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RESEARCH

Living in the middle of the edge: an insight into ancient subsistence practices in Myanmar

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Abstract
The origins of agriculture have been a focal point of interest in Southeast Asia because of the profound influence domestication of cereal crops had on the ancient inhabitants of the region. Historically, an emphasis has been placed on the movement of farmers from China into Southeast Asia during the Neolithic, however, the origin of agriculture in Myanmar remains unknown. Recently, stable carbon and oxygen isotope analyses have provided insight into the subsistence practices of two prehistoric communities, Oakaie 1 and Nyaung'gan, living in north-central Myanmar during the late Neolithic and early Bronze Age, ca. 1300−700 BCE, but lacked the temporal resolution to identify any changes in the intensification of agriculture. Here, we report new C and O stable isotope analysis of individuals from Oakaie 1, and the UNESCO World Heritage complex of Halin excavated between 2017 and 2020. With a longer chronological sequence—dating between ca. 2700 BCE and 1300 CE— Halin provides the opportunity to examine diachronic changes in these practices. The results suggest individuals from Myanmar had a mixed subsistence economy focused on C_3/C_4 resources during the late Neolithic to Bronze Age and a less variable subsistence focused on C_3 resources in the Iron Age, possibly associated with the intensification of wet rice agriculture and changes in water management practices. Situated in north-central Myanmar on the edge of mainland Southeast Asia, we suggest that southwest China, with a subsistence economy of rice and millet, played a role in the movement of this mixed farming strategy into Myanmar.

Keywords Myanmar · Oxygen isotope values · Carbon isotope values · Tooth enamel · Diet

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Introduction

The origins of agriculture have been a focal point of interest in Southeast Asia because of the profound influence the arrival of domesticated cereal crops had on the ancient inhabitants of the region during the third and second millennia BCE. Historically, an emphasis has been placed on linguistic, bioarchaeological and archaeological evidence to understand the movement of farmers from China into wider Southeast Asia, particularly Thailand and Vietnam, during the Neolithic (Bellwood 2005; Blench et al. 2005; Higham 2002; Stevens and Fuller 2017).

Around 7000 BCE cereals began being cultivated in China, with Japonica rice (*Oryza sativa japonica*) in the lower Yangtze Valley region (Fuller et al. 2010; Zhao 2011) and foxtail (*Setaria italica*) and broomcorn (*Panicum miliaceum*) millets in the Yellow River region (Liu et al. 2009; Stevens and Fuller 2017; Zhao 2011). From early cultivation, both regions followed a similar trajectory with communities transitioning from hunting and gathering to more intensive farming of the respective crops over two thousand years. Following this period, dry-land agricultural farming of millet developed between ca. 5000 to 4000 BCE in the Yellow River valley, earlier than rice agriculture subsistence in the Yangtze Valley from ca. 4500 to 2500 BCE (Zhao 2011). Domesticated millets and rice began being transported with people from these regions as they started migrating to different areas, and by 4000 BCE there was a fusion of these agricultural cropping practices and the adoption and development of mixed cropping systems among single communities (Stevens and Fuller 2017). Recently, palaeobotanical analyses have highlighted the importance of this mixed subsistence economy (Dal Martello 2022, p. 77; Dal Martello et al. 2018; Dal Martello et al. 2021; Jin et al. 2014; Xue et al. 2022). A mixed cropping economy of wetland rice and dryland millet was practised at Baodun in Sichuan ca. 2700−1700 BCE (d'Alpoim Guedes et al. 2013), which likely spread to Yunnan as an established package (Dal Martello et al. 2018; Huan et al. 2022). Beginning in the Neolithic, the earliest evidence from Yunnan is found at Baiyangcun ca. 2650−2050 BCE (Dal Martello et al. 2018), then at Dadunzi from ca. 2000−1600 BCE (Dal Martello et al. 2018; Jin et al. 2014), at Haimenkou ca. 1600−300 BCE (Xue et al. 2022), and Dayingzhuang from around 750−390 BCE (Dal Martello et al. 2021). Although the favoured crop fluctuated, both millets and rice persisted for millennia, despite the introduction of other crops, such as wheat and barley (Dal Martello 2022).

Recent palaeobotanical research is providing a more nuanced understanding of the first rice and millet farmers of mainland Southeast Asia (d'Alpoim Guedes et al. 2020), which likely came in successive waves along different routes. While there is evidence for dry rainfed millet agriculture among some early mainland Southeast Asian communities in north-central Thailand (d'Alpoim Guedes et al. 2020; Weber et al. 2010), many seem to have relied on rainfed dryland rice agriculture (Castillo et al. 2016a, b; Fuller and Castillo 2021; Fuller et al. 2016), until the later focus on wet rice agricultural systems in the Iron Age (Castillo et al. 2018). These findings are supported by regional stable isotope analyses which indicate rice agriculture was focal in the subsistence economy (Bentley et al. 2005, 2007, 2009; Cox et al. 2011; King et al. 2015; Liu 2018; Schalburg-Clayton 2023).

Situated on the edge of mainland Southeast Asia, the origin of agriculture in Myanmar remains unknown, however, preliminary stable carbon and oxygen isotope analyses provided insight into the subsistence practices of individuals living at Oakaie 1 and Nyaung'gan (Willis et al. 2023) in north-central Myanmar during the late Neolithic and Early Bronze Age, ca. 1300−700 BCE (Pryce et al. 2018b). These preliminary data indicated that the subsistence economy during this period in Myanmar was more like China than mainland Southeast Asian sites in Thailand, but lacked the temporal resolution to identify any changes in the trajectory and intensification of agriculture. However, the Halin complex, excavated by the multinational team of the French Archaeological Mission in Myanmar between 2017 and 2020, has a longer chronological sequence dating between ca. 2700 BCE to 1300 CE (Pryce et al. 2024b) providing an opportunity to investigate aspects of human behaviour and changes in agricultural practices.

Due to its proximity to Myanmar and likely connection through major river systems, we argue that the subsistence practices focused on mixed cropping systems of wet rice and dry millet in Yunnan (Dal Martello et al. 2018, 2021; Jin et al. 2014; Xue et al. 2022) were influential in the adoption and intensification of agriculture in Myanmar. Recent genomic research undertaken on individuals dating to ca. 2500−2200 BCE from Gaoshan in Sichuan and ca. 1500−1000 BCE from Haimenkou, Yunnan (Tao et al. 2023) suggests that Tibeto-Burman populations of southwest China share a genetic affinity with Neolithic millet farmers of the Yellow River and Hòabìnhian hunter-gatherers but not rice farmers. Although based on a limited number of individuals from only two sites, the findings indicate that the communities at Gaoshan and Haimenkou, at least, adopted rice farming techniques to complement millet farming without significant admixing with rice farming communities, and this practice persisted from the Neolithic to the Bronze Age (Tao et al. 2023). These findings are consistent with the farming dispersal and northern-origin language hypothesis (Sagart et al. 2019; Zhang et al. 2019, 2020), which suggests Sino-Tibetans were millet farmers in the Yellow River region and supports previous findings demonstrating a close genetic affinity between proto-Sino-Tibetan millet farmers from the late Neolithic Yellow River region and contemporary Tibeto-Burman populations in southwest China (Guo et al. 2022, p. 334). Similar to individuals from the Neolithic and Bronze Age in Yunnan (Tao et al. 2023), the ancient DNA of two late Neolithic individuals from Oakaie 1 suggested they were likely descendent from Sino-Tibetan speaking populations of East Asian origin (Lipson et al. 2018) and share a genetic affinity with present-day Tibeto-Burman speaking Myanmarese populations (Yang et al. 2020a, b). In contrast to other sites in mainland Southeast Asia studied (Yang et al. 2020a), the individuals from Oakaie 1 shared no genetic affinity with Austroasiatic populations (Lipson et al. 2018).

Here, we present the results of stable carbon and oxygen isotope analyses of individuals from Halin and new data from Oakaie 1, refocusing our research questions to evaluate the strength of our current understanding. We use $\delta^{13}C$ and $\delta^{18}O$ as a proxy to understand the diet of individuals living in these communities and to assess whether there were temporal shifts in subsistence practices between those communities during different temporal periods. We examine whether any differences in diet existed between the biological sexes, determined through proteomic analysis, and investigate evidence of human and animal interaction within the environmental context. Finally, we evaluate the findings in the broader regional and temporal contexts.

The geographic, climatic, and archaeological context of Myanmar

Geographically situated at the juncture of South, East, and Southeast Asia, Myanmar represents a pivotal location for trans-Eurasian interactions. Encircled by mountain ranges, the alluvial central lowlands of Myanmar were carved by rivers and streams over thousands of years of monsoonal flooding (Boori et al. 2017; Church 2017, p. 105). Flowing from the confluence between the N'mai and Mali Rivers originating in the glacial region of northern Myanmar (Chapman et al. 2015), the Irrawaddy River and its tributaries bisect the region. To the east, three great rivers run parallel through Yunnan, the Salween, the Mekong, and the Yangtze Rivers (Fig. 1). Overlapping monsoon systems and undulating geological topography contribute to complex variations in precipitation and temperature across Myanmar (D'Arrigo and Ummenhofer 2015; Oo 2023). Recent palaeoclimatic reconstructions from analyses of lake sediments taken from Twintaung, Monywa, Myanmar, suggests a gradual weakening of the summer monsoon from around 6000 BCE (Chu et al. 2020), with evidence for cyclical periods of drought (Chu et al. 2020; Li et al. 2024b).

Recent work over the last few decades has contributed to understanding the late prehistory and chronology of the region (Coupey 2008, 2010, 2013; Favereau et al. 2018; Pautreau 2007; Pautreau et al. 2010a, b; Pradier 2019, 2022; Pryce et al. 2018a, b, 2024b), but the origin and transmission of agriculture remain unknown. This study focuses on two areas, Oakaie and Halin, each representing a significant archaeological complex in the Sagaing region of north-central Myanmar. Located in a tropical savannah-like environment at the northern reaches of the 'arid, steppe, hot' area (Köppen–Geiger classification of climate) (Beck et al. 2023) the region has an annual rainfall ca. 750 mm (Boori et al. 2017; Murphy and Win Kyaing 2016; Stargardt 1990). Oakaie lies ca. 10 km east of the Chindwin River and Halin 15 km west of the Irrawaddy River (Fig. 2). Punctuated by rivers and streams, the risk in this region is not scarcity of water, but rather the seasonal and spatial variability (Boori et al. 2017).

