Received: 18 July 2022 | Revised: 20 December 2022 | Accepted: 6 January 2023
DOI: 10.1002/ajpa.24698

RESEARCH ARTICLE

AMERICAN JOURNAL OF BIOLOGICAL ANTHROPOLOGY
WILEY

Scurvy in the tropics: Evidence for increasing non-adult micronutrient deficiency with the transition to agriculture in northern Vietnam

Melandri Vlok[1,2] | Marc Fredrick Oxenham[3,4] | Kate Domett[5] | Hiep Hoang Trinh[6] | Tran Thi Minh[6] | Nguyen Thi Mai Huong[6] | Hirofumi Matsumura[7] | Nghia Truong Huu[6] | Lan Cuong Nguyen[6] | Anna Willis[8] | Hallie Buckley[2]

[1]Sydney Southeast Asia Centre, The University of Sydney, Camperdown, Australia
[2]Department of Anatomy, University of Otago, Dunedin, New Zealand
[3]School of Archaeology and Anthropology, Australian National University, Canberra, Australia
[4]Department of Archaeology, School of Geosciences, University of Aberdeen, Aberdeen, UK
[5]College of Medicine and Dentistry, James Cook University, Townsville, Australia
[6]Institute of Archaeology, Vietnam Academy of Social Sciences, Hanoi, Vietnam
[7]School of Health Science, Sapporo Medical University, Sapporo, Japan
[8]College of Arts, Society and Education, James Cook University, Townsville, Australia

Correspondence
Melandri Vlok, Sydney Southeast Asia Centre, The University of Sydney, Camperdown, Australia.
Email: melandri.vlok@sydney.edu.au

Funding information
Australian Research Council, Grant/Award Numbers: DP110101097, FT120100299; National Geographic Society, Grant/Award Number: EC-54332R-18; Royal Society Te Apārangi (Skinner Fund); University of Otago (Doctoral Scholarship)

Abstract

Objective: Scurvy in non-adults was assessed at the Pre-Neolithic site of Con Co Ngua and the Neolithic site of Man Bac in northern Vietnam to investigate nutritional stress during the agricultural transition in Mainland Southeast Asia (MSEA).

Materials: One hundred and four human skeletons under the age of 20 years old were assessed.

Methods: Lesions were recorded macroscopically and radiographically. Differential diagnosis using prior established paleopathological diagnostic criteria for scurvy was conducted.

Results: There was no clear evidence for scurvy at Con Co Ngua and a high burden of scurvy was present at Man Bac (>79% diagnosed with probable scurvy). Scurvy levels were high across all non-adult ages at Man Bac indicating significant burden throughout childhood and adolescence.

Conclusions: No scurvy at Con Co Ngua is consistent with widely available food sources at the peak of the Holocene thermal maximum. High levels of scurvy at Man Bac corresponds with decreased dietary diversity, high pathogen load, and increased population stress with the transition to agriculture around the time of the 4.2 ka desertification event.

Significance: This is the first systematic population-level non-adult investigation of specific nutritional disease in MSEA and demonstrates an increase in nutritional stress during the Neolithic transition in northern Vietnam.

Limitations: Subperiosteal new bone deposits can be due to normal growth in infants and young children, therefore, identification of scurvy in children under the age of 4 years needs to be considered critically.

Suggestions for Further Research: Further work in diagnosing specific nutritional disease in other non-adult cohorts throughout MSEA is required.

KEYWORDS
agriculture, diet, health, MSEA, Neolithic, nutritional disease

1 | INTRODUCTION

It is now well established in bioarchaeological research that the agricultural transition had variable consequences to human health in the past (Bocquet-Appel et al., 2008; Eshed et al., 2010; Oxenham, 2006; Snoddy et al., 2017; Temple & Larsen, 2013). In Mainland Southeast Asia (MSEA) there has been extensive bioarchaeological work focused on the agricultural transition. The research has demonstrated a pattern of fewer negative health impacts compared to the Eurasian and American continents where paleopathological works of the last half century have been primarily focused (Buikstra et al., 1986; Larsen, 2006; Larsen et al., 2015). Work by Tayles et al. (2000), Halcrow et al. (2013), Oxenham (2006), and Oxenham et al. (2018) argued that the reliance on domesticated rice, millet and pigs, was a gradual transition and that subsistence strategies were dominated by mixed foraging-farming practices rather than single crops. Thus, the agricultural transition was not associated with a distinct "decline" in health. This previous research has primarily focused on non-specific stress markers as evidence of physiological stress rather than the systematic study of specific diseases during the agricultural transition. New research has questioned a simplified definition of 'decline' in health and revealed a level of epidemiological complexity only visible through the diagnosis of specific infectious diseases. For example, Vlok et al. (2020) and (2022) demonstrated a shift from environmentally driven to human driven infectious diseases with the adoption of agriculture in northern Vietnam. This region is a geographical friction zone between forager groups from MSEA and farmers from modern day southern China, eventually leading to both demographic and technological change (Bellwood & Oxenham, 2008; Higham, Guangmao, & Qiang, 2011). However, Vlok et al. (2021) have also presented skeletal evidence for the presence of malaria in hunter-gatherer communities of northern Vietnam at least 2500 years before the adoption of agriculture. Malaria, previously thought to have been introduced with agriculture and worsened with the intensification of wet rice farming (see King et al., 2017; Tayles, 1996), is now recognised to have impacted Pre-Neolithic hunter-gatherer communities of northern Vietnam (see Table 1 for time periods in MSEA).

1.1 | Nutritional deficiency with the introduction of agricultural foods

A reliance on domesticated cereals with poor dietary diversity to meet the energy requirements of large agricultural populations appears to have also led to deficiencies of many micronutrients (Brickley et al., 2020; Larsen, 2006). Depending on the cereal, insufficient levels of micronutrients such as iron, zinc, calcium, Vitamin A, B12, B3, B9, and C may have caused associated clinical deficiencies (Bouis & Welch, 2010; Larsen, 2006; Pettifor, 2004; Snoddy et al., 2017). For example, Snoddy et al. (2017) identified evidence of Vitamin C deficiency causing scurvy in the early agricultural transition period in the Atacama Desert, northern Chile. No such research on specific nutritional disease yet exists focusing on populations living during the adoption and intensification of agriculture in MSEA. Therefore, it is largely unknown to what degree this transition directly had on the nutrition of these ancient groups.

Only a certain number of micronutrient deficiencies affect the skeleton macroscopically. These include scurvy (Vitamin C deficiency), rickets (Vitamin D, calcium, or phosphate deficiency), hypovitaminosis A (Vitamin A deficiency), pellagra (Vitamin B3 deficiency) as well as the iron, folate and B12 deficiency anemias. Scurvy has well established methods for diagnosis in paleopathology (Brickley et al., 2020; Brickley & Ives, 2010; Ortner, 2003; Ortner & Ericksen, 1997; Snoddy et al., 2018), can be directly linked to dietary deficiency, and is therefore useful for investigating the impact of micronutrient deficiency during periods of subsistence change. Thus, evidence of scurvy is used in this research as a proxy for dietary deficiency.

1.2 | Pathophysiology of skeletal scurvy

A biological approach for diagnosis is the predominant basis for identification of scurvy in the skeletal record. This approach was first employed by Ortner and Ericksen (1997) and is based on biological inference of skeletal lesion patterning through an understanding of anatomical implications of disease. Mays (2018) argued that this approach is elemental to scientific rigor when diagnosing disease from skeletal lesions. Skeletal changes in non-adult scurvy result from both direct and indirect impacts of malproduction of collagen on skeletal tissue (Fain, 2005). Regions of association between blood vessels in contact with bone, and underlying habitually used muscles, that cause repeated episodes of weakened vessel rupture, have been identified as eliciting subperiosteal new bone (SPNB) as an inflammatory response (Brickley et al., 2020; Brickley & Ives, 2010). Abnormal cortical porosity occurs due to increased capillary formation as a consequence of the repeated microtrauma to weakened blood vessels in connective tissues (Ortner & Ericksen, 1997). The external greater wing of the sphenoid bone and ectocranial temporal bone are regions known to express pathological porosity related to scurvy due to the habitual use of the *temporalis* muscles in the chewing of food (Ortner & Ericksen, 1997). Similarly, movement of the *supraspinatus* and *infraspinatus* muscles result in pooling of blood leading to SPNB deposits and abnormal cortical porosity in the supraspinous and infraspinous fossae of the scapula that form in response to the hematomas (Snoddy et al., 2018). As the actions of these muscles occur bilaterally, scorbutic subperiosteal hemorrhagic lesions (and associated new bone response) tend to be symmetrical and bilateral (Ortner &

TABLE 1 Approximate dates for time periods in MSEA.

Time period	Approximate dates	References
Pre-Neolithic	Before 2300 BC	(Oxenham et al., 2018)
Neolithic	2300–1000 BC	(Bellwood et al., 2011; Higham, Higham, & Douka, 2019; T. Higham et al., 2022; Vlok et al., 2020)
Bronze Age (Metal Age)	1000–500 BC	(Higham, Higham, & Kijngam, 2011; Higham, Higham, & Douka, 2019; T. Higham et al., 2022)
Iron Age (Metal Age)	500 BC–500 AD	(Higham, Higham, & Douka, 2019; Higham, Manly, et al., 2019)

Note: There is considerable intraregional variation in the timing of these periods.
Abbreviation: MSEA, Mainland Southeast Asia.

Ericksen, 1997; Snoddy et al., 2018). Lesions can also be unilateral, particularly if the individual is ambulatory, as they are dependent on the hemorrhaging from microtrauma due to activity of weightbearing bones (Brickley et al., 2020; Maat, 2004). However, unilateral lesions may be difficult to distinguish from other microtraumas due to muscle strain. As ascorbic acid is essential in osteoid formation, for SPNB to form, some reintroduction of Vitamin C in the diet is required. Therefore, evidence of SPNB in scurvy indicates periods of Vitamin C recovery, although likely only small amounts are necessary to elicit new bone formation (Brickley & Ives, 2006; Geber & Murphy, 2012; Klaus, 2017; Snoddy et al., 2018).

