^{13}\text{C}$ of CO₂ between the Pleistocene and Holocene (Hare *et al.*, 2017).

Methods

Sites and samples

We sampled a total of 88 small-mammal teeth from the New Ireland sites of Buang Merabak ($n=19$), Matenbek ($n=25$) and Matenkupkum ($n=45$) for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analysis and undertook fresh evaluation of the published $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ from 59 terrestrial fauna from the site of Pamwak on Manus Island (Fig. 1). The full list of samples and their contexts can be found in Supplementary Data Table 1, while further site and stratigraphic information is available in Supplementary Note 1. Chronologies for the samples were based on the latest published literature and subsequently calibrated using the IntCal20 and Marine20 curves (Heaton *et al.*, 2020; Reimer *et al.*, 2020) (Supplementary Data Table 2) (see also Supplementary Note 1 for details). Sampled phases 2 and 3 at Buang Merabak date to 13.2–7.8 and 23.5–19.2 ka, respectively (Leavesley, 2004; 2017; Rosenfeld, 1997), while phases 1, 3 and 4 at Matenbek represent 1.9–1.3 ka, 8.6–8.1 ka and 24.0–20.7 ka, respectively (Allen *et al.*, 1989; Freslov, 1989). Matenkupkum phases 1 to 6 represent the longest studied sequence extending from 'modern' ages through to 25.3–23.9 ka, with phases 6 and 5–2 covering the LGM to the terminal Pleistocene–Holocene transition, respectively (Gosden and Robertson, 1991). The published Pamwak sequence from Unit A to Unit E was recently recalibrated and spans 6.7–2.0 ka to 29.0–24.0 ka (Roberts *et al.*, 2022). Therefore, together, the sample set offers an important opportunity to track environmental changes relevant to human hunter-gatherers across the LGM and into the Holocene within a Bismarck Archipelago context.

Mammal identifications were facilitated by comparisons with specimens from the ANU Archaeology and Natural History Osteology Laboratory and University of Otago's reference collections. The fauna sampled at Buang Merabak, Matenbek and Matenkupkum are all dominated by the northern common cuscus *Phalanger orientalis*, following its arrival around 20 000 years ago, and an unidentified species of rat (see Supplementary Data Table 1). *P. orientalis* is today found in primary tropical forests ranging from gallery rainforest to montane rainforest (Flannery, 1995; Leary *et al.*, 2016). Nevertheless, it most frequently occurs in disturbed habitats such as secondary forests and gardens (Flannery, 1995), making it a potentially sensitive taxon for tracking environmental change in the past. Its sensitivity to climatic changes may be further enhanced by its status as an arboreal folivore, though it is also known to consume fruit (Flannery, 1995). The published Pamwak dataset, by contrast, includes samples of bats, the murids *Rattus detentus* and *Melomys matambuai*, marsupial *Spiloglossus kraemeri* and a bandicoot *Echymipera cf. kalubu* (Supplementary Data Table 1), which was introduced by humans to Manus from either New Guinea or New Britain (Flannery, 1995; Helgen and Flannery, 2004) (Supplementary Data Table 1). This latter taxon is omnivorous and prefers closed rainforest and montane forest habitats today. See Supplementary Note 2 for more background information on sampled animal feeding behaviours where available.

Stable isotope analysis

The collection of the tooth enamel samples followed protocols developed by Jeffrey *et al.* (2016) and applied by Roberts *et al.* (2017b) in an Oceanian context. This involved the cleaning of the exterior surfaces of all teeth using aluminium sand blasting to remove any external material. The roots of molar teeth were then separated and the tooth was then crudely sectioned in order to be able to clean away dentine and dirt from inside the tooth. Due to the fact that the sampled teeth are very small, each tooth was crushed using an agate mortar and pestle in order to produce enough enamel powder for pretreatment and analysis. While efforts were made to minimise dentine contamination, given the relatively short formation times for these teeth it is also reasonable to assume that any remaining dentine apatite would represent the same period and conditions as the enamel apatite (Roberts *et al.*, 2017b). Previous Fourier Transform Infrared Spectroscopy work on samples from Pamwak and Pleistocene–Holocene sequences in Wallacea provide high confidence that diagenesis is unlikely to be a major factor in interpreting the isotopic results (Roberts *et al.*, 2020b, 2022).

To reduce the risk of contamination from diagenetic alteration still further, all enamel powder was pretreated using a consistent, published technique which is focused on the removal of organic and secondary carbonate contaminants (Roberts *et al.*, 2015, 2020a, 2020b). This involves the sample being submerged in 1.5% sodium hypochlorite for 60 min, followed by three rinses in purified H₂O and centrifugation. 0.1 M acetic acid is then added to the sample for 10 min, followed by another three rinses in purified H₂O. Samples are then lyophilised in a freeze-drier for a period of 3 h. Following reaction with 100% phosphoric acid, gases evolved from the samples were analysed for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ using a Thermo Gas Bench 2 connected to a Thermo Delta V Advantage Mass Spectrometer housed at the Max Planck Institute for Geoanthropology. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values were compared against International Standards (IAEA-603 ($\delta^{13}\text{C}=2.5\text{‰}$; $\delta^{18}\text{O}=-2.4\text{‰}$); IAEA-CO-8 ($\delta^{13}\text{C}=-5.8\text{‰}$; $\delta^{18}\text{O}=-22.7\text{‰}$); USGS44 ($\delta^{13}\text{C}=-42.2\text{‰}$) and an in-house standard (MERCK ($\delta^{13}\text{C}=-41.3\text{‰}$; $\delta^{18}\text{O}=-14.4\text{‰}$)). Replicate analysis of MERCK standards suggests that the measurement error is c. $\pm 0.1\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.2\text{‰}$ for $\delta^{18}\text{O}$. Overall measurement precision was additionally studied through the measurement of repeat extracts from a bovid enamel standard ($n=20$, $\pm 0.2\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.3\text{‰}$ for $\delta^{18}\text{O}$).

Statistical analysis

We applied Levene's test for equality of variance in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ between phases at each site, and we used the Shapiro–Wilk test to assess normality. Where variance was unequal and the data were non-normally distributed, and where only two phases existed or where only two phases had sufficient >3 samples, we applied a Mann–Whitney U-test to compare differences between phases in terms of median $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. For sites with unequal variances and non-normal data distribution that had more than two phases, we applied a Kruskal–Wallis test followed by pairwise Wilcoxon tests. Where variance was equal and the data were normally distributed, and where only two phases existed or where only two phases had sufficient >3 samples, we applied Student's *t*-test. Where these conditions were met but where more than two phases could be compared, we applied a one-way ANOVA followed by Tukey's honestly significant difference *post hoc* comparisons. To explore how $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ covary while controlling for taxon and site, we constructed a general linear model using

the R package *glmulti*. Only taxa with $n > 3$ were included in the generalised linear model. All statistical analyses were conducted using the free R software (R Core Team, 2013).

Results

The results of the date calibration for all of the sampled phases are shown in Supplementary Data Table 2, and they represent a significant resource for future discussions of prehistory and palaeoenvironmental change in the Bismarck Archipelago. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ results for the analysed small mammals are shown in Supplementary Data Table 1. We briefly present the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ for each site chronology before returning to this more extensive temporal comparison. For the 'modern' samples from Matenkupkum, the measured $\delta^{13}\text{C}$ values have been corrected by $+1.5\text{‰}$ to account for the fossil fuel effect (Friedli *et al.*, 1986) and to bring them into line with the other Pleistocene–Holocene data.