Although previously excavated by archaeologists from the Ministry of Religious Affairs and Culture (formerly the Ministry of Culture), recent work by the French Archaeological Mission in Myanmar, has revealed a more detailed and nuanced understanding of the chronology and history of the region and sites (Pryce et al. 2018b, 2024b). Modelled on a solid series of over 150 sequential radiocarbon dates, the chronology of the sites largely aligns with the broader regional pattern, with a shift from the Neolithic to the Bronze Age ca. 1000 BCE (1100−900 BCE), with the Bronze Age transitioning into the Iron Age around 500 BCE (600−400 BCE). Oakaie covers the late Neolithic to the early Bronze Age (ca. 1300−700 BCE), while Halin encompasses the early Neolithic to the historic Bagan period (ca. 2700 BCE-1300 CE), although the Neolithic transition has not yet been captured. Representing communities founded during the Neolithic, and in the case of Halin, one that grew into a thriving urban citystate in the Pyu period (ca. 100 CE-900 CE), these sites are highly significant nationally and regionally. The individuals buried in the various cemeteries at these sites provide insight into the people's lives as those communities transformed over time, yielding an opportunity to examine changes in human behaviour, water management practices, and subsistence.

Written historical records from China provide evidence for the interaction and movement of people between Yunnan and Myanmar during the Pyu period (Bin 2019; Liu et al. 2019; Moore 2004, 2019), and clear parallels exist in artefactual evidence (Hudson 2004; Moore 2010). Going back further in time, artefacts such as shouldered stone hoes and spades, ceramic vessels and jadeite artefacts provide possible evidence for migration through Sichuan–Yunnan–Assam (Jacques and Stevens 2024), and linguistic (Sagart et al. 2019) and mitochondrial DNA (Wang et al. 2018) evidence

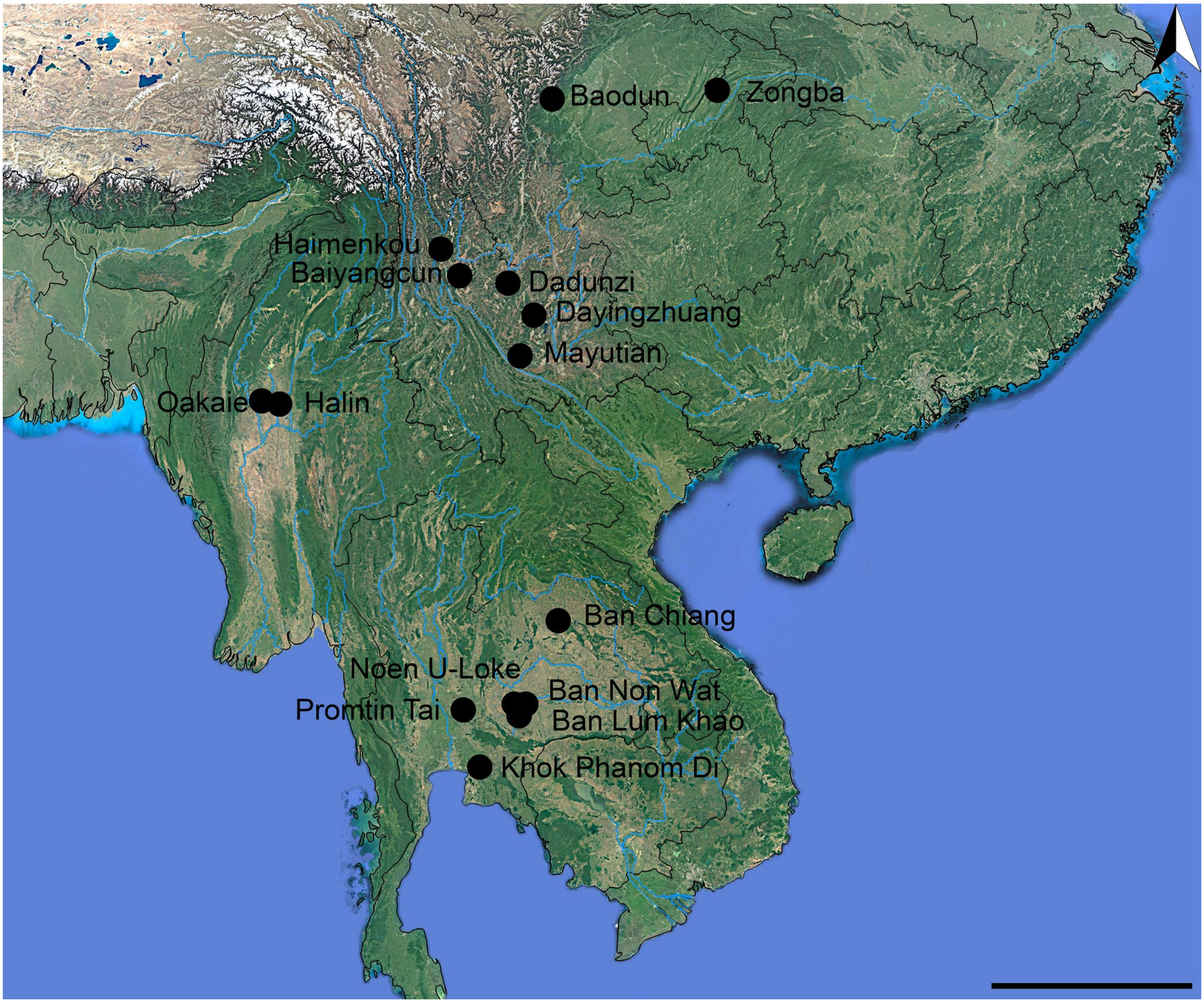

Fig. 1 Location of sites in north-central Myanmar, Thailand, and China. Scale 500 km. Map data: Google Earth Pro 2024. Image Landsat/Copernicus Data SIO, NOAA, U.S Navy, NGA, GEBCO, US Geological Survey

suggest a probable connection from southwest Yunnan to northern Myanmar and northeastern India (Jacques and Stevens 2024, p. 14). Finds of cowrie shells and perforated shell knives have also been used to infer regional connections (Jacques and Stevens 2024; Ma et al. 2022). While no artefacts or practices yet provide solid evidence of a definitive connection between Yunnan, northern Myanmar and northeastern India, there are similarities in the shouldered stone adzes in Assam and Manipur in northeast India (Dikshit and Hazarika 2012 Figs. 4, 5 and 10), Chuankouba and Xiaohedong in Yunnan (Yao 2010 Fig. 4) and Halin (Aung 2019 Fig. 6 ; Hudson 2004 Fig. 17). Perforated stone knives from China are distinctive (Wu et al. 2024; Xue et al. 2025) and characterised by one or more centralised perforations along the back (Li et al. 2024a). Stylistically similar knives have been found at Baiyangcun and Haimenkou in Yunnan (Dal Martello 2020 Figs. 5-6 and 6-6; Kan 1981; Xiao 1995) and northeast India (Dikshit and Hazarika 2012 Figs. 26 and 43). Although this style of artefact is lacking at Halin, there are stone tools with a single perforation at one end (Hudson 2004 Fig. 9). Currently, the purpose of these is unknown, but it is possible they served a similar function and represent a local adaptation or innovation. Clear stylistic similarities in bronze bells, daggers and yue can be seen between Halin (Hudson 2004 Fig. 28; Pryce et al. 2024a Fig. 5), and Dabona, Haimenkou and Dayingzhuang in Yunnan (Chiou-Peng 2009 Fig. 3; Dal Martello 2020 Figs. 6-7 and 6-8; Yunnan Provincial Institute of Cultural Relics and Archaeology 2016 Figs. 19, 21, 22 and 26).

Fig. 2 Location of Oakaie, Halin and Shwebo. Scale 10 km. Map data: Google Earth Pro 2024. Image Landsat/Copernicus Data SIO, NOAA, U.S Navy, NGA, GEBCO, US Geological Survey

Stable isotope analysis

Fundamentally, when analysing $\delta^{13}C$ in carbonate from tooth enamel, "you are what you eat plus a few ‰" (DeNiro and Epstein 1976), but implicitly, this reflects the $\delta^{13}C$ values of plants and the movement and fractionation of $\delta^{13}C$ values from primary consumers to end consumers. Representing the way they photosynthesise CO_2 in the atmosphere, C_3 and C_4 plants have distinctive non-overlapping $\delta^{13}C$ values, and CAM (crassulacean acid metabolism) plants are intermediary. C_3 plants have an average $\delta^{13}C$ value around −26.5‰, while C_4 plants have a higher mean $\delta^{13}C$ value around −12.5‰ (Kohn and Cerling 2002; Smith and Epstein 1971; Tykot 2006). C_3 plants are predominant and include rice, wheat, and soybean, while fewer are C_4 including millet, corn, and sorghum. Although relatively stable and reliable, differences in environmental conditions such as sunlight exposure, humidity, precipitation and water availability can influence the $\delta^{13}C$ values of these plants (Ehleringer et al. 1993; Farquhar et al. 1989; O'Leary 1981). Differences in diet to carbonate isotope fractionation among species, including humans, are influenced by body mass and digestive physiology (Cerling et al. 2021; Codron et al. 2018; Tieszen and Fagre 1993). Specifically, the isotopic offset in $\delta^{13}C$ values between diet and carbonate has been estimated at approximately 12–14‰ in herbivorous animals and 8–9‰ in carnivorous animals (Ambrose and Norr 1993; Krueger and Sullivan 1984; Lee-Thorp et al. 1989; Tieszen and Fagre 1993). For humans, an average offset of ~9‰ exists (Ambrose et al. 1997). Additionally, there is a subtle trophic level increase of about 1‰ from primary consumers to end consumers (Schwarcz and Schoeninger 2011).