Lower limb changes are common in infants and children with a predilection for the femur, tibia and fibula, and lateral bulging of the legs are often observed in affected infants due to subperiosteal hemorrhaging (Jaffe, 1972, p. 450). Pain is less common in the upper extremities suggesting lesion expression of the upper limb is likely to be less frequent than the lower limb (Jaffe, 1972, p. 450). Enlargement at the costochondral junction of the ribs due to subperiosteal hemorrhage, known as scorbutic rosary, is also a frequent clinical finding in infants (Jaffe, 1972, p. 453).

The skeletal indicators of scurvy-related bone growth disruption can be observed both macroscopically and radiographically. Porosity extending from the metaphyseal plate is a normal occurrence in growing juveniles as osteoclastic activity resorbs bone at the metaphyseal plate to allow for continued longitudinal growth (Ortner et al., 2001). However, in children with scurvy, the porosity exceeds beyond that of normal growth. Currently, porosity observed more than 10 mm from the metaphyseal plate is arbitrarily considered to be abnormal by Ortner et al. (2001). Radiographically, this disturbance presents as a translucent zone in the metaphyses called a "Trümmerfeld zone" or "Scurvy" line (Jaffe, 1972; Resnick, 1995). This area of radiolucency is often accompanied by a radiodense metaphyseal plate due to poor resorption of calcified cartilage, termed a "White line of Fraenkel." A similar radiodense line around the epiphyseal plate (Wimberger ring sign) can also occur (Snoddy et al., 2018). Given the disruption to osteoid formation, the structural integrity of the bone is compromised and fractures at the corners of the metaphyseal plates (Pelkan spurs) are clinically reported (Snoddy et al., 2018). Radiographic signs of "ground glass" osteopenia of the trabeculae is also another suggestive indicator of scurvy, as it can result from poor osteoid formation, but is observed in many metabolic conditions (Brickley et al., 2020). Radiographic signs tend to be observed bilaterally and across multiple bones representing signs of systemic growth disruption.

This article aims to explore the nutritional impact of the initial adoption of farming in northern Vietnam by assessing the skeletal evidence of scurvy in the non-adult cohort of Con Co Ngua, a pre-agricultural forager community (ca. 7-6500 BP; $n = 60$). Results will be compared with the early agricultural site of Man Bac (ca. 4-3500 BP; $n = 44$) which marks the initial adoption of domesticated rice and pigs in the region. Our research questions are: (a) was there a change in nutritional disease levels with the agricultural transition? And if so, (b) what were the health consequences for non-adults through infancy and childhood? Ultimately, by answering these research questions we can address the boarder issue: what does the findings at Man Bac and Con Co Ngua mean for the non-adults and overall populations during the transition of agriculture in MSEA?

2 | METHODS AND MATERIALS

The two sites for this study lie within 15 km of each other on the coast of northern Vietnam (Figure 1). Their proximity to each other and the high representation of infants and children in both assemblages make these sites particularly suitable to meet the objectives of this study. Con Co Ngua dates to the height of the Holocene thermal maximum (HTM) in northern Southeast Asia and southern China, whereas Man Bac directly postdates the 4.2 ka desertification event.

2.1 | The unique context of the agricultural transition in Southeast Asia

Prior to the agricultural revolution, forager communities that descended from the first populations out of Africa and into Asia benefitted greatly from the warmer climate of the HTM which reached its peak in MSEA by ~8–6 kya (Renssen et al., 2012). During the HTM there was ~1°C mean annual temperature increase compared to industrial period temperatures in the region, and intensification of summer monsoon precipitation encouraged significant tropical floral and faunal diversity (Maher & Hu, 2006; Renssen et al., 2012). A consequence of this high resource abundance meant mobile foraging groups in northern Vietnam and southern China were capable of reorganizing into large sedentary settlements (Oxenham et al., 2018). A rapid drying and desertification period post-HTM, known as the 4.2 ka event, likely significantly altered the resource returns of these large sedentary groups of foragers, possibly becoming unsustainable

FIGURE 1 Location of Man Bac and Con Co Ngua. The present-day capital city of Hanoi is provided for comparison.

(Oxenham et al., 2018; Renssen, 2022). From ~4 kya, farmers from southern China migrated to MSEA and interacted with the local indigenous foragers (Bellwood & Oxenham, 2008). This migration prompted a subsistence transition with the introduction of domesticated pigs and dogs, and rice and/or millet farming (Castillo, 2011; Jones et al., 2019; Piper et al., 2014; Weber et al., 2010). However, variation within MSEA as to the degree of adoption and intensification of agricultural foods led to a heterogenous impact on health (King et al., 2017; Oxenham & Tayles, 2006). Foraging supplemented farming at many, if not all, sites in the region, which may have provided a buffer from nutritional deficiencies caused by a reliance on a single staple (Castillo et al., 2018; C. Higham & Thosarat, 2005; Jones et al., 2019; Oxenham, 2015; Oxenham et al., 2011). Indeed, full agricultural dependence did not perhaps occur until the Late Iron Age (500 BC–500 AD; Table 1) with the intensification of wet rice agriculture and the construction of moated settlements (Halcrow et al., 2016; C. Higham, 2007; C. F. Higham et al., 2014; King et al., 2014; McGrath & Boyd, 2001).

2.2 | The pre-agricultural site: Con Co Ngua (ca. 7-6500 BP)

Con Co Ngua is a habitation and burial site in the Thanh Hoa province, dating to the early seventh millennium BP. The site was excavated in 1979–1980 and again in 2013. During its occupation, at the height of the HTM the site was likely situated on an estuary (Oxenham et al., 2018). The climate was warmer and wetter than present day, and the indigenous food resources were more abundant. For this reason, the inhabitants of Con Co Ngua settled as sedentary hunter-gatherers, managing wild buffalo and potentially other large fauna, in contrast to the rice growing agricultural groups who occupied areas of China further north (Oxenham et al., 2018; Scott et al., 2019; Vlok et al., 2021). Foraging of a wide range of abundant terrestrial, riverine, estuarine, and marine resources allowed for the development of a large sedentary community (Jones, 2017; Jones et al., 2019; Oxenham et al., 2018). The Con Co Ngua assemblage includes a total number of 155 individuals representing 60 non-adults under 20 (39%), and 95 adults (61%) (see Table 3).

2.3 | The agricultural site: Man Bac

Man Bac is a habitation and burial site just north of Con Co Ngua in the Ninh Binh province, dating to 3906–3523 cal BP, excavated in 1999, 2005, and 2007 (Oxenham et al., 2011; Vlok et al., 2020). In the past, the surrounding ecology included riverine, coastal, and estuarine flora and fauna (Tanabe et al., 2006). The site is associated with the Phung Ngyuen period known for early agriculture, distinct pottery designs, and interactions with farmers in what is now geo-politically southern China (Hiep & Phung, 2004; Oxenham et al., 2011). Long grain rice phytoliths were found within the cultural layers of Man Bac similarly identified at other Phung Nguyen sites (Bellwood & Oxenham, 2008; Jones et al., 2019; Mai Huong, 2013, 2016; Willis & Oxenham, 2013). The remains of domesticated pigs and a considerably lower diversity of faunal taxa when compared to Con Co Ngua, have been noted (Jones et al., 2019; Oxenham et al., 2018; Sawada et al., 2011). Preliminary carbon isotope results suggest a lower reliance on C3 plants, such as rice, than subsequent Bronze and Iron Age assemblages in Vietnam, supporting a gradual intensification of agriculture over time (Oxenham et al., 2011; Yoneda, 2008). Isotopic and faunal evidence demonstrate a continued exploitation of marine, freshwater, estuarine and terrestrial resources, and a mixed subsistence base of foraging and farming is proposed for Man Bac (Jones, 2017; Jones et al., 2019; Sawada et al., 2011; Toizumi et al., 2011; Yoneda, 2008). The Man Bac assemblage comprises a total of 70 individuals with 44 non-adults under 20 (63%) and 26 adults (37%) (see Table 3). The high proportion of non-adults in the Man Bac assemblage is indicative of an increase in fertility and population growth compared to Con Co Ngua (McFadden et al., 2018).

2.4 | Skeletal preservation

The non-adult bones from Con Co Ngua can be predominantly described as having poor preservation. The bones were fragmented and most non-adults, particularly infants were represented by less than 50% of their total skeleton. Skeletal surfaces exhibited moderate surface erosion (Grade 3–4 of McKinley (2004)).

However, Man Bac displayed excellent non-adult preservation. More than half of the assemblage had a minimum of 75% completeness of the skeleton. Skeletal surfaces exhibited minimal to slight surface erosion (Grade 0–1 of McKinley (2004)). Beetle chewing and rodent gnawing was identified in one individual, and concretions of solidified soil matrix were present in some individuals but had minimal impact on pathological observations. Infrequently, endocranial surfaces were unobservable due to concretions inside the cranium. It is recognized that significant differentiation in the preservation of the non-adults in the two assemblages is a confounding factor, but as later discussed non-specific new bone lesion distributions indicate real difference in disease patterns regardless of the poor preservation of some elements in the Con Co Ngua assemblage.

2.5 | Age and sex estimation

Dental eruption and calcification methods were used and compared to standards presented by Moorrees et al. (1963) and Ubelaker (1989) published in Buikstra and Ubelaker (1994) and White et al. (2000). Where dentition was not available, long bone diaphyseal lengths were compared to other children within the assemblage with a recorded dental age. For individuals over the age of ~12 years, standards for epiphyseal fusion methods were used based on Scheuer and Black (2000). As most individuals are pre-pubertal, sex was not assessed in this investigation. Frequencies for infants were separated into 6-month categories, and post-infancy, 5-year categories.

2.6 | Lesion recording and diagnostic protocol

All cranial and postcranial non-articular lesions were recorded macroscopically, and long bones were radiographed for each non-adult with macroscopic evidence of scurvy. Standardized methods for scurvy diagnosis by Snoddy et al. (2018) was employed for this analysis (Table 2). The Snoddy et al. (2018) threshold approach presents weighted diagnostic criteria to objectively standardize diagnosis of scurvy. The weighted criteria give greater diagnostic value to lesions that are clinically described in the medical literature and/or are anatomically intuitive, with reported lesions in the paleopathological literature given lesser diagnostic weight. Lesions are considered as "diagnostic" when they are clinically described or anatomically intuitive with strong paleopathological literature backing. Lesions considered "suggestive" of scurvy are associated with cases of scurvy in the clinical or paleopathological literature, but can also be found in other diseases, such as other metabolic disorders. The approach is conservative in that it does not allow for a definite diagnosis, recognizing the

TABLE 2 Diagnostic lesions of scurvy.