Buang Merabak

The $\delta^{13}\text{C}$ values range between -18.4 and -12.1‰ at Buang Merabak, while $\delta^{18}\text{O}$ values range between -11.9 and -4.5‰ . There are very small increasing trends in median values in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ between phases 3 (23.5–19.2 ka) and 2 (13.2–7.8 ka) (Fig. 2, Supplementary Fig. 2). However, these are not statistically significant and are probably driven by a single *P. orientalis* individual in phase 3 with very low values. The variance in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ is different between the two phases defined at the site ($F(13,4)=0.06$ and 0.14 , respectively, with $p < 0.01$), and Mann–Whitney U-tests suggest that the median $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values do not differ between phases ($W=66$, $p=0.10$ and $W=39$, $p=0.65$, respectively).

Matenbek

The $\delta^{13}\text{C}$ values range between -14.2 and -11.1‰ at Matenbek, while $\delta^{18}\text{O}$ values range between -6.2‰ and -3.9‰ . No clear trend can be observed in $\delta^{13}\text{C}$ values between phases 4 (24.0–23.1 ka), 3 (8.6–8.1 ka) and 1 (7.4–6.7 ka). A slight decrease in $\delta^{18}\text{O}$ is observed from phase 4 to phase 3 (Fig. 2, Supplementary Fig. 3). Only two of the Matenbek phases have an $n > 3$. The variance in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ is similar between these two phases ($F(9,13)=1.19$, $p=0.76$ and $F(9,13)=0.90$, $p=0.90$, respectively), and Shapiro–Wilk tests suggest that each distribution is normally distributed. *T*-tests

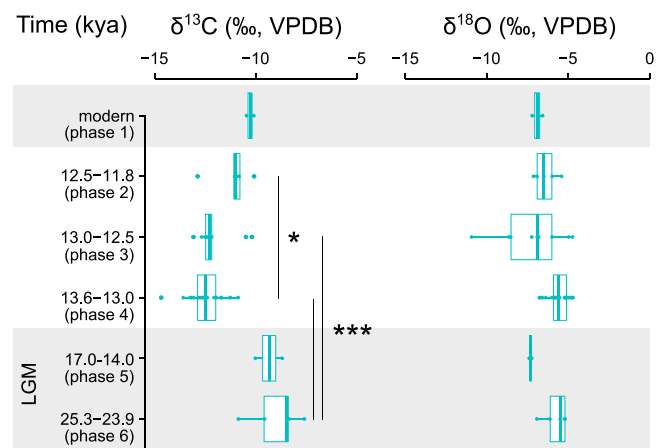


Figure 2. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ measurements of small mammals at Matenkupkum, New Ireland, divided by phase. Results of *post hoc* Tukey test are shown, with $*p \leq 0.05$ and $***p < 0.001$. [Color figure can be viewed at wileyonlinelibrary.com]

suggest that the difference in mean $\delta^{13}\text{C}$ between phases is non-significant (Student $t(22) = -0.65$, $p = 0.52$), and the same is true for $\delta^{18}\text{O}$ ($t(22) = -0.49$, $p = 0.63$).

Matenkupkum

The $\delta^{13}\text{C}$ values range between -14.7 and -7.6% at Matenkupkum, while $\delta^{18}\text{O}$ values range between -10.9 and -4.7% . Some trends in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ are noticeable throughout the sequence. In terms of $\delta^{13}\text{C}$, values are highest during phase 6, dated to the LGM, before declining in phase 5 to their lowest values in phases 4 and 3. The values then subtly increase again in phases 2 and 1 (Figs 2 and 3). For the purpose of statistical testing, this site includes data from four phases with $n > 3$ (phases 2, 3, 4 and 6). A one-way ANOVA shows significant differences in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ among these phases ($F(3,36) = 18.45$ and 4.73 , respectively, with $p < 0.0007$). The model for $\delta^{13}\text{C}$ passes Levene's test for equal variance ($F = 0.22$, $p = 0.88$) and Shapiro–Wilk tests suggest that only the phase 3 data are not normally distributed ($W = 0.80$, $p = 0.02$). *Post hoc* Tukey tests suggest that mean $\delta^{13}\text{C}$ values significantly differ between all phases with $n > 3$ ($p < 0.05$), with the exception of phase 4 to 3 and phase 3 to 2 (Supplementary Table 3). The model for $\delta^{18}\text{O}$ failed Levene's test ($F = 3.87$, $p = 0.02$), but significant differences in $\delta^{18}\text{O}$ among phases is supported by a Kruskal–Wallis test ($H(3) = 8.41$, $p = 0.04$), with phase 4 appearing to stand out. Nevertheless, *post hoc* Wilcoxon tests fail to identify significant differences in $\delta^{18}\text{O}$ between phases, and this is true regardless of the choice of p -value correction (according to Bonferroni versus Benjamini and Hochberg, 1995).

Pamwak

The $\delta^{13}\text{C}$ values range between -24.8 and -10.3% at Pamwak, while $\delta^{18}\text{O}$ values range between -15.7 and -5.4% . There is a clear increasing trend in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values from the LGM Unit E to the Mid–Late Holocene Unit A (Figs 2 and 4). Pamwak has five phases with $n > 3$. One-way ANOVA suggests that there are significant differences in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ between these phases ($F(4,53) = 6.43$ and 7.57 , respectively, with $p < 0.001$). Both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ models fail Levene's test for equal variance ($F = 4.90$ and 4.06 , respectively, with $p < 0.006$), but significant differences in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ are further supported by Kruskal–Wallis tests ($H(4) = 23.04$ and 17.36 , respectively, with $p < 0.002$). *Post hoc* Wilcoxon tests suggest that Unit E has $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values that are significantly different from those of

Units A and B ($p < 0.03$ according to Bonferroni correction) (Supplementary Table 4). A less conservative approach with the same test suggests that $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values from Unit E are distinct from those of all other units ($p < 0.03$, with the exception of Unit C $\delta^{13}\text{C}$ data, with $p = 0.06$) and that the median $\delta^{13}\text{C}$ value from Unit A is significantly different from that in Unit D ($p = 0.05$).

Site and temporal comparison

While local trends are evident in the site data presented above, we sought to also compare the data from the sites together in an attempt to discern whether there were any overall temporal trends for the region as well as any site-specific sources of variation. The R package *glmulti* suggests that the model that most parsimoniously explains variation in $\delta^{18}\text{O}$ values includes predictors of $\delta^{13}\text{C}$, site, taxon and $\delta^{13}\text{C} \times \text{site}$ ($\text{AIC} = 398.90$). This model includes a significant direct effect of $\delta^{13}\text{C}$ on $\delta^{18}\text{O}$ values ($p < 0.0001$) (see Supplementary Table 5). As can be seen in Fig. 5, however, there is a clear impact of site and taxon on this relationship. A positive correlation in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ can be seen for Pamwak and Buang Merabak, but not at Matenkupkum and Matenkupkum where a weak negative correlation is visible. Together, this highlights the local heterogeneity observed between the sites.

One source of this variation could be the representation of different species at different sites. When the compiled dataset is divided by species, a positive correlation between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ is most visible for murids and *E. cf. kalubu*, with weaker positive trends for *P. orientalis* and negative correlations seen among other rodent samples and *Rattus* sp. Significantly, here the majority of murids, with the observed strong correlation between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, come from a single Unit at Pamwak. Although this could suggest a temporal trend, it also highlights how species-specific values may drive site-based trends. Indeed, the categories of *Rattus* sp. and murids could include potentially different unidentifiable species which could further increase this variability. A similar situation exists for Buang Merabak where one individual seems to be responsible for driving the strong trend. Indeed, if this individual is excluded then the Buang Merabak range becomes much more in keeping with the other sites.