$\delta^{18}O$ values in carbonate from tooth enamel reflect water consumption and respiration (Kohn 1996) but globally are influenced by latitude, altitude, and proximity to geographical coastlines (Dansgaard 1964; Lightfoot and O'Connell 2016; Pederzani and Britton 2019). Locally, meteoric rainwater reflects the $\delta^{18}O$ values of precipitation but is also influenced by temperature and humidity. Furthermore, different reservoirs of meteoric water, for example, surface water in rivers, streams and lakes, groundwater beneath the surface in aquifers or wells, or standing water that does not flow in lakes, ponds, reservoirs and troughs, vary due to differential evaporative processes (Bowen and Revenaugh 2003; Daux et al. 2021; Pederzani and Britton 2019). In areas with highly variable, seasonal fluctuations in temperature, humidity, and precipitation, $\delta^{18}O$ values can vary incrementally in tooth enamel by several ‰ over a year (Vaiglova et al. 2024) due to environmental influences on the $\delta^{18}O$ values of water consumed. Bulk sampling generally dampens and averages the variability but may contribute to the heterogeneity observed among individuals in these environments. While temperature has the largest influence on $\delta^{18}O$ values in meteoric water (Bird et al. 2020; Bowen et al. 2019; Dansgaard 1964), plants are more sensitive to variations in humidity and precipitation, which can influence their $\delta^{18}O$ values through evapotranspiration. More impactful on non-obligate drinking or drought-adapted fauna from arid environments, leaf water is less influential on the $\delta^{18}O$ values of obligate drinkers, such as humans (Levin et al. 2006). Highly detailed regional and global data exist for $\delta^{18}O$ (IAEA/WMO 2024) demonstrating a broad latitudinal cline globally (Pederzani and Britton 2019), with relative homogeneity among regions like Southeast Asia.

Materials and methods

The *Mission Archéologique Française au Myanmar* (MAFM), a collaborative, multidisciplinary research project from 2001 to 2020 between the Ministry for Religious Affairs and Culture (MoRAC) in Myanmar and the National Centre for Scientific Research (CNRS) in France, undertook archaeological investigations at cemetery, industrial and settlement locations at Oakaie between 2014 and 2016 and at Halin between 2017 and 2020.

Oakaie 1

Located in a geologically diverse area, Oakaie 1 (22°23'23"N, 95°02'57"E) is close to Twintaung, one of a series of shoshonite basalt volcanic craters formed during the late Cenozoic (Lee et al. 2016) (Fig. 2). Cut into underlying volcanic matrices, the cemetery contained graves of fifty-five individuals, each placed in a supine extended position (Pradier et al. 2019). Based on the radiocarbon chronology for nearby settlement sites, the cemetery dates to ca. 1300−700 BCE (Pryce et al. 2018b), but, unfortunately, establishing the absolute diachronic relationship between the burials was not possible as the cemetery lacked botanical remains for absolute dating.

Halin

Officially recognised as a UNESCO World Heritage site in 2014, Halin (22°28'18"N, 95°48'53"E) represents the ruins of an impressive ancient Pyu period city and citadel which would have posed a striking feature against the surrounding landscape. Built from baked brick (Donovan et al. 1998) between ca. 50–450 CE (Hudson 2004, 2018), the walled city has survived the test of time, a testament to the early brick masons who constructed it. Although Halin represents an early phase of urbanism in Southeast Asia, recent archaeological research (Pryce et al. 2024b) has detailed a record of deeper antiquity. Located on a fertile alluvial area with hot water saline pools and punctuated by streams, between the Irrawaddy and Mu Rivers, the choice of location was strategic and risk-averse as it provided access to small streams but reduced the risk of serious flooding (Stargardt 2016). Like Sri Ksetra, a larger and contemporaneous Pyu citadel ca. 400 km south, the community at Halin engaged in water management practices. Banks and damns redirected a stream northeast of the city walls into the surrounding moat to the north, east and west of the walls, and through the citadel to the southern seasonal lake. A dam outside the southeast walls captured water in the Nagayon tank (Fig. 3) (Stargardt 1986, 1990, p. 25 and 33; Win 2018). A main canal west of the city fed smaller distributary canals that watered adjacent land further west (Stargardt 1990, p. 83). Although much smaller, the shape of the ancient citadel is reminiscent of the nearby moated Konbaung dynasty (1752–1885 CE) city of Shwebo, which appears a striking feature when viewed aerially (Fig. 2).

While the area of Halin was occupied from the Neolithic to the Bagan period, here we focus on the cemetery sites that date between ca. 1200 BCE and 200 CE. Cut into the grey monsoon-washed matrix, the burials in these cemeteries represent individuals from different temporal periods with distinct mortuary traditions and associated artefacts.

HL29

Located southwest of the walls of Halin (Fig. 3), the cemetery of HL29 contained the graves of fifty-one individuals, each placed in a supine extended position, and the cremated remains of nine individuals placed in ceramic vessels. Representing communities from different periods, the cemetery has three distinct layers. The first contained cremation urns from the Bagan period, and the second and third contained Bronze Age burials (Pradier 2022). Based on the charcoal-derived dates (95.4% probability) from the radiocarbon chronology for the cemetery and surrounding area for HL29, the cremation urns date to ca. 900–1400 CE. The burials in the cemetery date to between ca. 1000 and 550 BCE (Pryce et al. 2024c). Preliminary archaeobotanical analysis recovered millet (*Setaria* sp.) and rice (*Oryza* sp.) seeds in six Bagan samples from HL29 (unpublished data) during systematic flotation (Pryce et al. 2017). The millet is possibly *Setaria italica* (foxtail millet) and demonstrates millet cultivation by at least ca. 1000–1200 CE.

HL30

Located about 300 m southwest of HL29, the HL30 cemetery (Fig. 3) contained the graves of eighteen individuals. Representing individuals from three different periods, the Neolithic, Bronze and Iron Ages, the individuals had distinct mortuary practices. Three Neolithic and four Iron Age individuals were in a primary supine extended position, three Iron Age individuals were placed in a secondary

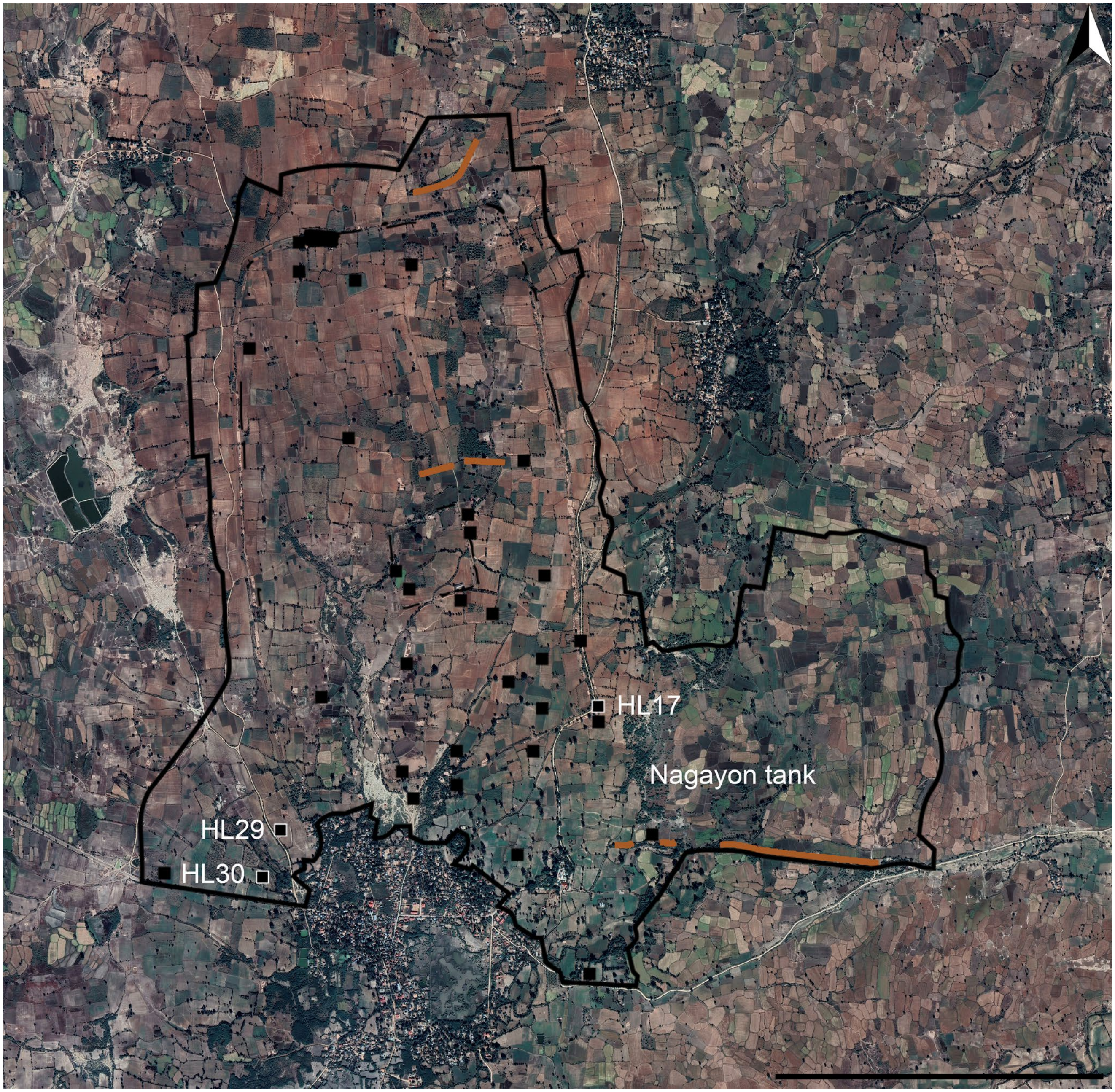

Fig. 3 Archaeological remnants of Halin city (rectangle) and inner citadel (square) within the UNESCO World Heritage area (black line) with previous excavation areas (black squares) and cemetery sites (black squares with white border), and brick dams and embankments (brown) across ancient waterways (naturally greener areas). Scale 1 km. Map data: Google Earth Pro 2024. Image Landsat/Copernicus Data SIO, NOAA, U.S Navy, NGA, GEBCO, US Geological Survey. CNES/Airbus, Maxar Technologies

bundled position, and the remains of eight infants in ceramic vessels dated to the Bronze Age (Pradier 2022). Based on the charcoal-derived dates from the radiocarbon chronology for the cemetery and surrounding area, the Neolithic burials from HL30 date between ca. 1200−1000 BCE, the Bronze from between ca. 1000−400 BCE and the Iron from ca. 400−200 BCE (Pryce et al. 2024c). Two carbonised rice grains (*Oryza* sp.) were recovered from an elderly female Neolithic burial, B21, from HL30 during flotation (Pryce et al. 2024c).