Pathology	Differential diagnosis
Macroscopic signs	
Abnormal cortical porosity/ subperiosteal new bone (SPNB) on: Ectocranial parietal/squamous temporal bones	Trauma, infection, anemia
External greater wing of sphenoid	Trauma, infection
Foramen rotundum	Appositional growth (juveniles)
Pterygoid fossae and/or plates	Appositional growth (juveniles)
Anterior surface of maxillae/ infraorbital foramina	Trauma, infection
Posterior surface of maxillae	Alveolar resorption
Palatal surface of maxillae	Infection, trauma
Medial surfaces of coronoid processes of mandible	Infection, trauma
Supraspinous fossae of the scapula	Trauma, appositional growth
Infraspinous fossae of the scapula	Trauma, appositional growth
Orbital roof	Trauma, anemia
Abnormal endochondral porosity extending >10 mm from the distal metaphyseal plate of long bones	Rickets, longitudinal growth
Radiographic signs	
White line of Fraenkel	Normal variation, lead toxicity, rickets
Trümmerfeld zone	Osteopenia, trauma, anemia
Wimberger ring sign	Normal variation
Corner fracture at position of dense zone of calcification (Pelkan's spur) Can also be observed macroscopically.	Trauma

Note: One diagnostic lesion is consistent with a possible case. Two or more diagnostic lesions are consistent with a probable case. Suggestive lesions that supplement diagnoses are provided in Table S1 (Brickley & Ives, 2010, p. 65; Geber & Murphy, 2012; Ortner et al., 2001; Schattmann et al., 2016; Snoddy et al., 2017, 2018).

uncertainties associated with scurvy diagnosis in dry bone, such as confounding factors of growth in infancy and porosity due to normal human variation. The Snoddy criteria is derived from a comprehensive synthesis of the prior paleopathological and medical literature on scurvy diagnosis, and each lesion is justified through literature review and/or statistical testing of its designated diagnostic value. It is arguably a more transparent approach from critical review of cases in the archaeological record and allows for consistency in diagnosis which is potentially useful for estimating prevalence in population-based approaches in paleopathology.

Application of Snoddy et al. (2018) criteria requires rigorous differential diagnosis of lesions. While it is a quantitative approach attempting to standardize criteria for determining *possible* versus *probable* cases, each lesion is considered within the realms of a standard differential diagnostic approach. It is expected that researchers critically engage with a differential diagnosis of similar etiologies such as rickets and pellagra when considering the contribution of each lesion to the diagnosis of scurvy. It is also expected that the researcher understands the etiology of the lesion contributing to diagnosis and how pathophysiological processes of other diseases can lead to the same expression in dry bone. Mays (2018) argues that quantitative approaches such as the Snoddy et al. (2018) criteria require comparison to more traditional approaches. Therefore, in this study, a "traditional" differential diagnosis was carried out alongside the Snoddy et al. (2018) criteria (see Text S2).

Following the Snoddy et al. (2018) criteria, diagnosis of disease was determined as consistent with a *possible* or a *probable* diagnosis following these standards. A minimum of one *diagnostic* or two *suggestive* lesions was required for a possible diagnosis, with a probable diagnosis requiring at minimum two diagnostic lesions. SPNB deposits on long bones have been considered by Snoddy et al. (2018) as diagnostic for scurvy when cranial SPNB is present. However, the presence of treponemal disease in non-adults at Man Bac (11.4% of the non-adult assemblage) suggests possible co-morbidity (Vlok et al., 2020) and thalassemia occurred at both sites (Vlok et al., 2021). Therefore, diaphyseal SPNB was excluded from the diagnostic criteria for scurvy as these bone changes are a common occurrence in both of these diseases. Additionally, as scorbutic lesions are most commonly symmetrical, unilateral lesions were not considered diagnostic for scurvy. Abnormal endochondral porosity exceeding 10 mm from the proximal or distal metaphyseal plates were also considered here as a diagnostic lesion for scurvy following Ortner's standards (Ortner et al., 2001; Snoddy et al., 2017). Lastly, active scurvy was recorded as follows. "Active" scurvy was identified through the presence of at least one diagnostic SPNB lesion exhibiting no signs of remodeling (woven bone present only), indicative of recent scurvy-related skeletal activity. There remain challenges to identifying clear boundaries between active, healing, healed, and recurrent episodes of scurvy (Schattmann et al., 2016). Therefore, active only lesions provide a proxy to assess the most recent cases where in the child was still or had recently suffered a case of Vitamin C deficiency and had yet to recover when they died. Complete remodeling is observed where lesions present as lamellar bone only, but the original margins of the lesion have not yet been reduced to the contour of normal bone.

Due to the availability of radiographs, and continued debates in the literature about diagnostic issues in infants, we have further separated the classification of disease diagnosis into:

1. Probable case (corroborated by radiographs).
2. Probable case (macroscopic signs only).
3. Possible case.

2.7 | Statistical analysis

Fisher's exact tests were applied to test whether there was a:

1. Significant difference in the prevalence of scurvy across time periods.
2. Significant difference in the prevalence of scurvy between children under versus over the age of 5 in each site.
3. Significant difference in the prevalence of *active* scurvy between children under versus over the age of 5 in each site.

The "under-five" morbidity and mortality rate is a common epidemiological age comparator, with children under the age of 5 years recognized to be more susceptible to diseases than their older counterparts (World Health Organization, 2016). Significance was considered at $p < 0.05$. Where a cell was "0," a score of "0.5" was inputted as is standard for Fisher's exact test.

Odds ratio analyses were also applied to test the size of the effect in the prevalence of scurvy across time periods (see Smith (2020) on discussion of importance for size of effect in bioanthropological data).

3 | RESULTS

3.1 | Lesion distribution and radiographic outcome

3.1.1 | Con Co Ngua

The infants all exhibited diffuse active new bone. However, the layered and uniform distribution indicated these were due to normal growth and were remarkably different to the new bone identified as abnormal in the Man Bac assemblage (Figure 2). While there are differences in the preservation between the sites, the differences in pathological versus non-pathological new bone in infants can be determined. One adolescent exhibited abnormal porosity and new bone of the temporal bones. While the porosity is bilateral it is not symmetrical and does not follow any of the predictable anatomical locations observed in cases of scurvy, such as the of the *temporalis* muscle attachments on the cranium and mandible.

3.1.2 | Man Bac

The general lesion pattern observed in the Man Bac non-adults was 1) symmetrical discrete subperiosteal new bone with abnormal cortical

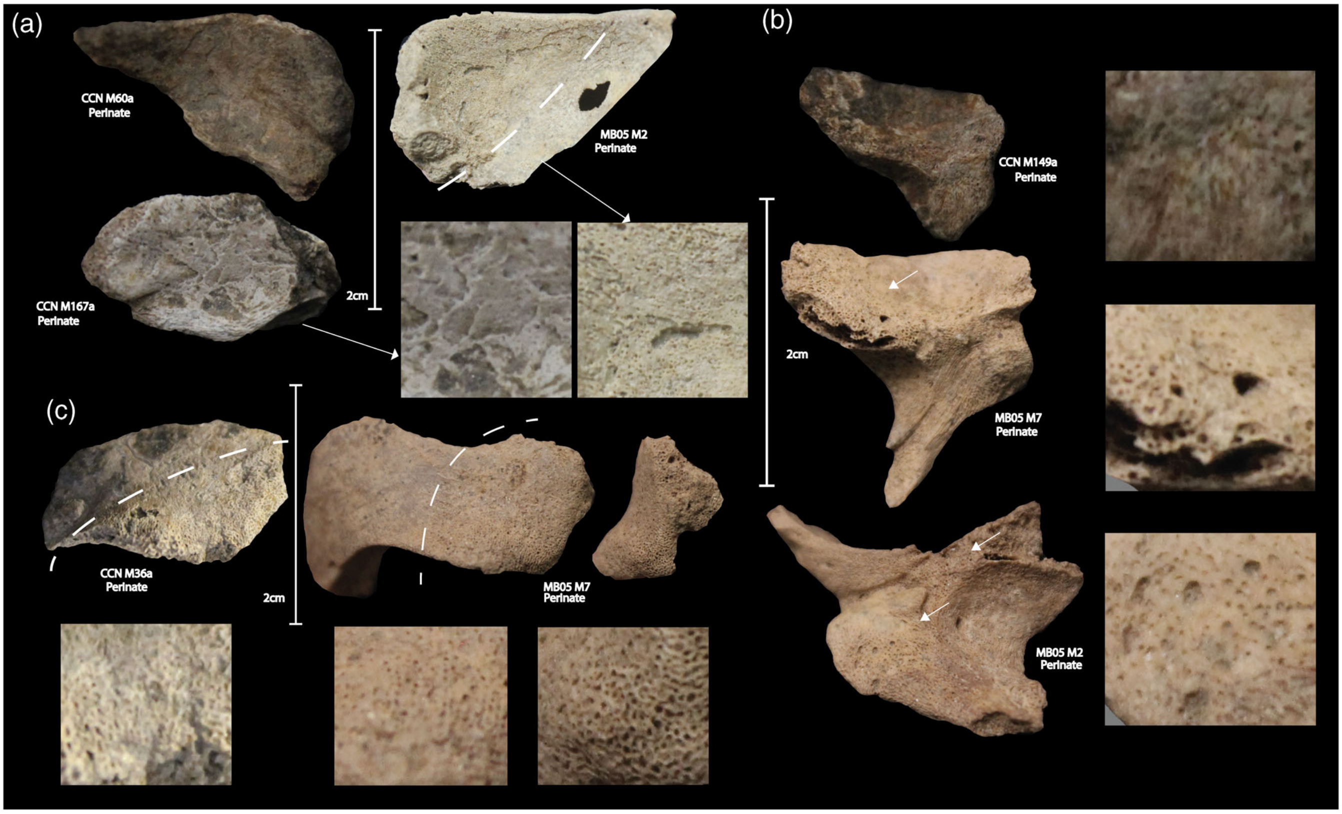

FIGURE 2 Comparisons of normal porosity and new bone in infants from Con Co Ngua (CCN), and pathological porosity and new bone in infants from Man Bac (MB). (a) Difference in appositional new bone versus porous pathological new bone in the orbits. (b) Cortical porosity perpendicular to bone surface of the posterior zygoma in the MB infants is absent in the CCN infant. (c) Porosity and new bone in the MB infant cover a region extending far beyond the margins of the growing frontal bone. Normal new bone at the fontanelle margins is observed in the CCN infant without evidence of cortical porosity.

porosity of the facial bones, sphenoid bones, and temporal bones, 2) diffuse new bone across the long bones, and 3) abnormal endochondral porosity of the metaphyses of long bones associated with zones of radiolucency, and radio dense metaphyseal plates (Figure 2). The Man Bac perinates and neonates presented with distinct regions of cortical porosity that were absent in the Con Co Ngua perinates and neonates clearly indicating these lesions are not due to normal growth (Figures 2 and 3; Data S1).