The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ from all of the sites are shown together on the same temporal scale in boxplots in Fig. 5 to illustrate broad changes across the LGM and Terminal Pleistocene–Holocene transition. In this figure, both site-specific and broader regional trends are apparent. While no consistent temporal changes were found across all sites across the entire length of their sequences, relatively high $\delta^{13}\text{C}$ values can be seen in the 25.3–23.9 ka and 17.0–14.1 ka layers at Matenkupkum, while high $\delta^{18}\text{O}$ values are observed at Buang Merabak, Matenkupkum and Matenkupkum between 25.3 and 19.2 ka. The $\delta^{13}\text{C}$ values then remain relatively stable across the sites between 14.5 and 1.3 ka, with a potential further slight increase observed at Matenkupkum at 12.5–11.8 ka. $\delta^{18}\text{O}$ is more variable, with further increases seen in the record between 13.6 and 12.5 ka and again at 8.6–8.1 ka.

Discussion and conclusions

Our small-mammal $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data from the sites of Buang Merabak, Matenkupkum and Matenkupkum on New Ireland, and Pamwak on Manus Island, provide novel 'on-site' palaeoenvironmental records for exploring the effects of climate change on human behaviour in the island settings of Near Oceania across the LGM and Terminal Pleistocene–Holocene transition. We observe site-specific variation in the isotopic data and inferred environmental changes, with varying relationships

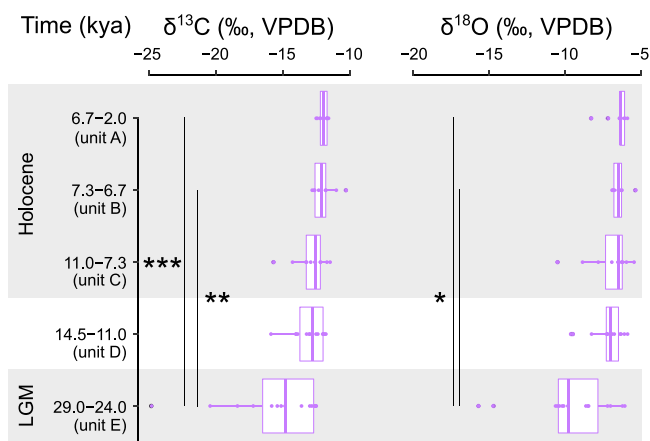


Figure 3. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ measurements of small mammals at Pamwak, Manus Island, divided by phase. Results of *post hoc* Mann–Whitney U-tests are shown, with Bonferroni corrected $*p \leq 0.05$, $**p < 0.01$ and $***p < 0.001$. [Color figure can be viewed at wileyonlinelibrary.com]

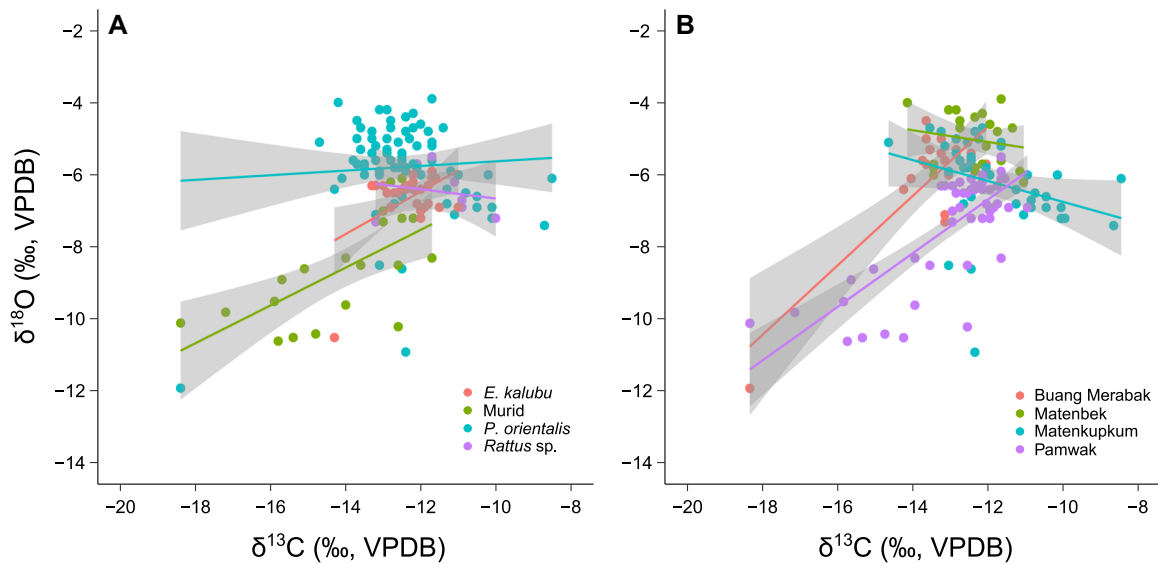


Figure 4. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ measurements with points coloured according to taxon (A) and site (B), with site- and taxon-specific regression lines (plus 95% confidence bands) included. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

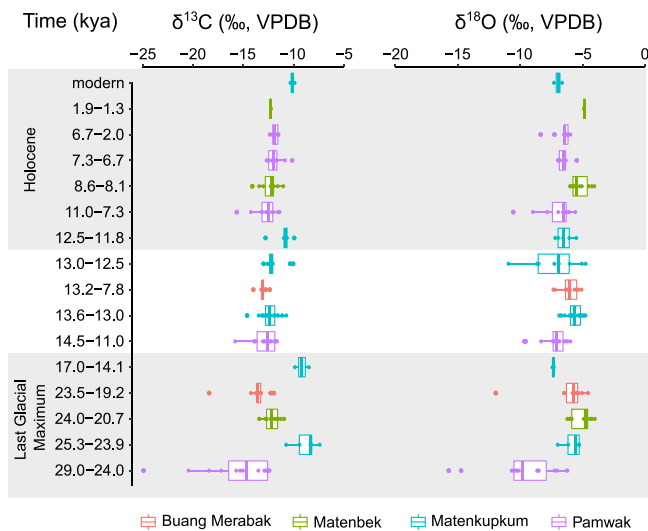


Figure 5. Summaries of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data from colour-coded sites, with distributions grouped and approximately ordered according to site-specific chronological periods (see Supplementary Note 1 for details). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ proxies, and thus vegetation and hydrological conditions. Data from the sites of Buang Merabak and Matenbek suggest clear stability between the LGM and the Terminal Pleistocene/Early Holocene and the Early Holocene, respectively. Meanwhile, the Matenkupkum record shows much more variability across the late-glacial period. At Pamwak, on Manus Island, the LGM actually appears to be the most forested and most humid period, with gradual drying and opening occurring into the Holocene. The scale of this local heterogeneity is, to some extent, unexpected. For example, Matenbek and Matenkupkum lie extremely close to each other, yet apparently show a discrepancy in environmental trends (stability at Matenbek and subtle variability at Matenkupkum).

Part of this inter-site variability is clearly taxon-related with certain murid samples at Buang Merabak and Pamwak likely driving strong trends. For the murids at Pamwak, it is possible that these small rodents utilised the more immediate environments of the limestone caves which were covered in rainforest, thus explaining their strong correlation between canopy-driven $\delta^{13}\text{C}$

(including very low values) and water-driven $\delta^{18}\text{O}$. The ‘outlier’ at Buang Merabak is a Phalanger individual and it may represent an animal brought from a particular local habitat by human hunters or from further afield (strontium isotope analysis would be needed to distinguish the two scenarios). This highlights the role that human selectivity (in terms of hunting area and exploited taxa) can play in isotopic variation from ‘on-site’ records. Indeed, at Pamwak, the observed trend of forest cover and humidity during the LGM, followed by Holocene forest opening and drying, has elsewhere been tentatively linked to deliberate anthropogenic intervention in the form of arboriculture and forest opening to boost resources (Gosden, 1995; Roberts *et al.*, 2022). Other sources of variability, particularly in terms of the relationship between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ at the different sites and changes through time could include relatively small sample sizes, variation in the source water impacting enamel $\delta^{18}\text{O}$ values, and the complex interplay between precipitation, sea-level and vegetation on different islands in this part of the world (Rabett, 2012). A further point which should be considered is variability in temporal resolution between the sites, including variations in radiocarbon ranges and precision and the possibility of movement within contexts despite stratigraphic integrity being documented at all of the sites.