HL17

Located adjacent to the southeast gate, the Iron Age cemetery HL17 (Fig. 3) contained the graves of ten individuals and a mass burial of at least eleven individuals, including subadults and adults (Pradier 2022). The charcoal-derived radiocarbon determinations suggest an activity range between ca. 1000−500 BCE (Pryce et al. 2024c), which is older than expected based on the presence of iron and steel artefacts in some of the burials. While these dates may indicate a local transition to the Iron Age ca. 6th c. BCE, slightly earlier than the 5th -4th c. BCE typical for mainland Southeast Asia (Pryce et al. 2024b), as none of the burials with iron artefacts could be dated, unfortunately the chronological extent of the Iron Age cemetery is not yet well characterised.

Samples

Tooth enamel samples were taken from the remains of 59 human and three faunal individuals, a suid, a cervid and a bovine (Table S1). Third (M3), second (M2) or first (M1) maxillary or mandibular molars were selected from 55 adult individuals and second deciduous molars (dm2) from four subadult individuals. Developing and calcifying at different ages in a relatively consistent pattern, the period from initial cusp completion (Coc) until crown completion (Crc) represents the enamel-forming period of each tooth. The cusp for the deciduous second molar (dm2) forms at around 1.5 months and finishes around 10.5 months, while the formation of the permanent molars reflects the period between ca. 1.5 to 3.5 years (M1), 4.5 to 7.5 (M2) and 10.5 to 14.5 years (M3) (AlQahtani et al. 2010). A regional understanding of the expected baseline for flora and fauna is normally a requisite to understanding and interpreting data. However, lacking local baseline values, we followed previously established practice and used well-established endpoint values from −14 to −12‰ as pure C_3 and values from 0 to 2‰ as pure C_4 (Kohn and Cerling 2002, p. 472; Tykot 2006, p. 133).

Biological profile

Standard bioarchaeological methods were used to develop a biological profile of each individual. Age was estimated using mineralisation and eruption of dentition (AlQahtani et al. 2010), and length and epiphyseal fusion of long bones (Scheuer and Black 2000) for subadults, and pubic symphyseal morphology (Brooks and Suchey 1990) and occlusal tooth wear (Scott 1979) for adults. Sex was estimated using a morphological assessment of the pelvis (Phenice 1969) and cranium (Walrath et al. 2004) and a morphometrical assessment of dimorphism. Biological sex was determined using sex-specific peptides in amelogenin from tooth enamel (Gowland et al. 2021; Stewart et al. 2016, 2017). Peptide analysis was undertaken at the Centre for Protein Research (CPR) at the University of Otago, New Zealand (Online resource 1). Applications to undertake fieldwork and export samples for MAFM research were submitted and approved each year by the MoRAC which provided the permission and permits. Approval to analyse human samples was granted by the Human Research Ethics Committee of James Cook University (HREC- H8312).

Stable isotope analysis

Sample preparation and pretreatment were performed at the Advanced Analytical Centre (AAC) on the Bebegu Yumba campus of James Cook University, Townsville, following Ventresca Miller et al. (2018) (Online resource 1). Stable isotope analysis was undertaken at the Stable Isotope Laboratory in the Research School of Earth Sciences, Australian National University (Online resource 1).

Statistical analyses were undertaken using IBM SPSS Statistics 18. Data were assessed for normality using the Shapiro-Wilk test. Outliers were identified in SPSS using the interquartile range (IQR) at two thresholds 1.5 IQR below Q1 or more than 1.5 IQR above Q3, and 3 IQR below Q1 or more than 3 IQR above Q3 (Lightfoot and O'Connell 2016). Representing 50% of the data, the IQR is the first quartile (Q1), the median value of the lower data, to the third quartile (Q3), the median value of the higher data (Q1-Q3).

Non-parametric tests were run to determine if there were differences in $\delta^{13}C$ or $\delta^{18}O$ values between independent groups. Mann-Whitney U tests were run to compare two independent groups (i.e. males and females). Kruskal-Wallis H tests were run to compare more than two groups (i.e. site) and, where significant, were further examined using Dunn's procedure with a Bonferroni correction. Here, outliers were broadly included, but were excluded in regional comparisons as justified below. To compare the $\delta^{13}C$ and $\delta^{18}O$ values of animal samples with the human population, z-scores ($z = (x - \mu) / \sigma$) were calculated in R to standardise the animal values relative to the mean and standard deviation of the human population. ANOVA tests were run to compare regional sites. An α level of 0.05 was applied in all statistical analyses.

Drawing on published work, the stable isotope results from Oakaie 1 and Halin (HL29 and HL17) were contextualised regionally, and within the broader context of mainland Southeast Asia (Bentley et al. 2005, 2007, 2009; Cox et al. 2011; King et al. 2015; Liu 2018; Schalburg-Clayton 2023) and China (Lanehart et al. 2011; Tian et al. 2008; Zhang et al. 2014). HL30 was not included due to the small sample population and temporal characteristics of the cemetery, representing disparate individuals from the Neolithic and Iron Age. Common among these datasets are individuals with outlying isotope values who provide valuable insight into the movement and migration of people with different subsistence economies or from regions with different underlying geology. To compare the normal characteristics of community subsistence, these individuals were excluded from the statistical analyses (Table S3). However, they are included in the bivariate Figures to emphasise their value.

Results

Humans

The δ^{13}C values of the individuals (59) from Halin (HL17, HL29 and HL30) and Oakaie 1 ranged from −13.1‰ to −2.7‰, with a mean value (μ) of −8.3‰ (Table 1). The individuals from the areas of Halin had δ^{13}C values ranging from −13.1‰ to −8.3‰ at HL17 with a mean value of −11.9‰, −11.8‰ to −2.7‰ (μ = −7.6‰) (HL29), and −12.2‰ to −3.6‰ (μ = −9.1‰) (HL30) (Table 1; Fig. 4). At Oakaie 1, the individual's values ranged from −8.8‰ to −3.5‰ with a mean value of −6.5‰ (Table 1; Fig. 4). Three outliers were identified at HL17, two males, B4 and B5 and a female, B10 with the highest δ^{13}C values, and three outliers were identified at Oakaie 1, one male, S4 and two females, S6 and S31 with the highest δ^{13}C values. The δ^{18}O values of all 59 individuals from the sites ranged from 23.9‰ to 28.0‰ with a mean value of 25.7‰ (Table 1). The individuals from HL17, HL29 and HL30 had δ^{18}O values ranging from 23.9‰ to 25.4‰ with a mean value of 24.7‰, 23.9‰ to 28.0‰ (μ = 25.9‰), and 24.7‰ to 27.8‰ (μ = 26.1‰), respectively (Table 1; Fig. 4). At Oakaie 1, the individuals' values ranged from 24.3‰ to 27.5‰ with a mean value of 25.9‰ (Table 1; Fig. 4). One individual was an outlier at HL30, a female, B5. Kruskal-Wallis H Tests demonstrated statistically significant differences in the stable carbon ($\chi 2(3) = 27.048$, $p = < 0.001$) and oxygen ($\chi 2(3) = 15.262$, $p = 0.002$) isotopes values of the individuals between the four areas (Table 2). Specifically, post hoc analysis revealed that HL17 had statistically significantly lower δ^{13}C and δ^{18}O values than HL29 ($p = 0.001$ and 0.007) and Oakaie 1 ($p = 0.000$ and 0.002), respectively.

Temporal differences between the sites

Because HL30 had so few individuals and they dated to such disparate temporal periods, the Neolithic and Iron Ages, differences were also examined by period. Burials 20 and B21 were Neolithic and B5, B6 and B11 were Iron Age burials (Table S1). The δ^{13}C values of individuals ranged from −8.8‰ to −3.5‰ with a mean value of −6.3‰ (Neolithic), −11.8‰ to −2.7‰ (μ = −7.6‰) (Bronze Age) and −13.1‰ to −8.3‰ (μ = −11.9‰) (Iron Age) (Table 1, Table S1 and Fig. 5). The δ^{18}O values ranged from 24.3‰ to 27.5‰ with a mean value of 26.0‰, 23.9‰ to 28.0‰ (μ = 25.9‰) and

Table 1 Descriptive statistics for δ^{13}C and δ^{18}O isotope values of human samples