Over 95% (95.4%; $n = 42/44$) of the Man Bac assemblage had lesions in two or more skeletal elements, suggesting a pattern of systemic disease as defined by Ortner (1992) and Buckley and Tayles (2003). The lesions were predominantly bilateral and symmetrical islands of SPNB, with association of abnormal cortical porosity, particularly in the cranium. Ninety-three percent ($n = 40/43$) had lesions on the crania, and 88.6% had lesions on the postcranial bones ($n = 39/44$). While not considered here as diagnostic in their own right, vascular impressions in association with symmetrical discrete SPNB and abnormal cortical porosity further suggests hematoma formation (Klaus, 2017). Vascular impressions were observed particularly in children under the age of 5 years on the anterior and posterior zygomatic bones and maxillae of children with subperiosteal lesions. Abnormal deep endochondral porosity of the long bones, extending more than 10 mm from the metaphyseal plates, was evident in 52.3% ($n = 23/44$) of the assemblage. Fifty percent ($n = 22/44$) of the nonadults also presented with White lines of Fraenkel, Trümmerfeld zones, and/or Pelkan spurs (corner fractures of metaphyses) in conjunction with macroscopic lesions.

3.2 | Diagnosis of scurvy

There were no lesions diagnostic for scurvy present in the Con Co Ngua non-adults. The new bone (and the associated porosity) on the skull of an adolescent, appeared asymmetrical, more consistent with an inflammatory response to systemic infection than metabolic disorder. In contrast the lesions at Man Bac were highly consistent with metabolic disease and/or intrinsic disorders demonstrating a wide distribution of symmetrical lesions across the skeleton. Caffey's disease, nutritional rickets, hypophosphatemia, pellagra, and scurvy were included in the traditional differential diagnosis for non-adults from Man Bac (Data S2). Scurvy was the most likely candidate at Man Bac, with some pathological overlap with nutritional rickets. Caffey's disease, hypophosphatemia and pellagra were ruled out based on clinical and contextual grounds. Co-occurrence of scurvy with rickets is common

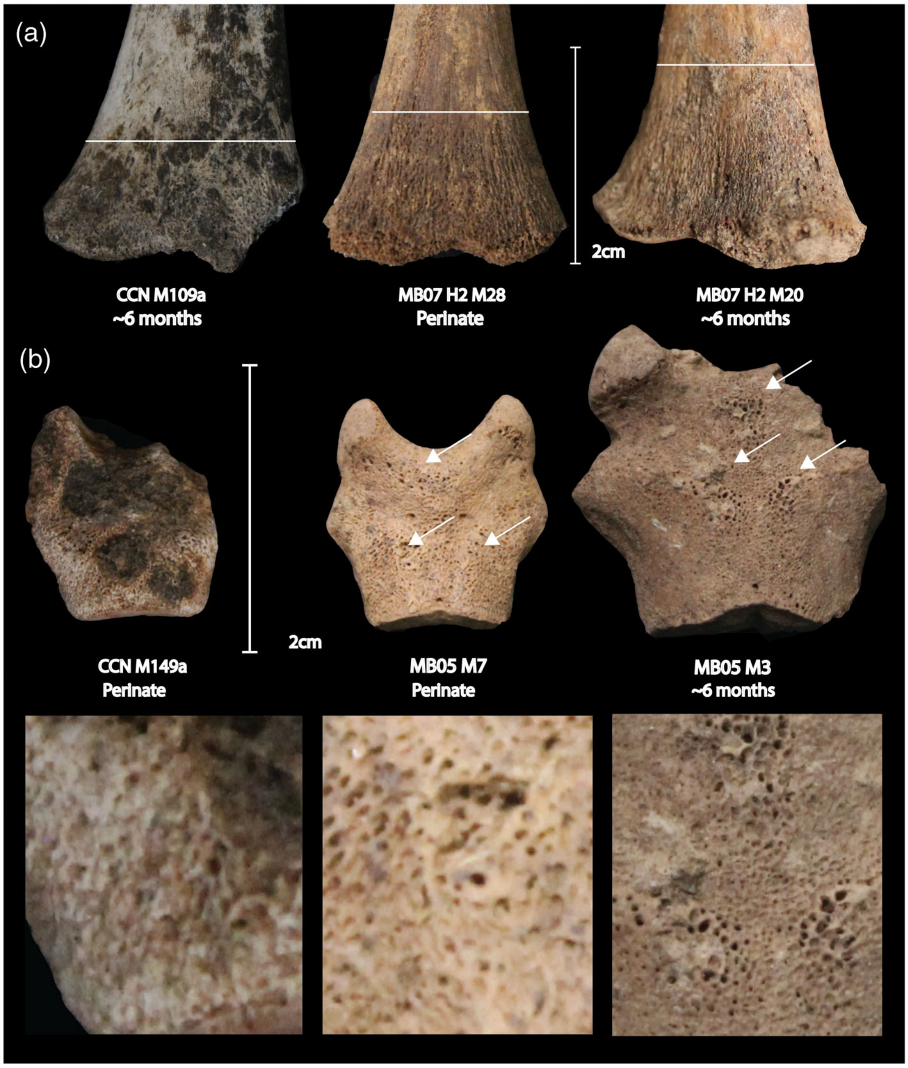

FIGURE 3 Further comparisons of normal porosity and new bone in infants from Con Co Ngua (CCN), and pathological porosity and new bone in infants from Man Bac (MB). (a) Posterior aspect of distal femora displayed. The MB individuals exhibit abnormal endochondral porosity extending beyond that observed at CCN. Note the linear striated formation of the metaphyseal region in the MB infants indicating defect in bone deposition. (b) Clustered deposits of perpendicular porosity are present in the MB infants and absent in the CCN infant.

(Schattmann et al., 2016), and was observed in some of the non-adults in the assemblage (Vlok et al., forthcoming).

The application of Snoddy et al. (2018)'s criteria for diagnosis of scurvy identified that 79.5% ($n = 35/44$) of the assemblage met the minimum threshold criteria for diagnosis of probable scurvy and 95.5% ($n = 42/44$) met the threshold criteria for, at minimum, possible scurvy (see Figure 4; Table 3). However, given radiographs were available, and the prevalence for scurvy at Man Bac is uniquely high, the evidence for scurvy was further divided into three diagnostic classifications to investigate the validity of the prevalence generated by the Snoddy et al. (2018) method. Almost 60% ($n = 25/42$) of the individuals exhibited active only lesions related to scurvy. No scorbutic non-adult lesions were completely remodeled.

3.2.1 | Evidence for probable scurvy corroborated by radiographs (Man Bac)

Out of the 35 individuals who met the criteria for a probable diagnosis, 23 individuals had long bones exhibiting radiographic signs for scurvy. Therefore, a total of 52.3% ($n = 23/44$) of the assemblage could be confidently diagnosed with probable scurvy with both macroscopic and radiographic evidence for the disease. Macroscopic *and* radiographic features for scurvy were identified in all age groups including the perinates (Figure 5).

3.2.2 | Evidence for probable scurvy by macroscopic evidence only (Man Bac)

Only 12 individuals had macroscopic evidence consistent with a probable case of scurvy who lacked radiographic signs of scurvy. Most of these cases were 10 years of age or older at time of death during a period of slower long bone growth than in early childhood. Therefore, it is unlikely radiographic signs would be valuable for diagnosis at this age (Figure 6a). For children under the age of 2 years old at death, the 6 month to under 1 year of age-at-death cohort presented with the highest prevalence for scurvy. This pattern is observed when considering only macroscopic signs as well as a combination of macroscopic *and* radiographic signs (Figure 6b).