Further studies in the region on different taxa, and renewed chronological modelling (e.g. as done at Pamwak; Roberts *et al.*, 2022), should provide further insights into the drivers behind local isotopic variability and its relationship to broader palaeoenvironmental change. Our data do, however, potentially reveal some regionally relevant palaeoenvironmental trends. Enamel $\delta^{13}\text{C}$ values at Matenkupkum indicate most open conditions at 25.3–23.9 ka and 17.0–14.1 ka. Meanwhile, high $\delta^{18}\text{O}$ values are observed at Buang Merabak, Matenkupkum and Matenbek between 25.3 and 19.2 ka. Together, these data may highlight the impact of the LGM on increasing aridity and catalysing more open forest landscapes in this part of the world. That said, it should be noted that only the $\delta^{13}\text{C}$ of samples at Matenkupkum record clear reductions in forest cover, suggesting a muted and local response to aridity at this time. Beyond this, data from across the sites suggest relative stability in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ across the Terminal Pleistocene and Holocene transition and through the Holocene, with some minor incursions at different sites. This implies that environments remained relatively stable across this period in contrast to other parts of the globe. This broad pattern of precipitation and vegetation change has also been

documented for Island Southeast Asia (Rabett, 2012; Roberts *et al.*, 2020b), with shifts in the extent of tropical forest apparently responding to changes in monsoon precipitation, sea level and decreasing seasonality (Haberle *et al.*, 2001; Haberle, 2003, 2005; Rabett, 2012; Hamilton *et al.*, 2019). This perhaps highlights how the mesic oceanic effects of small island sites located near the coast could have buffered the effects of aridity and cooling seen elsewhere in the region (O'Connor and Aplin, 2007) and in other parts of the world, something which may also explain clear local heterogeneity in isotopic trends.

Comparison of our data with the existing zooarchaeological, archaeobotanical, and archaeological evidence available further supports the simultaneous observation of subtle change and continuity presented in our isotope data. Taking the New Ireland sites together, it is clear that there is no obvious abandonment of this island during the LGM or the Terminal Pleistocene–Holocene transition, and the same is true for Pamwak. Similarly, the same faunal and plant taxa are broadly exploited, using similar technological assemblages, throughout the period of occupation. The notable exception is the introduction of *P. orientalis* on New Ireland and *E. cf. kalubu* and *Spiloscusus kraemeri* at Pamwak (Gosden and Robertson, 1991; Flannery, 1995; Williams, 1997, 1999), which would have provided stable sources of dietary protein. While *E. cf. kalubu* and *S. kraemeri* prefer mature forest types, *P. orientalis* has been documented as thriving in disturbed as well as intact forest (Flannery, 1995; Supplementary Note 2), perhaps making the latter a particularly important resource in times of climatic and environmental change. There is also evidence for the use of local forest trees such as *Canarium* sp. and *Celtis* sp. and, at Pamwak and indeed elsewhere in the Bismarck Archipelago and Solomon Islands, it has been tentatively suggested that humans may have played a growing role in the life cycles and promotion of such taxa over time (Gosden, 1995; Spriggs, 1997).

There is, however, some evidence for changes in human behaviour, notably in the period between the LGM and the Terminal Pleistocene/Early Holocene. Increased exploitation of shellfish, and more diverse shellfish species, are observed at Matenbek and Matenkupkum as the sea level rose following the LGM (Allen *et al.*, 1989; Gosden and Robertson, 1991). Meanwhile, Rosenfeld (1997) documents an increase in *Celtis* sp. seeds, *Canarium* sp. and *Aleurites* sp. (candlenut) at Buang Merabak in the Terminal Pleistocene and Early Holocene, perhaps as a consequence of human selection. There is also evidence for expanding and increasing social networking during the Terminal Pleistocene and Early Holocene, with the arrival of obsidian from New Britain in the New Ireland assemblages (Gosden and Robertson, 1991; Summerhayes and Allen, 1993), and the appearance and proliferation of the introduced *P. orientalis* (Gosden and Robertson, 1991). An expansion of social connectivity would have helped ensure the survival of wider populations (Summerhayes, 2007). In the case of Pamwak, the bandicoot (*E. cf. kalubu*) and *S. kraemeri* seem to have arrived from the New Guinea mainland or New Britain (Fredericksen *et al.*, 1993; Helgen and Flannery, 2004). A clear reliance on tropical forest resources in the Bismarck Archipelago during the Terminal Pleistocene is supported by the recent stable isotope analysis of human teeth from Pamwak dating to ~12–10 ka (Roberts *et al.*, 2022). A similar shift in behaviour has been seen in Wallacea, where initial coastal reliance during early human occupation in the Late Pleistocene (O'Connor *et al.*, 2011) gives way to increasing dietary specialisation, including interior forest resource use,

in the Terminal Pleistocene and Holocene. This is at a time of forest expansion and increased social connectivity (Roberts *et al.*, 2020b; Shipton *et al.*, 2020).

Our study further highlights the importance of exploring locality-specific impacts of the LGM and Terminal Pleistocene/Holocene transitions on human-exploited environments. The insular Near Oceania data may further support a scenario where this tropical setting provided something of a refuge against the harsher cooling and drying witnessed elsewhere (Hoffecker *et al.*, 2016; Burke *et al.*, 2017). The mesic oceanic settings and equatorial position led to less extreme shifts in regional climate and environment (Wurster *et al.*, 2010; Pouteau *et al.*, 2015). Nevertheless, such a scenario cannot be assumed for the entire tropics. Temperature shifts as high as 5°C have been identified in the New Guinea highland regions (Haberle *et al.*, 2001; Haberle, 2005), while aridity, rainfall seasonality and rainforest replacement by seasonally dry tropical forest or savanna have been observed in parts of Island Southeast Asia (O'Connor and Aplin, 2007; Wurster *et al.*, 2010; Russell *et al.*, 2014; Stevenson, 2018; Hamilton *et al.*, 2019). Within our dataset, although the trends are subtle and variable between the sites, we see some indication of increased aridity and forest openness ~25–20 ka, followed by forest expansion and stability (Fig. 2). These patterns have also been observed in Island Southeast Asia (Rabett, 2012) and in Sri Lanka (Premathilake, 2012; Roberts *et al.*, 2015, 2017a), suggesting a region-wide precipitation trend. In the Bismarck Archipelago, such climatic and environmental changes may have impacted local technology, subsistence and population connectivity, though records from different sites show variability. More site- and region-specific records in the tropics will help to further clarify the environmental consequences of this global period of climate change across the equatorial belt, where such human–environment interactions have often been deemed inherently less significant than those in temperate and arid zones.

Acknowledgements. PR would like to thank the Max Planck Society and European Research Council (starter grant PANTROPOCENE [no. 850709]) for support and funding. MS would like to thank the PNG National Museum, the Manus Provincial Government and the traditional owners of the Pamwak site, the people of Drabitou 2 village, under whose auspices the 1989 and 1990 excavations were undertaken, directed by Wal Ambrose and MS. Clayton Fredericksen assisted with the excavation in 1990 and analysed the stone material. The original identifications of the mammal fauna were carried out by Corrie Williams, then of Monash University, Victoria, Australia, as part of her PhD research. Funding for the excavations was provided by the then Department of Prehistory, Research School of Pacific Studies (now Archaeology and Natural History, College of Asia-Pacific), the Australian National University, where Wal Ambrose and MS were staff members at the time. We would also like to thank Jim Allen for his comments on a previous version of this manuscript. Open Access funding enabled and organized by Projekt DEAL.

Conflict of interest—The authors declare no competing financial interests or other conflicts of interest.