	HL17			HL29			HL30			OAI 1			Total			Period		
	Males	Females	Total	Males	Females	Total	Males	Females	Total	Males	Females	Total	Males	Females	Total	Neolithic	Bronze	Iron
δ^{13}C (‰ VPDB)																		
N	3	10	13	15	6	21	1	4	5	12	8	20	31	28	59	22	21	16
Mean	−11.1	−12.1	−11.9	−7.3	−8.3	−7.6	−12.2	−8.3	−9.1	−6.7	−6.2	−6.5	−7.6	−9.1	−8.3	−6.3	−7.6	−11.9
Minimum	−13.0	−13.1	−13.1	−11.6	−11.8	−11.8		−12.2	−12.2	−8.8	−7.8	−8.8	−13.0	−13.1	−13.1	−8.8	−11.8	−13.1
Maximum	−10.0	−8.3	−8.3	−2.7	−5.0	−2.7		−3.6	−3.6	−3.9	−3.5	−3.5	−2.7	−3.5	−2.7	−3.5	−2.7	−8.3
Range	2.9	4.8	4.8	8.9	6.9	9.2		8.6	8.6	4.9	4.2	5.3	10.3	9.6	10.5	5.3	9.2	4.8
SD	1.6	1.4	1.5	2.4	2.5	2.5		4.3	4.1	1.3	1.7	1.5	2.4	3.3	2.9	1.5	2.5	1.3
δ^{18}O (‰ VSMOW)																		
N	3	10	13	15	6	21	1	4	5	12	8	20	31	28	59	22	21	16
Mean	25.0	24.6	24.7	26.1	25.5	25.9	25.5	26.3	26.1	24.3	26.2	25.9	25.9	25.5	25.7	26.0	25.9	25.0
Minimum	24.4	23.9	23.9	23.9	24.2	23.9		24.7	24.7	24.4	25.0	24.3	23.9	23.9	23.9	24.3	23.9	23.9
Maximum	25.4	25.2	25.4	28.0	27.5	28.0		27.8	27.8	27.5	27.2	27.5	28.0	27.8	28.0	27.5	28.0	27.8
Range	1.0	1.3	1.6	4.1	3.3	4.1		3.1	3.1	3.3	2.1	3.3	4.1	3.9	4.1	3.3	4.1	3.9
SD	0.6	0.4	0.5	1.2	1.2	1.2		1.3	1.2	0.9	0.8	0.9	1.1	1.1	1.1	0.8	1.2	0.9

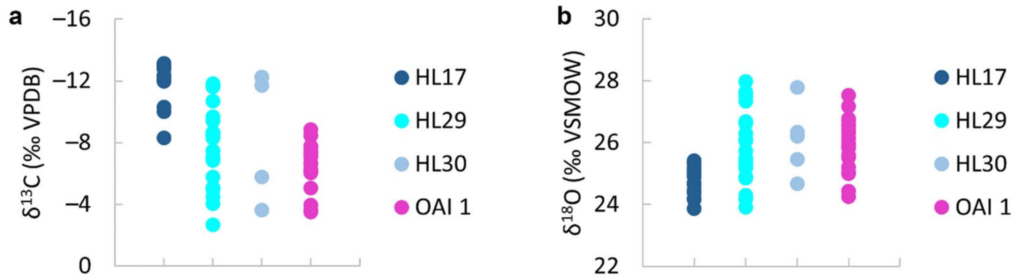

Fig. 4 **a** $\delta^{13}C$ and **b** $\delta^{18}O$ isotope values of human samples by site

23.9‰ to 27.8‰ (μ=25.0‰), respectively (Table 1 and Table S1). Kruskal-Wallis H Tests demonstrated statistically significant differences in the stable carbon ($\chi 2(2)=33.417$, $p<0.001$) and oxygen ($\chi 2(2)=12.375$, $p=0.002$) isotopes values of the individuals between the periods (Table 2). Specifically, post hoc analysis revealed that the individuals from the Iron Age had statistically significantly lower $\delta^{13}C$ and $\delta^{18}O$ values than those from the Neolithic ($p=0.000$ and 0.003) and Bronze Age ($p=0.000$ and 0.014), respectively.

Sex differences

The $\delta^{13}C$ values from the dental enamel of the male individuals (31) from Halin (HL17, HL29 and HL30) and Oakaie 1 ranged from −13.0‰ to −2.7‰ with a mean value of −7.6‰ and the females (28) ranged from −13.1‰ to −3.5‰ (μ = −9.1‰) (Table 1). There was one male outlier, B6 from HL17 with the lowest $\delta^{13}C$ value. The $\delta^{18}O$ values of the males ranged from 23.9‰ to 28.0‰ with a mean value of 25.9‰ and the females ranged from 23.9‰ to 27.8‰ (μ=25.5‰) (Table 1). Mann-Whitney U tests revealed no statistically significant differences in the $\delta^{13}C$ ($U=327.000$, $z=-1.624$, $p=0.104$ and $\delta^{18}O$ ($U=339.000$, $z=-1.442$, $p=0.149$) values of males and females (Table 3).

The $\delta^{13}C$ values of males and females from HL17 were similar. The male values ranged from −13.0‰ to −10.0‰ with a mean of −11.1‰ and the females ranged from −13.1‰ to −8.3‰ (μ = −12.1‰) (Table 1; Fig. 6). There was one female identified as an outlier, B10, with the highest $\delta^{13}C$ value (–8.3‰). The $\delta^{18}O$ values of males and females from HL17 were also similar. The male values ranged from 24.4‰ to 25.4‰ with a mean of 25.0‰ while the females ranged from 23.9‰ to 25.2‰ (μ=24.6‰) (Table 1; Fig. 6). Mann-Whitney U tests revealed there were no statistically significant differences in the $\delta^{13}C$ ($U=9.000$, $z=-1.014$, $p=0.371$) or $\delta^{18}O$ ($U=7.000$, $z=-1.352$, $p=0.217$) values of males and females at HL17, using an exact sampling distribution for U (Table 3).

The $\delta^{13}C$ values of males and females from HL29 were similar. The male values ranged from −11.6‰ to −2.7‰ with a mean of −7.3‰ and the females ranged from −11.8‰ to −5.0‰ (μ = −8.3‰) (Table 1; Fig. 6). The $\delta^{18}O$ values of males and females from HL17 were also similar ranging from 23.9‰ to 28.0‰ (μ=26.1‰) and 24.2‰ to 27.5‰ (μ=25.5‰), respectively (Table 1; Fig. 6). Mann-Whitney U tests revealed there were no statistically significant differences in the $\delta^{13}C$ ($U=38.000$, $z=-0.545$, $p=0.622$) or $\delta^{18}O$ ($U=31.000$, $z=-1.090$, $p=0.302$) values of males and females at HL29, using an exact sampling distribution for U (Table 3). The sample size of HL30 was too small to undertake statistical analyses. There was one male with a $\delta^{13}C$ value of −12.2‰ and four females with a range from −12.2‰ to −3.6‰ and an average of −8.3‰. The male's $\delta^{18}O$ value was 25.5‰ and the female's values ranged from 24.7‰ to 27.8‰ (μ=26.3‰) (Table 1; Fig. 6).

The $\delta^{13}C$ values of males and females from Oakaie 1 were similar. The male values ranged from −8.8‰ to −3.9‰ with a mean of −6.7‰ and the females ranged from −7.8‰ to −3.5‰ (μ = −6.2‰) (Table 1; Fig. 6). One outlier was identified, a male, S4, with the highest carbon value of −3.9‰. The $\delta^{18}O$ values of males and females at Oakaie 1 were also similar ranging from 24.4‰ to 27.5‰ (μ=24.3‰) and 25.0‰ to 27.2‰ (μ=26.2‰), respectively (Table 1; Fig. 6). Mann-Whitney U tests revealed there were no statistically significant differences in the $\delta^{13}C$ ($U=51.000$, $z=0.231$, $p=0.851$) or $\delta^{18}O$ ($U=62.000$, $z=1.080$, $p=0.305$) values of males and females at Oakaie 1, using an exact sampling distribution for U (Table 3).

Fauna

When comparing the fauna from Bronze Age Halin to humans from the same period (Table 1 and Table S1), the $\delta^{13}C$ values of the cervid (2.3‰) and bovine (–1.0‰) were significantly higher than the mean value of humans (–7.6‰). Z-scores indicated that the cervid ($z=3.96$, $p<0.001$) and bovine ($z=2.64$, $p=0.008$) values were higher than 99.99% and 99.59% of the human population, respectively. The suid's value (–6.3‰) was similar to humans ($z=0.52$, $p=0.603$) but higher than 69.85% of the human population (Table 4). The $\delta^{18}O$ value of the bovine (28.4‰) was significantly higher than the mean value of the humans (25.9‰)

Table 2 Kruskal-Wallis H statistics for $\delta^{13}C$ and $\delta^{18}O$ isotope values of human samples

	Halin and Oakaie									Halin and Oakaie						
	HL17		HL29		HL30		OAI 1			Neolithic		Bronze		Iron		
	M	MR	M	MR	M	MR	M	MR	*p*	M	MR	M	MR	M	MR	*p*
$\delta^{13}C$ (‰ VPDB)	−12.3	9.54	−8.3	33.14	−11.7	27.20	−6.7	40.70	**<0.001***	−6.7	44.17	−8.3	33.14	−12.2	9.69	**<0.001***
$\delta^{18}O$ (‰ VSMOW)	24.7	13.69	25.7	33.33	26.2	36.60	25.9	35.45	**0.002***	26.1	36.09	25.7	33.33	24.8	17.25	**0.002***

*Kruskal-Wallis H test; M = median; MR = mean rank

and 98.12% of the human population ($z = 2.08$, $p = 0.037$). Closer to the humans, the value of the cervid (27.6‰) and suid (26.5‰) were higher than 92.22 and 69.15% of the human population, but not significantly different ($z = 1.42$, $p = 0.157$, $z = 0.50$, $p = 0.617$) (Table 4; Fig. 7).

Regional comparison

A Welch ANOVA demonstrated statistically significant differences among the sites Welch's $F(12, 81.733) = 227.258$, $p < 0.001$. Specifically, post hoc analysis revealed that the individuals from Oakaie 1 and HL29, respectively, had statistically significantly higher mean $\delta^{13}C$ values than all the individuals from the Thai sites. In comparison to the Chinese sites, they had statistically significantly higher $\delta^{13}C$ values than Liangchengzhen, respectively. Oakaie had statistically significantly higher $\delta^{13}C$ values than Mayutian and both sites had statistically significantly lower $\delta^{13}C$ values than the individuals from Zhongba. Further, the post hoc analyses revealed that the mean $\delta^{13}C$ value of the individuals from HL17 was statistically significantly lower than those from Oakaie 1 and HL29, as identified earlier, and all the Chinese sites but statistically significantly higher than those from Ban Chiang, Ban Lum Khao, and Noen U-Loke. There were no significant differences between HL17 and Promtin Tai, Khok Phanom Di, Non Ban Jak or Ban Non Wat (Table 5; Fig. 8).