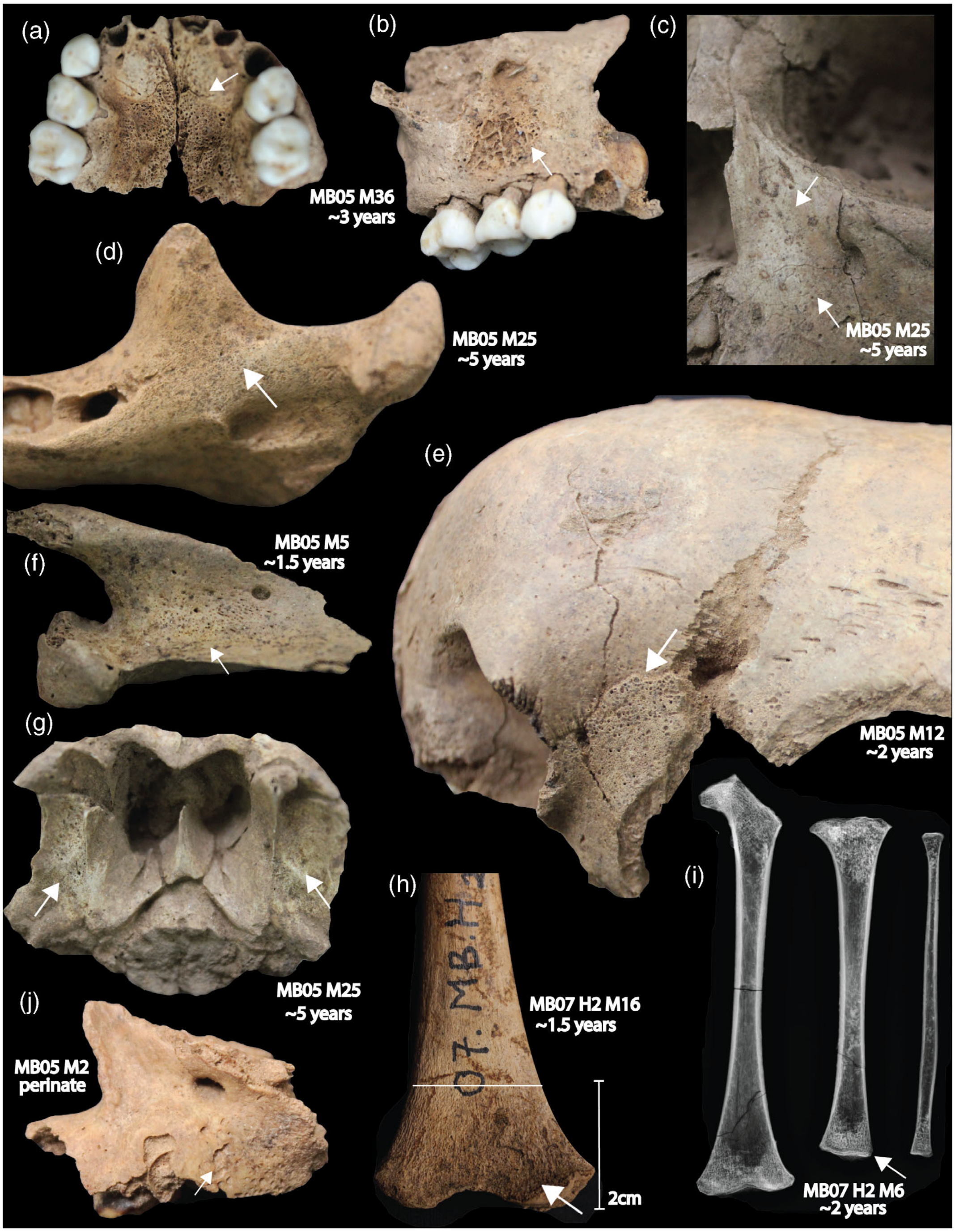

FIGURE 4 Lesions diagnostic for scurvy in Man Bac non-adults. Subperiosteal new bone (SPNB) and cortical porosity of the palate (a), anterior maxilla (b, c, and j), coronoid process of the mandible (d), lateral greater wings (e), and pterygoid processes of the sphenoid bone (g). These lesions were all symmetrical. Abnormal deep endochondral porosity of the distal femur twice extending twice as long as what is considered normal (<10 mm) (h). White lines of Fraenkel and Trümmerfeld zones observed in the radiographs of the long bones (i).

3.2.3 | Evidence for possible scurvy (Man Bac)

Only 18.2% ($n = 8/44$) of the Man Bac non-adult assemblage presented evidence of possible scurvy. Diagnosis for possible cases appear to be predominantly due to poor preservation, especially poor representation of the skull, as more weight in diagnosis is given to lesions of the face and cranium (Table S1). However, when all lesions that were considered diagnostic and suggestive for scurvy are represented within a skeletal distribution diagram, the lesion distribution from possible cases is similar to that of probable cases (Figure 7; Table S1).

The disparity observed between the diagnosis of possible and probable cases is due to the absence of diagnostic lesions of the fragile facial bones in the possible cases. That is, the diagnosis of possible

TABLE 3 Con Co Ngua (CCN) and Man Bac (MB) non-adult scurvy prevalence.

	Possible Affected/observed (%)		Probable Affected/observed (%)		Probable (corroborated) Affected/observed (%)	
Age cohort	CCN	MB	CCN	MB	CCN	MB
0–6 months	0/9 (0)	3/8 (37.5)	0/9 (0)	5/8 (62.5)	0/9 (0)	3/8 (37.5)
6 months to 1 year	0/4 (0)	0/6 (0)	0/4 (0)	6/6 (100)	0/4 (0)	6/6 (100)
1–5 years	0/10 (0)	3/20 (15)	0/10 (0)	16/20 (80)	0/10 (0)	10/20 (50)
5–10 years	0/8 (0)	0/4 (0)	0/8 (0)	4/4 (100)	0/8 (0)	4/4 (100)
10–15 years	0/6 (0)	1/3 (33.3)	0/6 (0)	2/3 (66.7)	0/6 (0)	0/3 (0)
15–20 years	0/17 (0)	0/4 (0)	0/17 (0)	3/4 (75)	0/17 (0)	0/4 (0)
Total	0/60 (0)	7/44 (16)*	0/60 (0)	35/44 (79.5)*	0/60 (0)	23/44 (52.3)*

Note: Table S1 provides a detailed scurvy diagnosis outcome for all non-adults at both sites.
*$p < 0.05$.

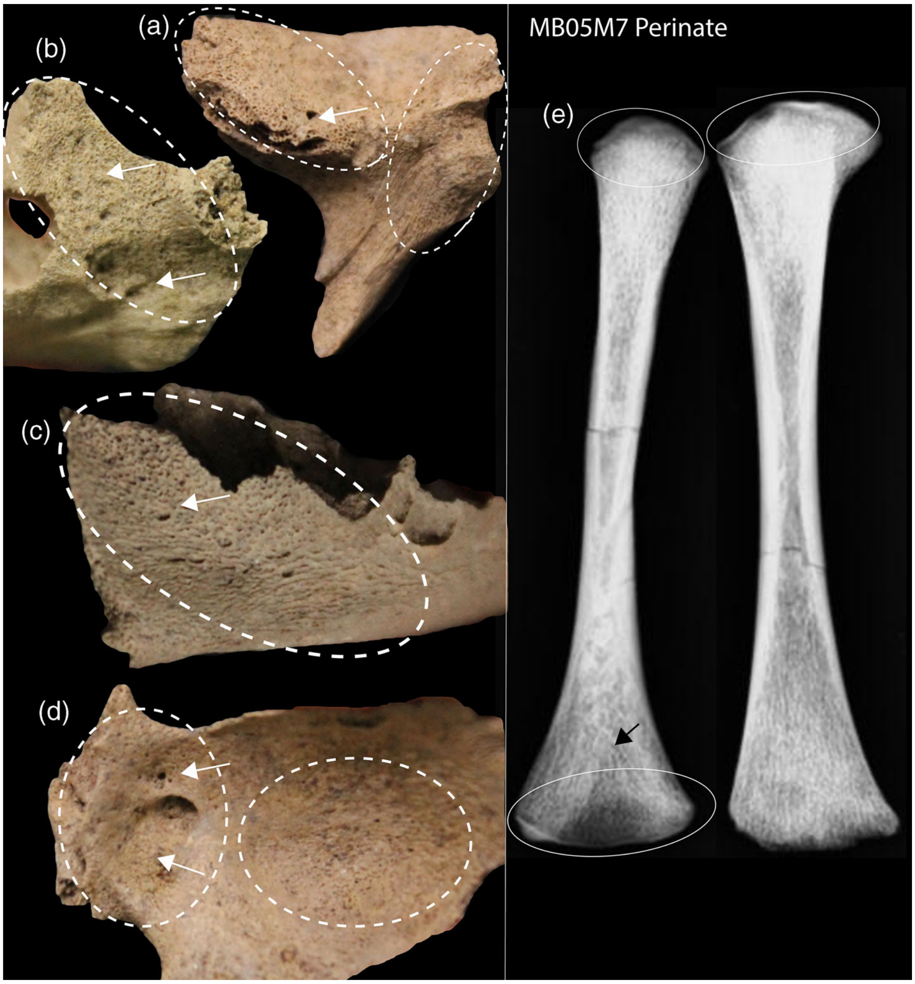

FIGURE 5 Macroscopic and Radiographic diagnostic features for scurvy in a Man Bac perinate (MB05M7). Porosity and new bone of the (a) posterior zygoma, (b) coronoid process of mandible, (c) incisive fossa of mandible, (d) greater wing and around foramen rotundum of the sphenoid, (e) radiograph showing White lines of Fraenkel and Trümmerfeld zones.

cases was a product of poor preservation inhibiting confidence in diagnosis. The most frequently observed evidence for scurvy at Man Bac were abnormal endochondral porosity of long bone metaphyses, and new bone lesions with cortical porosity of the mandibles, scapulae, zygomatics, and the sphenoid bones, followed by lesions of the cranium and maxillae, regardless of age of the individuals.

It is important to note that these possible cases identified at Man Bac, even with poor preservation, further distinguishes the pathological findings from the non-adults from Con Co Ngua. Despite similarly poor preservation of Con Co Ngua non-adults to those of possible cases at Man Bac, the older site presents no clear evidence for scurvy.