Data availability statement

The data that supports the findings of this study are available in the supplementary material of this article

Supporting information

Additional supporting information can be found in the online version of this article.

Abbreviations. ITCZ, Inter-Tropical Convergence Zone; ka, thousand years ago; LGM, Last Glacial Maximum.

References

- Allen, J. & Gosden, C. (1996) Spheres of interaction and integration: modelling the culture history of the Bismarck Archipelago. In: Davidson, J., Irwin, G., Leach, B., Pawley, A. & Brown, D. (Eds.) *Oceanic Culture History: Essays in Honour of Roger Green*. Auckland: New Zealand Journal of Archaeology. pp. 183–197.
- Allen, J., Gosden, C. & White, J.P. (1989) Human Pleistocene adaptations in the tropical island Pacific: recent evidence from New Ireland, a Greater Australian Outlier. *Antiquity*, 63, 548–561.
- Allen, J. (2000) From beach to beach: The development of maritime economies in prehistoric Melanesia. In: O'Connor, S. & Veth, P. (Eds.) *East of Wallace's Line: Studies of Past and Present Maritime Cultures of the Indo-Pacific Region. Modern Quaternary Research in Southeast Asia 16*. Rotterdam: A.A. Balkema. pp. 139–177.
- Anhuf, D., Ledru, M.-P., Behling, H., Da Cruz, F.W., Cordeiro, R.C., van der Hammen, T. et al. (2006) Paleo-environmental change in Amazonian and African rainforest during the LGM. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 239, 510–527.
- Baker, P.A., Seltzer, G.O., Frit, S.C., Dunbar, R.B., Grove, M.J., Tapia, P.M. et al. (2001) The history of South American tropical precipitation for the past 25,000 years. *Papers in the Earth and Atmospheric Sciences 7*: <https://digitalcommons.unl.edu/geosciencefacpub/7>
- Bartlein, P.J., Harrison, S.P., Brewer, S., Connor, S., Davis, B.A.S., Gajewski, K. et al. (2011) Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis. *Climate Dynamics*, 37, 775–802.
- Barton, H. & Torrence, R. (2015) Cooking up recipes for ancient starch: Assessing current methodologies and looking to the future. *Journal of Archaeological Science*, 56, 194–201.
- Benjamini, Y. & Hochberg, Y. (1995) Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal statistical society: Series B (Methodological)*, 57, 289–300.
- Beuning, K.R.M., Zimmerman, K.A., Ivory, S.J. & Cohen, A.S. (2011) Vegetation response to glacial-interglacial climate variability near Lake Malawi in the southern African tropics. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 303, 81–92.
- Bird, M.I., Taylor, D. & Hunt, C. (2005) Palaeoenvironments of insular Southeast Asia during the Last Glacial Period: a savanna corridor in Sundaland? *Quaternary Science Reviews*, 24, 2228–2242.
- Blome, M.W., Cohen, A.S., Tryon, C.A., Brooks, A.S. & Russell, J. (2012) The environmental context for the origins of modern human diversity: A synthesis of regional variability in African climate 150,000–30,000 years ago. *Journal of Human Evolution*, 62, 563–592.
- Bonnefille, R., Roeland, J.C. & Guiot, J. (1990) Temperature and rainfall estimates for the past 40,000 years in equatorial Africa. *Nature*, 346, 347–349.
- Bourgeon, L., Burke, A. & Higham, T. (2017) Earliest Human Presence in North America Dated to the Last Glacial Maximum: New Radiocarbon Dates from Bluefish Caves, Canada. *PLoS One*, 12, e0169486. Available from: <https://doi.org/10.1371/journal.pone.0169486>
- Bromley, G.R.M., Schaefer, J.M., Hall, B.L., Rademaker, K.M., Putnam, A.E., Todd, C.E. et al. (2016) A cosmogenic ^{10}Be chronology for the local last glacial maximum and termination in the Cordillera Oriental, southern Peruvian Andes: Implications for the tropical role in global climate. *Quaternary Science Reviews*, 148, 54–67.
- Buchmann, N. & Ehleringer, J.R. (1998) CO_2 concentration profiles, and carbon and oxygen isotopes in C_3 and C_4 crop canopies *Agriculture and Forest Meteorology*. 89, 45–58.
- Buchmann, N., Guehl, J.-M., Barigah, T.S. & Ehleringer, J.R. (1997) Interseasonal comparison of CO_2 concentrations, isotopic composition, and carbon dynamics in an Amazonian rainforest (French Guiana). *Oecologia*, 110, 120–131.
- Burke, A., Kageyama, M., Latombe, G., Fasel, M., Vrac, M., Ramstein, G. et al. (2017) Risky business: The impact of climate and climate variability on human population dynamics in Western Europe during the Last Glacial Maximum. *Quaternary Science Reviews*, 164, 217–229.
- Burke, A., Riel-Salvatore, J. & Barton, C.M. (2018) Human response to habitat suitability during the Last Glacial Maximum in Western Europe. *Journal of Quaternary Science*, 33, 335–345.
- Cannon, C.H., Morley, R.J. & Bush, A.B.G. (2009) The current refugial rainforests of Sundaland are unrepresentative of their biogeographic past and highly vulnerable to disturbance. *Proceedings of the National Academy of Sciences*, 106, 11188–11193.
- Carter, M.L. & Bradbury, M.W. (2015) Oxygen isotope ratios in primate bone carbonate reflect amount of leaves and vertical stratification in the diet. *American Journal of Primatology*, 78, 1086–1097. Available from: <https://doi.org/10.1002/ajp.22432>
- Cerling, T.E. & Harris, J.M. (1999) Carbon isotope fractionation between diet and bioapatite in ungulate mammals and implications for ecological and paleoecological studies. *Oecologia*, 120, 347–363.
- Cerling, T.E., Hart, J.A. & Hart, T.B. (2004) Stable isotope ecology in the Ituri Forest. *Oecologia*, 138, 5–12.
- Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B. et al. (2009) The Last Glacial Maximum. *Science*, 325, 710–714.
- Dam, R.A.C., Fluin, J., Suparan, P. & van der Kaars, S. (2001) Palaeoenvironmental developments in the Lake Tondano area (N. Sulawesi, Indonesia) since 33,000yr B.P. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 171, 147–183.
- Enright, N.J. & Gosden, C. (1992) Unstable archipelagos – south-west Pacific environment and prehistory since 30000 BP. In: Dodson, J. (Ed.) *The Naïve Lands: Prehistory and Environmental Change in Australia and the Southwest Pacific*. Melbourne: Longman Cheshire. pp. 160–198.
- ESA. (2017) Land Cover CCI Product User Guide Version 2. Tech. Rep. Available from: maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf
- Farquhar, G.D., Ehleringer, J.R. & Hubick, K.T. (1989) Carbon isotope discrimination and photosynthesis. *Annual Review of Plant Physiology and Plant Molecular Biology*, 40, 503–537.
- Flannery, T.F. (1995) *Mammals of New Guinea*. Ithaca: Cornell University Press.
- Fredericksen, C., Spriggs, M. & Ambrose, W. (1993) Pamwak rockshelter: A Pleistocene site on Manus Island, Papua New Guinea. In: Smith, M.A., Spriggs, M. & Fankhauser, B. (Eds.) *Sahul in Review: Pleistocene Archaeology in Australia, New Guinea and Island Melanesia*. Canberra: Department of Prehistory, Research School of Pacific Studies, Australian National University. pp. 144–152.
- Freslov, J. (1989) *Structure and Form in an 'Amorphous' Lithic Assemblage: A case study from New Ireland, Papua New Guinea*. Unpublished BA Honours Dissertation Melbourne, Bundoora: La Trobe University.
- Friedli, H., Löttscher, H., Oeschger, H., Siegenthaler, U. & Stauffer, B. (1986) Ice core record of the $^{13}\text{C}/^{12}\text{C}$ ratio of atmospheric CO_2 in the past two centuries. *Nature*, 324, 237–238.
- Fuhrmann, F., Diensberg, B., Gong, X., Lohmann, G. & Sirocko, F. (2020) Aridity synthesis for eight selected key regions of the global climate system during the last 60000 years. *Climate of the Past*, 16, 2221–2238.
- Gosden, C. (1995) Arboriculture and agriculture on coastal Papua New Guinea. In: Allen, J. & O'Connell, J.F. (Eds.) *Transitions: Pleistocene to Holocene in Australia and Papua New Guinea*. *Antiquity*, 69, pp. 807–817.
- Gosden, C. & Robertson, N. (1991) Models for Matenkupkum: interpreting a late Pleistocene site from Southern New Ireland, Papua New Guinea. In Allen, J. & Gosden, C. (Eds.) *Report of the Lapita Homeland Project*. Occasional Papers in Prehistory 20. Canberra: Department of Prehistory. Research School of Pacific Studies, The Australian National University. pp. 20–91.
- Grimes, S.T., Collinson, M.E., Hooker, J.J. & Matthey, D.P. (2008) Is small beautiful? A review of the advantages and limitations of using small mammal teeth and the direct laser fluorination analysis technique in the isotope reconstruction of past continental climate change. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 266, 39–50.
- Haberle, S.G. (2003) The emergence of an agricultural landscape in the highlands of New Guinea. *Archaeology in Oceania*, 38, 149–158.