A Welch ANOVA demonstrated statistically significant differences among the sites Welch's $F(12, 66.288) = 91.355$, $p < 0.001$. Specifically, post hoc analysis revealed that individuals from Oakaie 1 and HL29, respectively, had statistically significantly lower mean $\delta^{18}O$ values than the northeast Thai sites of Noen U-Loke and Ban Chiang, although only Oakaie 1 was statistically significantly different to the latter, and statistically significantly higher than those from Zhongba and Mayutian in China. Further, they revealed that the mean $\delta^{18}O$ value of the individuals from HL17 was statistically significantly lower than those from Oakaie 1 and HL29, as identified earlier, Khok Phanom Di, Ban Non Wat, Ban Chiang, Noen U-Loke, Promtin Tai and Non Ban Jak, and significantly higher than those from Zhonga and Mayutian (Table 6; Fig. 8).

Discussion

Recently, stable carbon and oxygen isotope analyses provided an insight into the subsistence practices of two prehistoric communities, Oakaie 1 and Nyaung'gan, living in north-central Myanmar during the late Neolithic and Early Bronze Age (Willis et al. 2023). Preliminary data indicated that individuals during this period had significantly higher

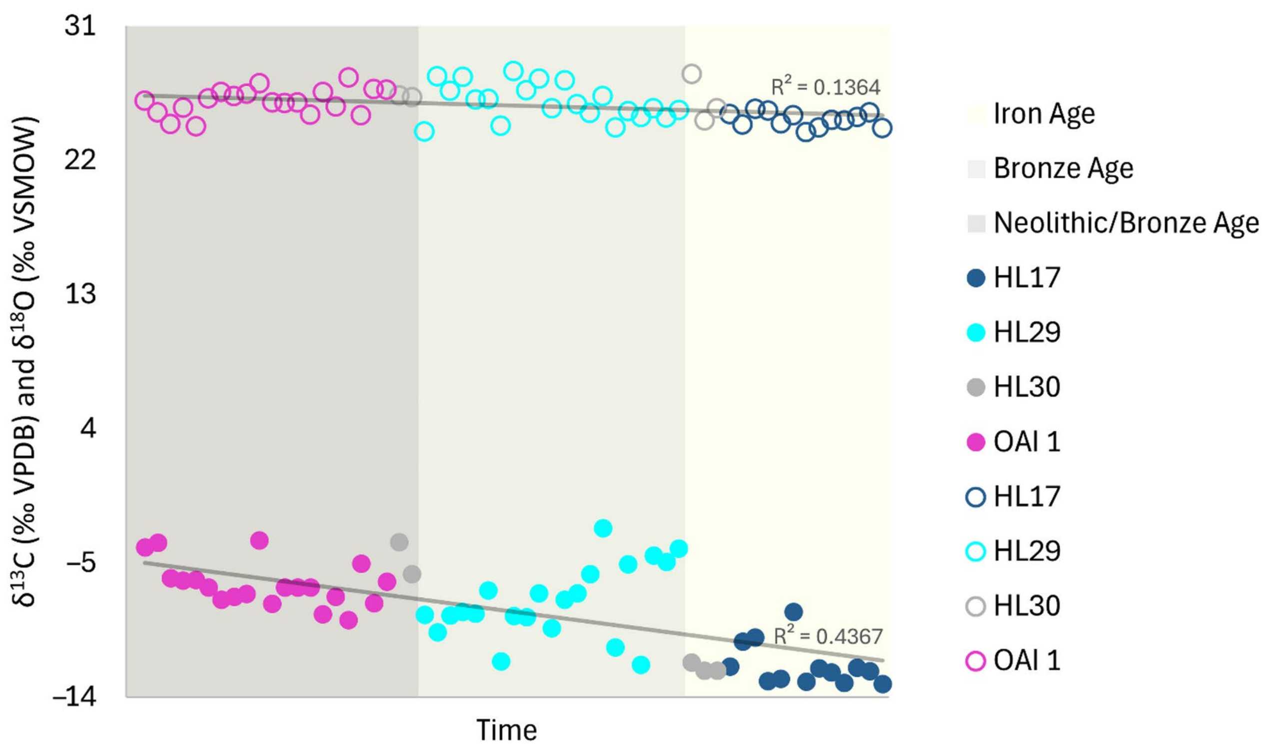

Fig. 5 $\delta^{13}C$ and $\delta^{18}O$ isotope values of human samples by time

$\delta^{13}C$ values than those from broadly contemporary mainland Southeast Asian communities of rice farmers, suggesting a different subsistence economy. However, this work lacked the necessary temporal resolution to identify any changes in the trajectory and intensification of agriculture through time. Halin, with a longer chronology, was investigated here to provide the opportunity to assess changes in north-central Myanmar agricultural practices and human behaviour over time. With a range of 10.5‰, the communities of Oakaie 1 and Halin practised a mixed subsistence strategy with variable contribution of C_3/C_4 resources encompassing the spectrum from pure C_3 to pure C_4 (Kohn and Cerling 2002; Tykot 2006). Here we frame our discussion to address five key questions to understand the source of diversity through a biosocial, temporal, and regional lens.

Is there any evidence of sex-based differences in diet in north-central myanmar?

When examining differences between the sites, very few outliers were identified. Among these individuals, two males (B4 and B5) and one female (B10) from HL17, and one male (S4) and two females (S6 and S31) from Oakaie 1 had the highest $\delta^{13}C$ values; one individual, a female (B5) from HL30 had the highest $\delta^{18}O$ value. When examining differences between the sexes by site, only two outliers remained: one female (B10) from HL17, and one male (S4) from Oakaie, each with the highest $\delta^{13}C$ values. Despite these outliers, there were no differences in the $\delta^{13}C$ or $\delta^{18}O$ values between males and females at any of the sites. There were no sex-based differences in the diet at Oakaie 1 or Halin based on stable isotope values, irrespective of period, indicating males and females had a similar diet with equal access to resources. These individuals could, however, have come from a different geological region where C_4 resources played a larger role in the subsistence economy, and each has a unique story. Consideration of the movement and migration of individuals is being further explored elsewhere (Pradier et al. under review; Willis et al. in preparation).

Is there any evidence of Temporal changes in environmental conditions in north-central myanmar?

While $\delta^{13}C$ and $\delta^{18}O$ values accurately and reliably reflect plants and water consumed, and changes in human behaviour and their subsistence strategies over time, several factors can influence their expression. The variable $\delta^{13}C$ values of the individuals living in the late Neolithic to early Bronze Age community of Oakaie 1 and the Bronze Age community at HL29 at Halin suggest they had a diverse and mixed subsistence economy, with a larger contribution

Table 3 Mann-Whitney U statistics for $\delta^{13}C$ and $\delta^{18}O$ isotope values of human samples

	Halin and Oakaie					HL17					HL29					OAI 1				
	Males		Females			Males		Females			Males		Females			Males		Females		
	M	MR	M	MR	*p*	M	MR	M	MR	*p*	M	MR	M	MR	*p*	M	MR	M	MR	*p*
$\delta^{13}C$ (‰ VPDB)	−7.5	33.45	−8.4	26.18	0.104*	−10.3	9.00	−12.3	6.40	0.371*	−8.3	11.47	−7.7	9.83	0.622*	−6.7	10.25	−6.7	10.88	0.851*
$\delta^{18}O$ (‰ VSMOW)	25.6	33.06	25.1	26.61	0.149*	25.3	9.67	24.7	6.20	0.217*	26.1	11.93	25.3	8.67	0.302*	25.8	9.33	26.2	12.25	0.305*

*Mann-Whitney U test. M = median, MR = mean rank

of C_4 resources, either from plant-based resources or terrestrial fauna. A clear temporal shift in subsistence strategy can be seen at HL17 in Halin, with lower and less variable $\delta^{13}C$ values suggesting a stable subsistence economy with a larger contribution of C_3 resources by the Iron Age. This could reflect temporal changes in agricultural practices, animal husbandry, or environmental conditions in the region. As both Oakaie 1 and Halin are located on the edge of the Central Dry Zone and plants grown in water-stressed or dryer conditions have higher $\delta^{13}C$ values (Carter and Chesson 2017; Yoneyama et al. 2010), the environmental context could have contributed to the higher values observed among individuals during the late Neolithic and Bronze Age. However, it does not explain the shift to lower $\delta^{13}C$ values seen at Iron Age HL17, given that the change occurred within the same environmental context and the region was arguably experiencing a weakening of the monsoon and drier conditions over time (Chu et al. 2020; Li et al. 2024b). If the regional climate was influencing the $\delta^{13}C$ values in plants, technological changes in water management and agricultural practices over time could have contributed to lower $\delta^{13}C$ values in the plants that people were consuming.

The individuals from the late Neolithic to early Bronze Age community of Oakaie 1 and the Bronze Age community at HL29 at Halin had wide-ranging $\delta^{18}O$ values. A clear temporal shift can be seen among the Iron Age HL17 community, with lower and less variable $\delta^{18}O$ values. These temporal changes may represent changes in the source of drinking water, technological changes in water management practices, or environmental changes in precipitation (Pederzani and Britton 2019). As the Central Dry Zone is in the rain shadow of the Rakhine mountain complex, the environmental context could have influenced the values among individuals during the late Neolithic and Bronze Age (Blisniuk and Stern 2005). However, it does not explain the shift to lower $\delta^{18}O$ values at Iron Age Halin, given that the change occurred within the same environmental context and the region was arguably experiencing drier conditions over time. If the regional climate and precipitation were influencing $\delta^{18}O$ values in water sources, technological changes in water use and storage over time could have contributed to lower $\delta^{18}O$ values in water sources that people were consuming.

Irrespective of geographic location, the similarities between the individuals from the late Neolithic and Bronze Age communities of HL29 at Halin and Oakaie 1, and the differences between them and the Iron Age community of HL17 at Halin strongly suggest the magnitude of temporal differences are the result of human behaviour and technological development, rather than anything geographical, environmental, or climatic. This aspect will be explored further below.