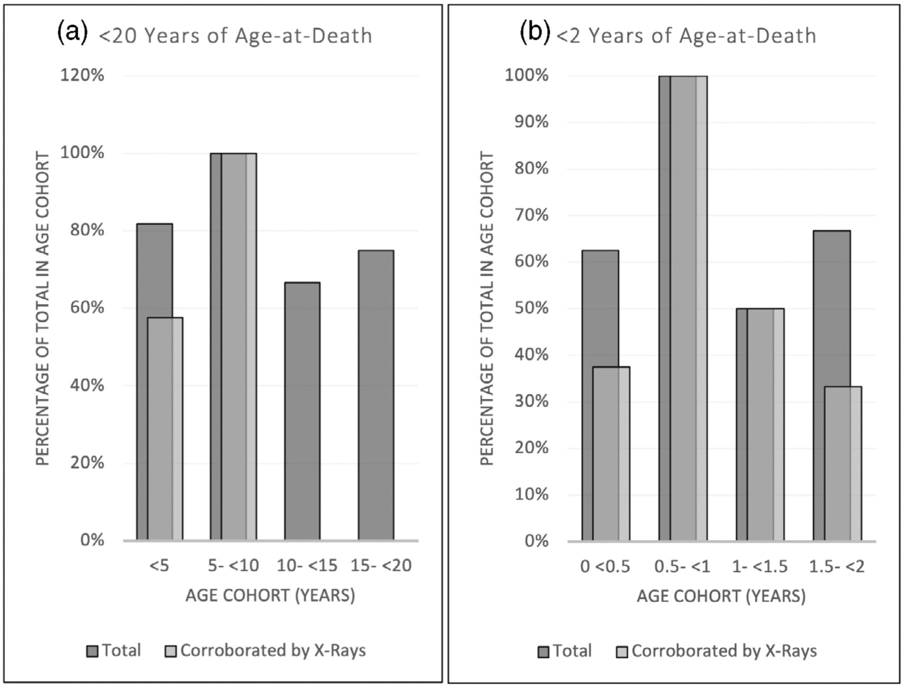

FIGURE 6 Prevalence of total probable scurvy versus probable scurvy corroborated by radiographs in Man Bac age groups (a) throughout the whole non-adult assemblage, and (b) under 2 years of age.

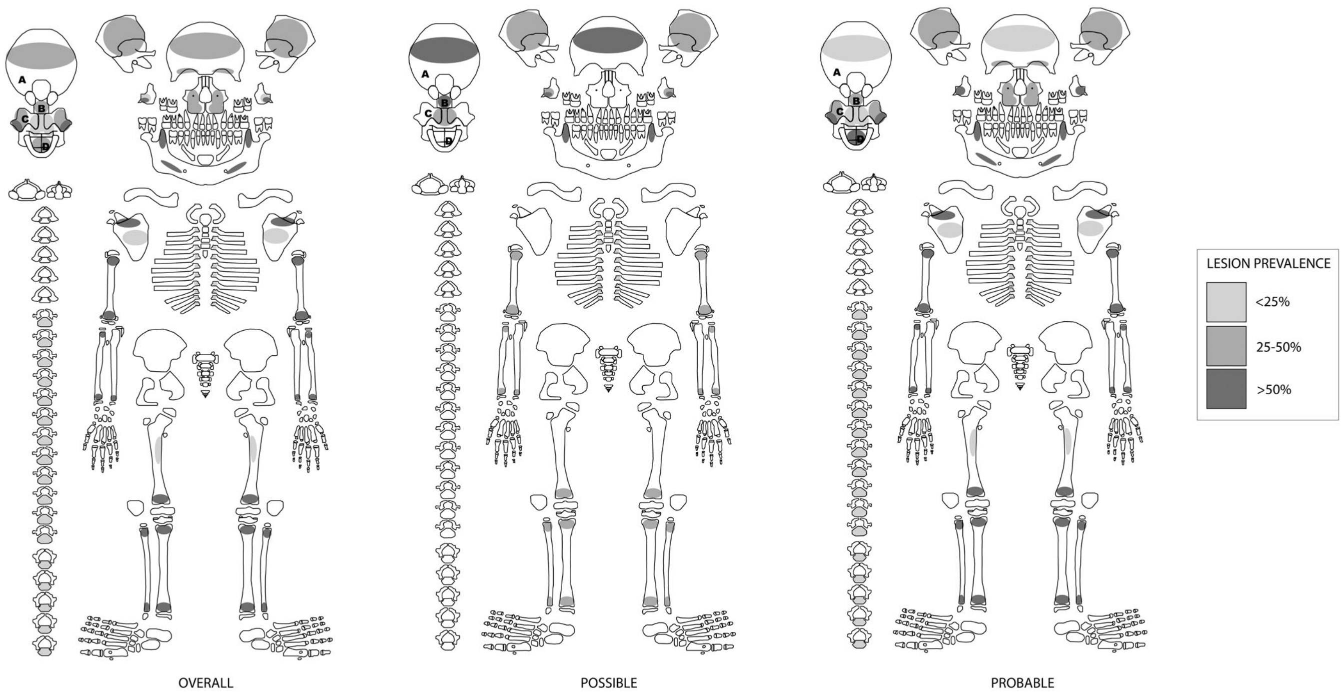

FIGURE 7 Distribution of diagnostic and suggestive macroscopic lesions for scurvy in the Man Bac non-adults. Individual data for each lesion prevalence per bone (NISP) can be found in Table S1.

3.3 | Statistical analysis

3.3.1 | Across time periods

The Fisher's exact test demonstrates a statistically significant difference between the prevalence of probable scurvy at Con Co Ngua versus Man Bac ($p < 0.0001$). Given the significance of the Fisher's exact test, the size of the effect was tested with odds ratio analysis. An odds ratio of 452.2 (95%CI: 25.5–8005.9; $p < 0.0001$) supports an exceptionally high effect size. The outcome is expected given remarkably no clear evidence for scurvy at Con Co Ngua, and exceptionally high prevalence at Man Bac.

TABLE 4 Prevalence of active scurvy at Man Bac across age-at-death cohorts.

Age cohort	Active/observed (%)
0–6 months	7/8 (87.5)
6 months to 1 year	5/6 (83.3)
1–5 years	11/19 (57.9)
5–10 years	0/3 (0)
10–15 years	1/3 (33)
15–20 years	1/3 (33)
Total	25/42 (59.5)

Note: Only cases where pathology was observed is included in the analysis.

3.3.2 | Across age groups by site (Man Bac)

Given the considerable evidence for scurvy at Man Bac, statistical analysis across different age-at-death cohorts was completed. There were no statistical differences in the prevalence of probable only ($p = 0.6$) or combined possible/probable scurvy ($p = 0.4$), under versus over 5 years of age. Therefore, age does not appear to play a significant role in the overall presence of scurvy at Man Bac. However, most non-adults (69.7%; $n = 23/33$) under the age of 5 years exhibited active scurvy, and only 22% of individuals 5 years and over presented with active scurvy ($n = 2/9$; Table 4). This difference was statistically significant ($p = 0.015$). Given the significance, the size of the effect was tested with odd ratio analysis. An odds ratio of 8 (95% CI: 1.4–45.8; $p = 0.019$) supports a great effect size. The greater effect size adds weight to the confidence to a significant outcome.

4 | DISCUSSION

Our results demonstrate a significant increase of non-adult scurvy from the Pre-Neolithic to early Neolithic periods in northern Vietnam. No clear evidence was found in the non-adults at Con Co Ngua, whereas almost 80% of the Man Bac assemblage exhibited pathology consistent with a diagnosis of probable scurvy.

4.1 | The use of radiographs to strengthen diagnosis in scurvy

The Snoddy criteria provided a useful standard for assessing diagnosis of scurvy across a large non-adult assemblage. However, as demonstrated in this article, the use of radiographs is further useful in increasing the confidence in diagnosis. While in the older children at Man Bac (>4 years of age) lesions related to scurvy were easy to discern macroscopically from underlying normal bone, the challenge of diagnosis remains in infants still undergoing rapid subperiosteal bone growth, particularly in those under 6 months of age (see discussion in M. E. Lewis, 2017). The Snoddy criteria (as well as other previous criteria for diagnosis of scurvy) does not provide clear definitions for differentiating lesions of normal growth from those due to pathological bone change in response to Vitamin C deficiency. In this research, we confronted this problem with comparisons of bone surfaces among two different groups with biosocial, environmental, and genetic affinities.

4.2 | Revisiting diagnosis of scurvy in infants under 1-year-of-age

Prior research has previously identified cases of scurvy in perinatal and neonatal skeletal remains (see Buckley et al., 2014; Kinaston et al., 2009; Snoddy et al., 2017). Attention to diagnosis of scurvy in infants is essential given the high proportion of this age cohort represented in the Man Bac non-adult assemblage. The benefit of such research is that diagnosis of scurvy in this cohort facilitates discussion of Vitamin C deficiency of the expecting or breastfeeding mother. At Man Bac all infants under 6 months of age (100%; $n = 8/8$) presented with possible or probable scurvy with 62.5% ($n = 5/8$) having probable scurvy. While it is possible that growth is playing some role in the bone changes observed in the young infants at Man Bac, the frequency of all individuals under the age of 6 months with probable scurvy was not higher than other age cohorts, which would be expected if the SPNB observed was strictly due to growth. Furthermore, White lines of Fraenkel associated with Trümmerfeld lines were present in 60% ($n = 3/5$) of these infants diagnosed with probable scurvy. These radiographic signs indicate disruptions to osteoid formation and do not share the same confounding factor of growth associated with macroscopic observations of SPNB. We argue here that the infant cohort of a skeletal assemblage can be assessed for scurvy and should not be excluded from paleopathological analyses based on age alone. This is particularly important in assemblages such as Man Bac with high fertility indices and therefore a greater proportion of the assemblage being represented by infants.

4.3 | Causes of scurvy at Man Bac

Even in the absence of any other systematic study of nutritional diseases in the region, the levels of scurvy in Man Bac non-adults is exceptionally high, but the presence of scurvy in a tropical context is not entirely unexpected given prior reports in tropical countries. Halcrow et al. (2014) report a case of scurvy in a non-adult from historical period Cambodia and a high prevalence of the disease was reported from a population in subsistence transition from the Pacific islands (Buckley et al., 2014). The excellent preservation of bone surfaces at Man Bac may also have contributed to this high rate, as active SPNB can be lost through a range of taphonomic factors (Roberts & Connell, 2004). The excellent preservation of crania at Man Bac may also have contributed to the high prevalence observed (Brickley & Ives, 2010; Snoddy et al., 2018). It is also conceivable that the frequencies of possible cases of scurvy is an overrepresentation of individuals with clinical scurvy. As previously mentioned, treponemal disease has been identified in the Man Bac assemblage, possibly contributing to the SPNB recorded in the non-adult assemblage (Vlok et al., 2020). However, regarding probable cases, 84.1% ($n = 37/44$) of Man Bac non-adults had more than three diagnostic lesions for scurvy, and 56.8% ($n = 25/44$) also presented with radiographic signs of scurvy, further strengthening the argument for high levels of non-adult scurvy at Man Bac.