- Haberle, S.G. (2005) A 23,000-yr Pollen Record from Lake Euramoo, Wet Tropics of NE Queensland, Australia. *Quaternary Research*, 64, 343–356.
- Haberle, S.G., Hope, G.S. & van der Kaars, S. (2001) Biomass burning in Indonesia and Papua New Guinea: natural and human induced fire events in the fossil record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 171, 259–268.
- Hamilton, R., Stevenson, J., Li, B. & Bijaksana, S. (2019) A 16,000-year record of climate, vegetation and fire from Wallacean lowland tropical forests. *Quaternary Science Reviews*, 224, 105929.
- Hawkins, S., O'Connor, S., Maloney, T.R., Litster, M., Kealy, S., Fenner, J.N. et al. (2017) Oldest human occupation of Wallacea at Laili Cave, Timor-Leste, shows broad-spectrum foraging responses to late Pleistocene environments. *Quaternary Science Reviews*, 171, 58–72.
- Heaton, T.J., Köhler, P., Butzin, M., Bard, E., Reimer, R.W., Austin, W.E.N. et al. (2020) Marine20 - The marine radiocarbon age calibration curve (0–55,000 cal BP). *Radiocarbon*, 62, 779–820.
- Helgen, K.M. & Flannery, T.F. (2004) Notes on the Phalangerid marsupial genus *Spilocuscus*, with description of a new species from Papua. *Journal of Mammalogy*, 85, 825–833.
- Helmens, K.F. (2014) The Last Interglacial-Glacial cycle (MIS5-2) re-examined based on long proxy records from central and northern Europe. *Quaternary Science Reviews*, 86, 115–143.
- Hoffecker, J.F., Elias, S.A., O'Rourke, D.H., Scott, G.R. & Bigelow, N.H. (2016) Beringia and the global dispersal of modern humans. *Evolutionary Anthropology: Issues, News, and Reviews*, 25, 64–78.
- Hope, G. (2001) Environmental change in the Late Pleistocene and later Holocene at Wanda site, Soroako, South Sulawesi, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 171, 129–145.
- Hope, G. (2009) Environmental change and fire in the Owen Stanley Ranges, Papua New Guinea. *Quaternary Science Reviews*, 28, 2261–2276.
- Hope, G. (2005) The Quaternary in Southeast Asia. In: Gupta, A., (ed.) *The Physical Geography of Southeast Asia*. Oxford: Oxford University Press. pp. 24–37.
- Hope, G. & Tulip, J. (1994) A long vegetation history from lowland Irian Jaya, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 109, 385–398.
- Hunt, C.O., Gilbertson, D.D. & Rushworth, G. (2012) A 50,000-year record of late Pleistocene tropical vegetation and human impact in lowland Borneo. *Quaternary Science Reviews*, 37, 61–80.
- Jeffrey, A., Denys, C., Stoetzel, E. & Lee-Thorp, J.A. (2015) Influences on the stable oxygen and carbon isotopes in gerbillid rodent teeth in semi-arid and arid environments: Implications for past climate and environmental reconstruction. *Earth and Planetary Science Letters*, 428, 84–96.
- Jeffrey, A., Stoetzel, E., Parfitt, S., Barton, N., Nespoulet, R., El Hajraoui, M.A. et al. (2016) Oxygen and carbon isotopes in *Gerbillinae* (gerbil) teeth provide palaeoaridity records in two Late Pleistocene Moroccan sites. *Quaternary International*, 404, 175.
- Jolly, D. & Haxeltine, A. (1997) Effect of low glacial atmospheric CO₂ on tropical African montane vegetation. *Science*, 276, 786–788.
- van der Kaars, S. (1998) Marine and terrestrial pollen records of the last glacial cycle from the Indonesian region: Bandung Basin and Banda Sea. *Paleoclimates – Data Modelling*, 3, 209–219.
- Kaars, S., Wang, X., Kershaw, P., Guichard, F. & Setiabudi, D.A. (2000) A Late Quaternary palaeoecological record from the Banda Sea, Indonesia: patterns of vegetation, climate and biomass burning in Indonesia and northern Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 155, 135–153.
- Kageyama, M., Braconnot, P., Bopp, L., Mariotti, V., Roy, T., Woillez, M.-N. et al. (2013) Mid-Holocene and last glacial maximum climate simulations with the IPSL model: part II: model-data comparisons. *Climate Dynamics*, 40, 2469–2495.
- Kohn, M.J., Schoeninger, M.J. & Valley, J.W. (1996) Herbivore tooth oxygen isotope compositions: effects of diet and physiology. *Geochimica et Cosmochimica Acta*, 60, 3889–3896.
- Kull, C., Imhof, S., Grosjean, M., Zech, R. & Veit, H. (2008) Late Pleistocene glaciation in the Central Andes: Temperature versus humidity control — A case study from the eastern Bolivian Andes (17°S) and regional synthesis. *Global and Planetary Change*, 60(1), 148–164.
- Lambeck, K., Rouby, H., Purcell, A., Sun, Y. & Sambridge, M. (2014) Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences*, 111, 15296–15303.
- Leary, T., Singadan, R., Menzies, J., Helgen, K., Wright, D., Allison, A. et al. (2016) Phalanger orientalis. *IUCN Red List of Threatened Species*, 2016, e.T16847A21951519. Available from: <https://doi.org/10.2305/IUCN.UK.2016-2.RLTS.T16847A21951519.en> Retrieved 12 November 2021
- Leavesley, M. & Allen, J. (1998) Dates, disturbance and artefact distributions: another analysis of Buang Merabak, a Pleistocene site on New Ireland, Papua New Guinea. *Archaeology in Oceania*, 33, 63–82.
- Leavesley, M. & Chappell, J. (2004) Buang Merabak: Additional early radiocarbon evidence of the colonisation of the Bismarck Archipelago, Papua New Guinea. *Antiquity Project Gallery*, 78(30). <http://antiquity.ac.uk/ProjGall/leavesley/index.html#leavesley>
- Leavesley, M. (2006) Late Pleistocene complexities in the Bismarck Archipelago. In: Lilley, I., (ed.) *Archaeology of Oceania*. Australia and the Pacific Islands. <https://doi.org/10.1002/9780470773475.ch9>
- Leavesley, M.G. (2004) Trees to the sky: Prehistoric hunting in New Ireland, Papua New Guinea. Thesis (PhD)—Australian National University.
- Leavesley, M.G. (2017) Themes in the zooarchaeology of Pleistocene Melanesia. In: Albarella, U., Rizzetto, M., Russ, H., Vickers, K. & Viner-Daniels, S. (Eds.) *The Oxford Handbook of Zooarchaeology*. New York: Oxford University Press. pp. 691–702.
- Lee-Thorp, J.A. & van der Merwe, N.J. (1987) Carbon isotope analysis of fossil bone apatite. *South African Journal of Science*, 83, 712–715.
- Lee-Thorp, J.A., Sealy, J.C. & van der Merwe, N.J. (1989) Stable carbon isotope ratio differences between bone collagen and bone apatite, and their relationship to diet. *Journal of Archaeological Science*, 16, 585–599.
- Levin, N.E., Cerling, T.E., Passey, B.H., Harris, J.M. & Ehleringer, J.R. (2006) A stable isotope aridity index for terrestrial environments. *Proceedings of the National Academy of Sciences*, 103, 11201–11205.
- Levin, N.E., Simpson, S.W., Quade, J., Cerling, T.E. & Frost, S.R. (2008) Herbivore enamel carbon isotopic composition and the environmental context of *Ardipithecus* at Gona, Ethiopia. *Geological Society of America, Special Papers*, 446, 215–234.
- Liu, Y., Lo, L., Shi, Z., Wei, K.Y., Chou, C.J., Chen, Y.C. et al. (2015) Obliquity pacing of the western Pacific Intertropical Convergence Zone over the past 282,000 years. *Nature Communications*, 6, 10018. Available from: <https://doi.org/10.1038/ncomms10018>
- Mayle, F.E., Beerling, D.J., Gosling, W.D. & Bush, M.B. (2004) Responses of Amazonian ecosystems to climatic and atmospheric carbon dioxide changes since the Last Glacial Maximum. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 359, 499–514. Available from: <https://doi.org/10.1098/rstb.2003.1434>
- McGee, D., Donohoe, A., Marshall, J. & Ferreira, D. (2014) Changes in ITCZ location and cross-equatorial heat transport at the Last Glacial Maximum, Heinrich Stadial 1, and the mid-Holocene. *Earth and Planetary Science Letters*, 390, 69–79.
- Munt, S., Roberts, A. & Gorman, A. (2018) An investigation of human responses to climatic fluctuations at Allen's Cave, South Australia, from ca 40,000 to 5,000 BP, by a technological analysis of stone artefacts. *Australian Archaeology*, 84, 67–83. Available from: <https://doi.org/10.1080/03122417.2018.1458446>
- O'Connor, S. & Aplin, K. (2007) A matter of balance: An overview of Pleistocene occupation history and the impact of the Last Glacial Phase in East Timor and the Aru Islands, eastern Indonesia. *Archaeology in Oceania*, 42, 82–90.
- O'Connor, S., Ono, R. & Clarkson, C. (2011) Pelagic fishing at 42,000 years before the present and the maritime skills of modern humans. *Science*, 334, 1117–1121.
- Pavlidis, C. (1999) The Story of Imlo: The organisation of flaked stone technologies from the lowland tropical rainforest of West New Britain, Papua New Guinea. PhD dissertation, La Trobe University.