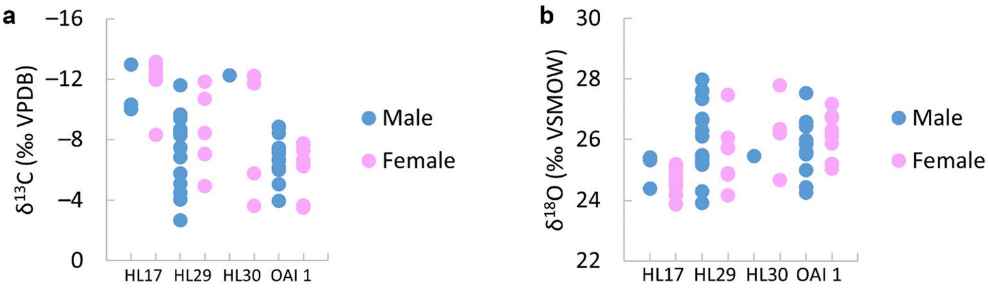

Fig. 6 **a** $\delta^{13}C$ and **b** $\delta^{18}O$ isotope values of human samples by sex

Table 4 z statistics for $\delta^{13}C$ and $\delta^{18}O$ isotope values of faunal samples compared to human and faunal samples

	Bronze Age							
	$\delta^{13}C$	*z*	*p*	%	$\delta^{18}O$	*z*	*p*	%
Cervid	2.3	3.96	**<0.001**	99.99	27.6	1.42	0.157	92.22
Suid	–6.3	0.52	0.603	69.85	26.5	0.50	0.617	69.15
Bovine	–1.0	2.64	**0.008**	99.59	28.4	2.08	**0.037**	98.12

z = *z* test score; percentage values derived from the standard normal (*z*) table

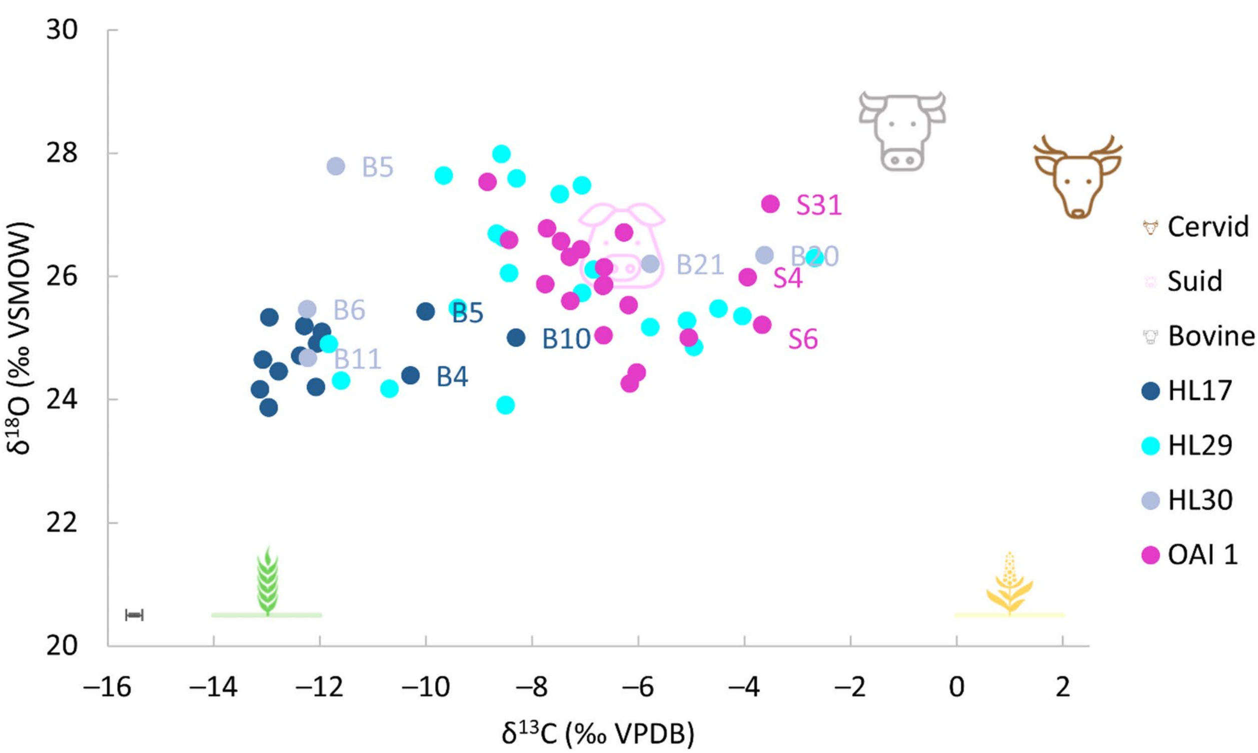

Fig. 7 $\delta^{13}C$ and $\delta^{18}O$ isotope values of human and faunal samples

Is there any evidence of animal husbandry in north-central myanmar?

Unfortunately, with so few faunal samples and without incremental data (Gillis et al. 2021; Vaiglova et al. 2018), we lack the necessary resolution to evaluate possible evidence of animal management practices in depth, but despite these limitations, some cautious interpretations are made. Three faunal samples from HL30's Bronze Age occupation deposit provided an opportunity to compare their feeding practices and range to humans from the same period. The suid was likely domesticated and corralled, while the cervid was likely wild and roaming free, however, the status of the bovine is less clear. The $\delta^{13}C$ values of the suid were

Table 5 Welch statistics for $\delta^{13}C$ isotope values of comparative sites

	OAI 1	HL29	Mayutian	Liangchengzhen	Khok Phanom Di	Non Ban Jak	Ban Non Wat	HL17	Promtin Tai	Zhongba	BanChiang	Ban Lum Khao
OAI 1												
HL29	0.994											
Mayutian	**0.010**	0.569										
Liangchengzhen	**<0.001**	**0.014**	0.756									
Khok Phanom Di	**<0.001**	**<0.001**	**<0.001**	**0.002**								
Non Ban Jak	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.004**							
Ban Non Wat	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.687						
HL17	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.996	0.707	0.149					
Promtin Tai	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.998	0.872	0.307	1.000				
Zhongba	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**			
Ban Chiang	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.002**	**0.007**	**<0.001**		
Ban Lum Khao	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	
Noen U-Loke	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.113	0.625

closest to the humans, indicating they may have been foddered on human food scraps, while the values of the cervid and bovine were different. The cervid value was slightly higher than the bovine, suggesting they were grazing C_4 forage exclusively, while the bovine may have been managed and pastured in dry grasslands surrounding the site. The $\delta^{18}O$ values of the suid, cervid and bovine indicate they were potentially consuming water from different sources. The suid had values closest to the humans, indicating they were likely watered from a similar source, while the values of the cervid and bovine suggest they were watering from different sources to humans. The slightly higher value of the bovine in comparison to the cervid suggests they may have been drinking from a more evaporatively enriched source, likely a source of standing water like a tank or trough, rather than a flowing water source.

Is there differences among individuals from communities in mainland Southeast Asia any evidence of, China, and north-central Myanmar?

To better understand the subsistence economy of Oakaie 1 and Halin, it is necessary to situate the interpretation within a broader regional context. Emphasising the variable subsistence economies across the region, the communities of northeast Thailand focused on dry rice agriculture throughout the Neolithic and Bronze Ages (Castillo 2011) shifting to wet rice in the Iron Age (Castillo et al. 2018; Wohlfarth et al. 2016). Meanwhile, the Chinese communities focused on both rice and millet (Dal Martello et al. 2018, 2021; Jin et al. 2014; Xue et al. 2022; Zhang et al. 2014) or exclusively on millet (Tian et al. 2008).

The individuals from the late Neolithic and Bronze Age sites of Oakaie 1 and HL29 in Myanmar had higher $\delta^{13}C$ values than individuals from all the other sites in Thailand. As discussed above, during the late Neolithic and Bronze Age periods, the subsistence strategy of the communities of Oakaie 1 and HL29 likely included a higher proportion of C_4 resources, either from plant-based foods or from terrestrial grazing fauna, but perhaps the former is more likely. The only way to clarify this would be to examine the influence of terrestrial protein in the diet, and/or investigate other isotopic trophic level indicators (e.g. Mg, Ca and Zn (Jaouen and Pons 2017), both of which would assist in understanding the underlying cause. Presumably, and based on zooarchaeological evidence (Higham 2021), individuals from Thailand and Myanmar would have been consuming terrestrial grazing fauna. The difference in $\delta^{13}C$ values between the individuals from the late Neolithic and Bronze Age sites of Oakaie 1 and HL29 and all the Thai sites suggests C_4 plant-based foods, like millet, likely played a greater role in the subsistence economy in Myanmar. The similarity in