Man Bac inhabitants had a broad-based diet. It is currently not known to what degree rice was relied on or to what degree indigenous plants supplemented the diet at Man Bac. Evidence for fruits and nuts of a wide variety have been found in Pre-Neolithic sites in northern Vietnam (Mai Huong, 2013; Oxenham et al., 2018) and the diverse ecologies exploited by the Man Bac community may have provided a range of available fruits and nuts. However, following climate cooling after the HTM decline at ~5 kya, the ecology of the region would have changed significantly. Globally, dietary diversity decreased with the transition to agriculture, and this pattern is also present at Man Bac with a decrease in faunal taxa exploitation around the introduction of agriculture (Jones et al., 2019). It is possible a similar reduction in floral diversity also occurred with the introduction of rice and concurrent climate change, that may partly explain the high levels of scurvy identified at Man Bac. Both wild and cultivated food sources may have been occasionally disrupted by frequent tropical storms, potentially increasing the nutritional stress already experienced with the decrease in dietary diversity (Oxenham, 2006), an interpretive point also used regarding the cases in the Pacific (Buckley et al., 2014).

Although at Man Bac there was a high reliance on various species from marine, freshwater, and brackish environments, all fish types provided inadequate levels of Vitamin C. Similarly, the terrestrial faunal assemblage would not have yielded sufficient levels of Vitamin C (Sawada et al., 2011). The cooking and processing of these foods would have further depleted the bioavailable Vitamin C (Mays, 2013; Rumm-Kreuter & Demmel, 1990). The interaction between local foragers and migrant farmers was also likely to have had an impact on nutritional stress. The migrants may have needed to adapt the process of growing domesticated crops in this new environment, and locals likely needed to navigate the change of their environment by the agricultural efforts from this new migrant group. The process of teaching the other group their subsistence strategies would also have been imperfect.

Finally, adequate intake of Vitamin C is essential for immune function. Man Bac has already demonstrated paleopathological evidence for an exceptional pathogen load of treponematosis and malaria (Vlok et al., 2020, 2021). A high pathogen load, where phagocytes are activated in the immune response, consequently, increases oxidative stress and increases the demand for Vitamin C, an antioxidant, in the body (Hemilä, 2017; Khaw & Woodhouse, 1995; Rokkas et al., 1995). Indeed, in a subtropical climate a high pathogen load from many infectious diseases is expected. Hookworm, roundworm, *Shigella* sp., *Salmonella* sp., schistosomiasis, malaria, and *Escherichia coli* are all possible causes for infectious diarrhea which decrease the absorption of Vitamin C (King et al., 2017; Oxenham, 2016). Weanling diarrhea, associated with the introduction of foods to supplement breast feeding may have also increased the dietary requirement for Vitamin C in infants. This synergy is possibly driving the high frequencies of scurvy identified in the Man Bac infants and has been argued to be a contributing factor in other tropical environments (Buckley, 2000). To date, no isotopic research has identified the terminal age of weaning at Man Bac, but passive immunity from the maternal intrauterine environment is known to be reduced by 3 months of age (M. E. Lewis, 2017). Furthermore, the high levels of fertility at Man Bac indicate shorter birth intervals which may have been facilitated by the early introduction of weaning foods (Buikstra et al., 1986; McFadden & Oxenham, 2018; Oxenham & Willis, 2017). It is possible the increased frequency of probable scurvy after 6 months of age is related to the decreased efficacy of passive immunity from the intrauterine environment combined with the introduction of weaning foods and increasing susceptibility of pathogens and the requirements for Vitamin C deficiency in these infants. In sum, a combination of restricted dietary diversity possibly due to environmental factors, combined with transition to agricultural subsistence, and high pathogen loads are likely underlying the outcome of high levels of non-adult scurvy at Man Bac.

4.4 | Epidemiology of scurvy at Man Bac

Active scurvy cases were highest under 1 year of age. Additionally, active cases of scurvy were significantly higher in individuals under the age of 5 years than those over the age of 5 years. Selective mortality is most likely at play regarding the presentation of scurvy in infants and young children. Children under the age of 5 were likely more susceptible to risk of death from scurvy than those over the age of 5 years who more commonly presented with patterns of healing. However, the increase in prevalence following the 6-month mark indicates additional factors beyond the mortality profile influencing the age-at-death distribution of scurvy. Potential impacts include weaning, the changing growth demands of an infant at this age, and introduction of pathogens via supplementary weaning foods. It is possible that breast milk provided some buffering to nutritional deficiency in the neonatal and early infant period. Indeed, scurvy is documented to be less common in breastfed infants. Even when not weaned, at 5 or 6 post-natal months, maternal stores of Vitamin C in breastmilk also tend to be depleted (World Health Organization, 1999). Additionally, infants between 6 months and 1 year are known to have an increased risk to nutritional disease when compared to infants under 6 months due to increased nutrient requirements (Devaney et al., 2004).

4.5 | The role of Vitamin C and complications of scurvy

Ascorbic acid (Vitamin C) is an antioxidant free radical compound with the ability to bind to aggressive oxidative compounds and make them less reactive, thereby playing a crucial role in the maintenance of the cellular membrane of intracellular organelles (Linster & Van Schaftingen, 2007). It also plays an antioxidant role in the plasma surrounding the lung, lens, and retina of the eye (Bendich et al., 1986). Oxidation occurs due to inflammatory immune response to pathogens, therefore Vitamin C plays an essential role in immune function (Wintergerst et al., 2006). Vitamin C is also essential in the production of collagen formation in the body. Lysyl and prolyl (procollagen molecules) are hydroxylized by enzymes which require ascorbic acid for proper function. With prolonged Vitamin C deficiency, collagen fibers are rendered unstable, weakening collagen-based structures in the body such as blood vessels (Hirschmann & Raugi, 1999; Maat, 2004). The chronic hemorrhaging as described above subsequently occurs in Vitamin C deficiency due to repeated rupturing of weak blood vessels causing the nutritional disease known as scurvy (Hirschmann & Raugi, 1999).

At minimum 10 mg a day is required to prevent clinical scurvy in an adult male, but requirements are poorly understood for non-adults (Hirschmann & Raugi, 1999). As observed in adults, within a few weeks of restricted dietary Vitamin C, fatigue develops as the first symptom (Hirschmann & Raugi, 1999). Within 90 days of deficiency, bodily stores of Vitamin C are depleted (Hirschmann & Raugi, 1999). Extended periods of scurvy over a few months can then result in hyperkeratotic papules around hair follicles, corkscrew hairs and eventually perifollicular and subperiosteal hemorrhaging as a consequence of weakened blood vessels (Hirschmann & Raugi, 1999; S. J. Lewis et al., 1998). Hemorrhages have been reported to occur in the conjunctiva, eye lids, retrobulbar space, the sheaths of the optic nerve and in the limbs (which can cause neuropathy) (Hirschmann & Raugi, 1999; S. J. Lewis et al., 1998).

A plethora of other symptoms can occur including joint pain, joint effusions, ankle edema, mucosal ulceration, weakness, shortness of breath, tooth loss and insufficiency fractures of the spine (Hirschmann & Raugi, 1999; Keenan et al., 2002; S. J. Lewis et al., 1998). Pain associated with swelling of joints, movement of limbs, and bone pain predominantly due to hemorrhaging can sometimes lead to difficulty walking in adults and children (Hirschmann & Raugi, 1999; Keenan et al., 2002; Ortner & Ericksen, 1997). Infantile scurvy usually presents as tenderness of the limbs, pseudoparalysis (paralysis caused by pain and not nerve damage), irritability, cessation of sitting or standing, the drawing up of legs into a frog position, pain of the chest resulting in difficulty breathing, and bleeding gums with erupting teeth (Woodruff, 1956).

The production of abnormal type X collagen in children causes the metaphyseal deformities in growing limb bones (Keenan et al., 2002). As Vitamin C plays a role in osteoid production, calcified cartilage at the provisional zone of calcification of the metaphyseal plates lacks this vital component of growing bone (Keenan et al., 2002). Deficiency also results in thinning trabeculae in the metaphyses and an increased occurrence of microfractures (Keenan et al., 2002). Lastly, death can occur due to pulmonary hypertension, myocardial hemorrhaging, pericardial hemorrhaging, and most commonly fatal shock due to internal blood loss and impaired vasoconstriction (Hirschmann & Raugi, 1999). Reintroduction of Vitamin C into the diet is curative. The high prevalence of scurvy in the Man Bac children suggests that a suite of the above signs and symptoms likely occurred among them, providing a significant care burden on the community. In conjunction with other non-specific signs of stress, it is clear these children required significant care beyond what is standard for infants (Oxenham & Willis, 2017).

4.6 | Non-adult health and the Neolithic transition in Southeast Asia

Non-adults are the most sensitive indicators of health in a population where due to their rapid bone development and overall fragility, disease is likely to be more visible in this cohort than in adults (Halcrow et al., 2016; M. E. Lewis, 2017). Much of the recent findings such as by Vlok et al. (2020, 2021) have been contingent on the identification of diseases in non-adults. Other paleopathological works in the region further demonstrate the importance this cohort has had on revealing details of health in MSEA's past (Halcrow et al., 2013, 2016; Oxenham et al., 2008; Tayles, 1996, 1999). For example, the research by Halcrow et al. (2013, 2016) have distinctly demonstrated a significant impact on the health of the younger individuals in Thailand from the Iron Age onwards with the rise of hierarchical urban proto states.

The adoption of agriculture in MSEA, and the degree of interactions between farmers and foragers were complex and non-linear, therefore variations in the impact to health is expected (Oxenham & Buckley, 2016). Indeed, subsistence, population interaction, population density and sedentism vary throughout Neolithic sites in MSEA. Therefore, Man Bac and Con Co Ngua do not reflect the overall impact of the Neolithic transition on health in the region. To date no other MSEA Neolithic site presents with non-adult SPNB levels as high as Man Bac (Halcrow et al., 2016; Pietrusewsky & Douglas, 2002; Tayles, 1999), further indicating that Man Bac may be a unique case in the overall transition to agriculture in the region. Additionally, scurvy has, to date, not been identified in other prehistoric sites in MSEA. Interestingly, the skeletal evidence of non-specific stress at Man Bac, particularly in children is comparative to that of Khok Phanom Di (Halcrow et al., 2016; Oxenham & Domett, 2011), possibly indicating that the initial adoption of agriculture may indeed have had a detrimental impact on health. However, to fully appreciate shifts in health with the adoption of agriculture, further paleopathological work on Pre-Neolithic sites is required beyond that of Con Co Ngua, the only systematically studied Pre-Neolithic site in MSEA to date. In other parts of MSEA such as modern day Thailand, Pre-Neolithic forager groups were smaller and more mobile, and a different transitional epidemiological pattern could be expected for these regions when agriculture was introduced (Shoocongdej, 2000).