- Pavlidis, C. (2004) From Misisil Cave to Eliva hamlet: rediscovering the Pleistocene in interior West New Britain. In: Attenbrow, V. & Fullager, R. (Eds.) *A Pacific Odyssey: Archaeology and Anthropology in the Western Pacific. Papers in Honour of Jim Specht*. Australian Museum: Records of the Australian Museum, Supplement 29. Sydney. pp. 97–108.
- Pavlidis, C. & Gosden, C. (1994) 35,000-year-old sites in the rainforests of West New Britain, Papua New Guinea. *Antiquity*, 68, 604–610.
- Posth, C., Renaud, G., Mittnik, A., Drucker, D.G., Rougier, H., Cupillard, C. et al. (2016) Pleistocene mitochondrial genomes suggest a single major dispersal of non-Africans and a late glacial population turnover in Europe. *Current Biology*, 26, 827–833.
- Pouteau, R., Trueba, S., Feild, T.S. & Isnard, S. (2015) New Caledonia: a Pleistocene refugium for rain forest lineages of relict angiosperms. *Journal of Biogeography*, 42, 2062–2077.
- Premathilake, R. (2012) Human used upper montane ecosystem in the Horton Plains, central Sri Lanka – a link to Lateglacial and early Holocene climate and environmental changes. *Quaternary Science Reviews*, 50, 23–42.
- R Core Team. (2013) R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria, <http://www.R-project.org/>
- Rabett, R.J. (2012) *Human Adaptation in the Asian Palaeolithic*. Cambridge: Cambridge University Press.
- Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B. et al. (2006) A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research: Atmospheres*, 111. Available at <https://doi.org/10.1029/2005JD006079>
- Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B. et al. (2014) A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews*, 106, 14–28.
- Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C. et al. (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon*, 62, 725–757. Available from: <https://doi.org/10.1017/RDC.2020.41>
- Roberts, P. (2019) *Tropical forests in prehistory, history and modernity*. Oxford: Oxford University Press.
- Roberts, P., Douka, K., Tromp, M., Bedford, S., Hawkins, S., Bouffandeau, L. et al. (2022) Fossils, fish and tropical forests: prehistoric human adaptations on the island frontiers of Oceania. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, 377, 20200495. Available from: <https://doi.org/10.1098/rstb.2020.0495>
- Roberts, P., Gaffney, D., Lee-Thorp, J. & Summerhayes, G. (2017b) Persistent tropical foraging in the Highlands of Terminal Pleistocene-Holocene New Guinea. *Nature Ecology and Evolution*, 1, 0044. Available from: <https://doi.org/10.1038/s41559-016-0044>
- Roberts, P., Louys, J., Zech, J., Shipton, C., Kealy, S., Samper Carro, S. et al. (2020b) Isotopic evidence for initial coastal colonization and subsequent diversification in the human occupation of Wallacea. *Nature Communications*, 11(2020), 2068. Available from: <https://doi.org/10.1038/s41467-020-15969-4>
- Roberts, P., Perera, N., Wedage, O., Deraniyagala, S., Perera, J., Eregama, S. et al. (2015) Direct evidence for human reliance on rainforest resources in late Pleistocene Sri Lanka. *Science*, 347(6227), 1246–1249.
- Roberts, P., Perera, N., Wedage, O., Deraniyagala, S.U., Perera, J., Eregama, S. et al. (2017a) Fruits of the forest: Human stable isotope ecology and rainforest adaptations in Late Pleistocene and Holocene (~36 to 3 ka) Sri Lanka. *Journal of Human Evolution*, 106, 102–118.
- Roberts, P., Prendergast, M.E., Janzen, A., Shipton, C., Blinkhorn, J., Zech, J. et al. (2020a) Late Pleistocene to Holocene human palaeoecology in the tropical environments of coastal eastern Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 537, 109438. Available from: <https://doi.org/10.1016/j.palaeo.2019.109438>
- Roberts, P. & Stewart, B.A. (2018) Defining the ‘generalist-specialist’ niche for Pleistocene *Homo sapiens*. *Nature Human Behaviour*, 2, 542–550. Available from: <https://doi.org/10.1038/s41562-018-0394-4>
- Rosenfeld, A. (1997) Excavation at Buang Merabak, central New Ireland. *Bulletin of the Indo-Pacific Prehistory Association*, 16, 213–224.
- Russell, J.M., Vogel, H., Konecky, B.L., Bijaksana, S., Huang, Y., Melles, M. et al. (2014) Glacial forcing of central Indonesian hydroclimate since 60,000 y B.P. *Proceedings of the National Academy of Sciences*, 111, 5100–5105.
- Shaw, B. (2021) *Palaeolandscapes in Archaeology: Lessons for the Past and Future*. Carson, M.T. (Ed.). 1st ed. Abingdon United Kingdom: Routledge. pp. 215–290.
- Shaw, B., Haro, J., Privat, K., Haberle, S., Hopf, F., Hull, E. et al. (2020) Smallest Late Pleistocene inhabited island in Australasia reveals the impact of post-glacial sea-level rise on human behaviour from 17,000 years ago. *Quaternary Science Reviews*, 245, 106522.
- Shipton, C., O’Connor, S., Reepmeyer, C., Kealy, S. & Jankowski, N. (2020) Shell Adzes, Exotic Obsidian, and Inter-Island Voyaging in the Early and Middle Holocene of Wallacea. *The Journal of Island and Coastal Archaeology*, 15, 525–546.
- Smith, J.A., Seltzer, G.O., Rodbell, D.T. & Klein, A.G. (2005) Regional synthesis of last glacial maximum snowlines in the tropical Andes, South America. *Quaternary International*, 138–139, 145–167.
- Specht, J., Lilley, I. & Normu, J. (1983) More on Radiocarbon Dates from West New Britain, Papua New Guinea. *Australian Archaeology*, 16, 92–95.
- Specht, J. (2005) Revisiting the Bismarcks: Some alternative views. In: Pawley, A., Attenborough, R., Golson, J. & Hide, R. (Eds.) *Papuan Pasts: Cultural, Linguistic and Biological Histories of Papuan-Speaking Peoples*. Pacific Linguistics 572, Research School of Pacific and Asian Studies. Canberra: The Australian National University. pp. 235–288.
- Spratt, R.M. & Lisiecki, L.E. (2016) A Late Pleistocene sea level stack. *Climate of the Past*, 12, 1079–1092.
- Spriggs, M. (1997) *The Island Melanesians*. Oxford: Blackwell Publishers.
- Spriggs, M. (1993) Island Melanesia: The last 10,000 years. In: Spriggs, M., Yen, D., Ambrose, W., Jones, R., Thorne, A. & Andrews, A. (Eds.) *A Community of Culture: The People and Prehistory*. Occasional Papers in Prehistory 21. Canberra: Canberra Department of Prehistory. Research School of Pacific Studies, Australian National University. pp. 187–205.
- Steadman, D.W., White, J.P. & Allen, J. (1999) Prehistoric birds from New Ireland, Papua New Guinea: Extinctions on a large Melanesian island. *Proceedings of the National Academy of Sciences*, 96, 2563–2568.
- Stevenson, J. (2018) Vegetation and climate of the Last Glacial Maximum in Sulawesi. In: O’Connor, S., Bulbeck, D. & Meyer, J. (Eds.) *The Archaeology of Sulawesi: Current research on the Pleistocene to the Historic period*. Terra Australis 48. Canberra: The Australian National University. pp. 17–30.
- Stiner, M.C., Dimitrijević, V., Mihailović, D. & Kuhn, S.L. (2022) Velika Pečina: Zooarchaeology, taphonomy and technology of a LGM Upper Paleolithic site in the central Balkans (Serbia). *Journal of Archaeological Science: Reports*, 41, 103328. Available from: <https://doi.org/10.1016/j.jasrep.2021.103328>
- Straus, L.G. (2016) Humans confront the Last Glacial maximum in Western Europe: Reflections on the Solutrean weaponry phenomenon in the broader contexts of technological change and cultural adaptation. *Quaternary International*, 425, 62–68.
- Summerhayes, G.R. & Allen, J. (1993) The transport of Mopir obsidian to late Pleistocene New Ireland. *Archaeology in Oceania*, 28, 144–148.
- Summerhayes, G.R., Field, J.H., Shaw, B. & Gaffney, D. (2017) The archaeology of forest exploitation and change in the tropics during the Pleistocene: the case of Northern Sahul (Pleistocene New Guinea). *Quaternary International*, 448, 14–30.
- Summerhayes, G.R. & Ford, A. (2014) Late Pleistocene Colonisation and Adaptation in New Guinea: Implications for Modeling Modern Human Behaviour. In: Dennell, R. & Poor, M. (Eds.) *Southern Asia, Australia and the search for Human Origins*. Cambridge: Cambridge University Press. pp. 213–227.
- Summerhayes, G.R. (2007) Island Melanesian Pasts: A View from Archeology. In: Friedlander, J.S. (Ed.) *Population Genetics, Linguistics, and Culture History in the Southwest Pacific*. Oxford: Oxford University Press. pp. 10–35.