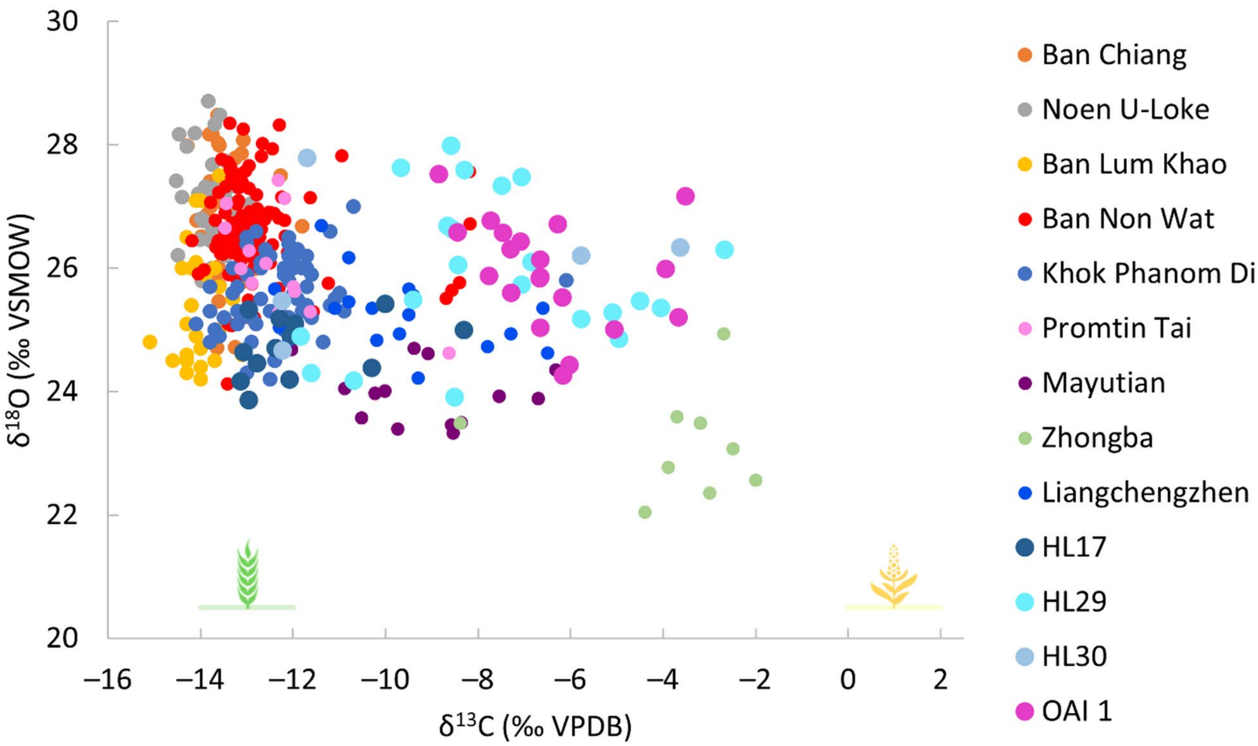

Fig. 8 $\delta^{13}C$ and $\delta^{18}O$ isotope values of human samples from Myanmar, Thailand, and China

$\delta^{13}C$ values between Bronze Age HL29 and Mayutian in southwest Yunnan supports the interpretation of a shift from a broader spectrum to mixed cropping systems in Myanmar. The difference in $\delta^{13}C$ values between individuals from Iron Age HL17 and individuals from the Chinese sites supports the interpretation of a move away from mixed cropping systems toward a more focal crop, while the similarity in $\delta^{13}C$ values between Iron Age HL17 and the moated multiperiod Ban Non Wat, and Iron Age Promtin Tai and Non Ban Jak from central and northeast Thailand provides support for the intensification of irrigated wet rice agriculture in Myanmar.

The high variability in $\delta^{18}O$ values among individuals at all the sites speaks to the complex interplay between seasonal environmental variables such as precipitation and temperature and subsequent evaporative effects on meteoric water and is difficult to interpret. Perhaps the only relevant observation here is that individuals from Iron Age HL17 had significantly lower $\delta^{18}O$ values than almost all other late prehistoric communities in mainland Southeast Asia.

Is there any evidence of temporal changes in water management and the intensification of agriculture in north-central Myanmar?

During the late Neolithic and early Bronze Age at Oakaie 1, the local community probably knew about millet and rice agriculture but also focused on gathering plants and hunting and catching resources from ecologically variable habitats, including wild fauna from surrounding grasslands (Willis et al. 2023) and aquatic resources from surrounding rivers and streams rather than engaging in intensive agriculture. During the Bronze Age at HL29 and HL30, the local community probably still engaged in many of these activities, especially hunting wild Cervidae (Pradier et al. under review), but mixed cropping systems and animal domestication likely began intensifying. During the Iron Age at HL30 and HL17, there were likely technological changes in water management practices, essential for wet rice agriculture (Fuller and Qin 2009) and potentially the beginning of more sophisticated irrigation systems seen in the later Pyu period. This is broadly consistent with practices during the contemporary late Dian and early Han periods in Yunnan (Dal Martello et al. 2021).

During the late Neolithic and Bronze Ages, the individuals from the communities at Oakaie 1 and HL29 probably collected meteoric surface water, either rainwater or from streams. Due to the variability and unpredictability of rainfall in the Central Dry Zone, the latter is more likely. Still, in either case, they were probably storing the water in ceramic vessels. With rates of evaporation twice as high as precipitation in the region (Boori et al. 2017), the evaporative effects likely increased the $\delta^{18}O$ of any reservoirs of stored water

Table 6 Welch statistics for $\delta^{18}O$ isotope values of comparative sites

	OAI 1	HL29	HL17	Liangchengzhen	Promtin Tai	Khok Phanom Di	Non Ban Jak	Ban Lum Khao	Ban Non Wat	Ban Chiang	Mayutian	Zhongba
OAI 1												
HL29	1.000											
HL17	**<0.001**	**0.017**										
Liangchengzhen	0.075	0.358	0.366									
Promtin Tai	1.000	1.000	**0.003**	0.082								
Khok Phanom Di	0.875	0.987	**<0.001**	0.169	0.706							
Non Ban Jak	0.997	1.000	**0.025**	0.746	0.963	1.000						
Ban Lum Khao	0.896	0.976	0.128	0.982	0.744	1.000	1.000					
Ban Non Wat	0.088	0.357	**<0.001**	**<0.001**	0.505	**<0.001**	**0.002**	**<0.001**				
Ban Chiang	**0.024**	0.137	**<0.001**	**<0.001**	0.217	**<0.001**	**<0.001**	**<0.001**	0.963			
Mayutian	**<0.001**	**<0.001**	**0.020**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**		
Zhongba	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.963**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.028**	
Noen U-Loke	**<0.001**	**0.017**	**<0.001**	**<0.001**	**0.031**	**<0.001**	**<0.001**	**<0.001**	0.069	0.989	**<0.001**	**<0.001**

(Daux et al. 2021; Pederzani and Britton 2019). During the Iron Age at Halin, technological changes in water management practices and an increased focus on sourcing groundwater for wells or constructing tanks for larger reservoirs of standing water could have contributed to the lower $\delta^{18}O$ in the water source they were drinking.

The most likely explanation for the decreasing $\delta^{13}C$ values and $\delta^{18}O$ values over time is an increased focus on rice consumption and standing water sources, and with an increasingly sophisticated knowledge of hydrology and harnessing the power of water, the development of agricultural and water management practices.

Synthesis, conclusions and future work

The origins of agriculture have been a focal point of interest in mainland Southeast Asia because of the profound influence domestication of cereal crops had on the ancient inhabitants of the region. Mountainous and forested but borderless and interconnected by river systems, it is not difficult to imagine how riverine communications contributed to the diverse mosaic of cultures and languages in late prehistoric Southeast Asia (Dal Martello et al. 2018). Palaeobotanical, metallurgical (Pryce et al. 2024a), genetic (Lipson et al. 2018; McColl et al. 2018; Tao et al. 2023; Wei et al. 2024; Yang et al. 2020a) and linguistic analyses (Sagart et al. 2019; Zhang et al. 2019, 2020) are crucial to understanding this (Dal Martello 2022). Similar to individuals from the Neolithic and Bronze Age in Yunnan (Tao et al. 2023), the ancient DNA of two individuals from Oakaie 1 suggested they were likely descendent from Sino-Tibetan speaking populations of East Asian origin (Lipson et al. 2018). Drawing on insights from recent stable isotope analysis (Willis et al. 2023), we focused on southwest China to explore possible cultural connections.

Recently, Yunnan has been highlighted as an important region for the early transmission of metallurgy into Myanmar and broader mainland Southeast Asia (Pryce et al. 2024b; Xue et al. 2022; Yao et al. 2020), intimating the presence of significant pre-existing Neolithic cultural connections from the early third millennium BCE. Due to its proximal position to Myanmar and connection through major river systems, we argue that the subsistence practices focused on mixed cropping systems of wet rice and dry millet in Yunnan (Dal Martello et al. 2018, 2021; Jin et al. 2014; Xue et al. 2022) were influential in the adoption and intensification of agriculture in Myanmar. Located between the Chindwin and Irrawaddy Rivers, the individuals in north-central Myanmar are likely descended from small low-density communities who travelled from Yunnan down the Irrawaddy River and tributary systems, bringing their knowledge of mixed millet and rice farming practices. Settling in the region in the Neolithic and establishing their communities, their subsistence economy was perhaps initially more focused on broad-spectrum subsistence and millet.

Situated strategically and intentionally, the location of Halin on the fringes of the Central Dry Zone would have provided soil suitable for rainfed dry millet agriculture and alluvial plains fed by streams from the Mu River suitable for wet rice cultivation during seasonal flooding. Similar to the Bronze Age in Yunnan (Yao et al. 2015, p. 224), the inhabitants of Halin likely focused initially on dry season crops with rice being less focal to their agricultural economy. The area's ecological diversity would have provided the inhabitants of Halin with a stable and reliable subsistence economy and was likely crucial for nourishing the growth and development of urbanisation and the rise of state society in the Pyu period. While not as sophisticated as the hydraulic systems of the later Pyu, these communities likely began developing water management innovation and engaging in irrigated agricultural practices, with an increased emphasis on rice over time.

In mainland Southeast Asia, tangible evidence for late prehistoric interaction spheres represents deeply intangible antiquity. Largely represented by ephemeral organic evidence, much regional prehistory is hidden. It is only when behaviours are repeated and enduring that they will be reflected in the archaeological record (Stargardt 2016). Our data support the suggestion Pyu people living at Halin likely represent people who migrated in low-density communities slowly from southwestern Yunnan into Myanmar (Stargardt 2016, p. 342), but here we suggest those migrations had a deeper antiquity, reaching into the second and perhaps third millennia BCE.

Situated within the broader regional context, the current data suggest decreasing $\delta^{13}C$ values and $\delta^{18}O$ values over time indicate increased focus on rice consumption and standing water sources, but unanswered questions remain. Future work focusing on aDNA, trophic level (e.g. Ca and Zn) and geoprovenancing indicators (e.g. Sr) will add further dimensionality to the present work and has the potential to modify this interpretation.

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Declarations

Competing interests The authors declare no competing interests.

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