- Summerhayes, G.R., Leavesley, M., Fairbairn, A., Mandui, H., Field, J., Ford, A. et al. (2010) Human Adaptation and Plant Use in Highland New Guinea 49,000 to 44,000 Years Ago. *Science*, 330, 78–81.
- Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.-N., Henderson, K.A., Cole-Dai, J. et al. (1995) Late Glacial Stage and Holocene Tropical Ice Core Records from Huascarán, Peru. *Science*, 269, 46–50.
- Tierney, J.E., Zhu, J., King, J., Malevich, S.B., Hakim, G.J. & Poulsen, C.J. (2020) Glacial cooling and climate sensitivity revisited. *Nature*, 584, 569–573.
- Torrence, R., Neall, V., Doelman, T., Rhodes, E., McKee, C., Davies, H. et al. (2004) Pleistocene colonisation of the Bismarck Archipelago: New evidence from West New Britain. *Archaeology in Oceania*, 39, 101–130.
- Van der Merwe, N.J. & Medina, E. (1991) The canopy effect, carbon isotope ratios and foodwebs in Amazonia. *Journal of Archaeological Science*, 18, 249–259.
- Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K. et al. (2002) Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Quaternary Science Reviews*, 21, 295–305.
- Wicaksono, S.A., Russell, J.M. & Bijaksana, S. (2015) Compound-specific carbon isotope records of vegetation and hydrologic change in central Sulawesi, Indonesia, since 53,000 yr BP. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 430, 47–56.
- Wicaksono, S.A., Russell, J.M., Holbourn, A. & Kuhnt, W. (2017) Hydrological and vegetation shifts in the Wallacean region of central Indonesia since the Last Glacial Maximum. *Quaternary Science Reviews*, 157, 152–163.
- Wickler, S. (2001) *The Prehistory of Buka: A Stepping Stone Island in the Northern Solomons*. Canberra: Department of Archaeology and Natural History and Centre for Archaeological Research, Australian National University. Terra Australis. p. 16
- Williams, A.N., Ulm, S., Cook, A.R., Langley, M.C. & Collard, M. (2013) Human refugia in Australia during the Last Glacial maximum and terminal Pleistocene: a geospatial analysis of the 25–12 ka Australian archaeological record. *Journal of Archaeological Science*, 40, 4612–4625.
- Williams, C. 1997. Zooarchaeology of the Pamwak site, Manus Island, PNG. Unpublished PhD thesis, Monash University, Victoria, Australia.
- Williams, C. (1999) Faunal composition of the Pamwak site, Manus Island, PNG. In: Galipaud, J.-C. & Lilley, I. (Eds.) *Le Pacifique de 5000 à 2000 avant le Présent/The Pacific from 5000-2000 BP*. Paris: Editions de IRD. pp. 241–249.
- Wren, C.D. & Burke, A. (2019) Habitat suitability and the genetic structure of human populations during the Last Glacial Maximum (LGM) in Western Europe. *PLoS One*, 14(6), e0217996. Available from: <https://doi.org/10.1371/journal.pone.0217996>
- Wurster, C.M., Bird, M.I., Bull, I.D., Creed, F., Bryant, C., Dungait, J.A.J. et al. (2010) Forest contraction in north equatorial Southeast Asia during the Last Glacial Period. *Proceedings of the National Academy of Sciences*, 107, 15508–15511.