There were very little differences in the prevalence of non-specific stress markers such as linear enamel hypoplasia and cribra orbitalia at Man Bac and Con Co Ngua (Oxenham et al., 2018; Oxenham & Domett, 2011). We now know that the inhabitants of

Con Co Ngua greatly suffered high infectious disease burdens including malaria, hydatid disease, as well as genetic anemia (Vlok et al., 2021, 2022), which would have obscured the differing nutritional trends contributing to non-specific stress, and now revealed through investigation for evidence of scurvy in the assemblages. That is, while the morbidity of general physiological stress was similar, the contribution of nutritional and infectious diseases to these stressors differed greatly between Con Co Ngua and Man Bac.

This trend in high burdens of disease revealed through specific and non-specific disease at Man Bac and Con Co Ngua is not observed in later Bronze and Iron Age sites that mark the intensification of agriculture (Halcrow et al., 2016). It is likely that factors not directly related to the dietary effects of rice, rather secondary impacts of initial agricultural adoption, such as a significant increase in fertility, and climatic decline of wild resource returns, are the drivers for an increase in nutritional stress at Man Bac. A reappraisal of prehistoric MSEA sites, employing recent approaches to identifying specific nutritional diseases is warranted to further investigate if this is a consistent (albeit generalized) temporal trend. Ultimately, the impact of agricultural transition on health should be investigated at a site level, and various lines of paleopathological study involving assessment of non-specific markers of stress *and* the diagnosis of specific diseases should be incorporated in the analysis of changes of health with the agricultural transition in this region.

5 | CONCLUSION

We document here paleopathological evidence for an exceptional increase in nutritional stress from the Pre-Neolithic to Neolithic of northern Vietnam. Between the conditions of the HTM experienced by the inhabitants of Con Co Ngua and the 4.2 ka event which affected the Man Bac inhabitants, the extremes of ecological, social, and biological change created a scenario wherein dramatic shifts in nutritional disease could be observed over time. Ultimately, a large climatic shift whereby a subsistence change to farming was likely necessary for survival, enacted a plethora of flow on effects with consequences to health. Increased sedentism, a higher juvenile to adult ratio, a greater burden of infectious disease, increased food demands, diminishing wild resource returns, and renegotiation of kinship and social structure would have all contributed to the most vulnerable in the population dying with scurvy (and all the other diseases that interact to exacerbate the effects of scurvy) prior to achieving adulthood. We conclude that it is not necessary for significant agricultural efforts (especially agricultural dependence) to occur for there to be potentially significant deleterious consequences to health, particularly in the context of climate change, as was the case at Man Bac.

AUTHOR CONTRIBUTIONS

Melandri Vlok: Conceptualization (lead); data curation (lead); formal analysis (lead); funding acquisition (lead); investigation (lead); methodology (lead); project administration (lead); resources (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **Marc Fredrick Oxenham:** Data curation (equal); funding acquisition (equal); project administration (equal); writing – original draft (supporting); writing – review and editing (supporting). **Kate Domett:** Data curation (supporting); investigation (supporting); project administration (supporting); resources (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Hiep Hoang Trinh:** Investigation (supporting); project administration (supporting); resources (equal); writing – original draft (supporting); writing – review and editing (supporting). **Tran Thi Minh:** Data curation (supporting); formal analysis (supporting); investigation (supporting); resources (supporting); validation (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Nguyen Thi Mai Huong:** Investigation (supporting); project administration (supporting); resources (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Hirofumi Matsumura:** Data curation (supporting); funding acquisition (supporting); project administration (supporting); resources (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Nghia Truong Huu:** Writing – original draft (supporting); writing – review and editing (supporting). **Lan Cuong Nguyen:** Data curation (supporting); investigation (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Anna Willis:** Data curation (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Hallie Buckley:** Conceptualization (equal); formal analysis (supporting); investigation (equal); methodology (supporting); project administration (supporting); resources (equal); supervision (lead); validation (equal); writing – original draft (equal); writing – review and editing (equal).

ACKNOWLEDGMENTS

We would like to thank Dr Ngo Anh Son, Dr Bui Van Khanh, and Ms Nellissa Ling for their assistance with the radiographs, and Dr Anne Marie Snoddy for discussions on the diagnosis of scurvy and comments on the manuscript. We would also like to thank Dr Clare McFadden for assistance on an earlier version of the manuscript. This work was supported by Australian Research Council (DP110101097, FT120100299); National Geographic Early Career Grant (EC-54332R-18); Royal Society of New Zealand Skinner Fund Grant; and a University of Otago Doctoral Scholarship. Open access publishing facilitated by The University of Sydney, as part of the Wiley - The University of Sydney agreement via the Council of Australian University Librarians.

DATA AVAILABILITY STATEMENT

Data is provided in the supplementary material.

ORCID

Melandri Vlok https://orcid.org/0000-0002-5259-3819
Marc Fredrick Oxenham https://orcid.org/0000-0002-5804-2145

REFERENCES

Bellwood, P., & Oxenham, M. (2008). The expansions of farming societies and the role of the Neolithic demographic transition. In J.-P. Bocquet-Appel & O. Bar-Yosef (Eds.), *The Neolithic demographic transition and its consequences* (pp. 13–34). Springer Science.

Bellwood, P., Oxenham, M. F., Hoang, B. C., Dzung, N. K., Willis, A., Sarjeant, C., Piper, P., Matsumura, H., Tanaka, K., Beavan, N., Higham, T., Manh, N., Kinh, D., Kien, N., Huong, V., Bich, V., Quy, T., Thao, N., Campos, F., … Beavan-Athfield, N. (2011). An Son and the Neolithic of Southern Vietnam. *Asian Perspectives*, *50*, 144–175.

Bendich, A., Machlin, L., Scandurra, O., Burton, G., & Wayner, D. (1986). The antioxidant role of vitamin C. *Advances in Free Radical Biology & Medicine*, *2*(2), 419–444.

Bocquet-Appel, J.-P., Naji, S., & Bandy, M. (2008). Demographic and health changes during the transition to agriculture in North America. In *Recent advances in palaeodemography* (pp. 277–292). Springer.

Bouis, H. E., & Welch, R. M. (2010). Biofortification—A sustainable agricultural strategy for reducing micronutrient malnutrition in the global south. *Crop Science*, *50*(Suppl 1), S-20–S-32.

Brickley, M., & Ives, R. (2006). Skeletal manifestations of infantile scurvy. *American Journal of Physical Anthropology: The Official Publication of the American Association of Physical Anthropologists*, *129*(2), 163–172.

Brickley, M., & Ives, R. (2010). *The bioarchaeology of metabolic bone disease*. Academic Press.

Brickley, M., Ives, R., & Mays, S. (2020). *The bioarchaeology of metabolic bone disease* (2nd ed.). Academic Press.

Buckley, H. R. (2000). Subadult health and disease in prehistoric Tonga, Polynesia. *American Journal of Physical Anthropology*, *113*(4), 481–505.

Buckley, H. R., Kinaston, R., Halcrow, S. E., Foster, A., Spriggs, M., & Bedford, S. (2014). Scurvy in a tropical paradise? Evaluating the possibility of infant and adult vitamin C deficiency in the Lapita skeletal sample of Teouma, Vanuatu, Pacific islands. *International Journal of Paleopathology*, *5*, 72–85.

Buckley, H. R., & Tayles, N. (2003). Skeletal pathology in a prehistoric Pacific Island sample: Issues in lesion recording, quantification, and interpretation. *American Journal of Physical Anthropology*, *122*(4), 303–324.

Buikstra, J. E., Konigsberg, L. W., & Bullington, J. (1986). Fertility and the development of agriculture in the prehistoric Midwest. *American Antiquity*, *51*(3), 528–546.

Buikstra, J. E., & Ubelaker, D. H. (1994). *Standards for data collection from human skeletal remains: Proceedings of a seminar at the Field Museum of natural history Arkansas Archaeological Survey Research series* (Vol. 44). Arkansas Archaeological Survey.

Castillo, C. (2011). Rice in Thailand: The archaeobotanical contribution. *Rice*, *4*(3), 114–120.

Castillo, C., Fuller, D. Q., Piper, P. J., Bellwood, P., & Oxenham, M. F. (2018). Hunter-gatherer specialization in the late Neolithic of southern Vietnam—The case of Rach Nui. *Quaternary International*, *489*, 63–79.

Devaney, B., Ziegler, P., Pac, S., Karwe, V., & Barr, S. I. (2004). Nutrient intakes of infants and toddlers. *Journal of the American Dietetic Association*, *104*, 14–21.

Eshed, V., Gopher, A., Pinhasi, R., & Hershkovitz, I. (2010). Paleopathology and the origin of agriculture in the Levant. *American Journal of Physical Anthropology*, *143*(1), 121–133.

Fain, O. (2005). Musculoskeletal manifestations of scurvy. *Joint, Bone, Spine*, *72*(2), 124–128.

Geber, J., & Murphy, E. (2012). Scurvy in the great Irish famine: Evidence of vitamin C deficiency from a mid-19th century skeletal population. *American Journal of Physical Anthropology*, *148*(4), 512–524.

Halcrow, S. E., Harris, N., Beavan, N., & Buckley, H. (2014). First bioarchaeological evidence of probable scurvy in Southeast Asia: Multifactorial etiologies of vitamin C deficiency in a tropical environment. *International Journal of Paleopathology*, *5*, 63–71.

Halcrow, S. E., Harris, N., Tayles, N., Ikehara-Quebral, R., & Pietrusewsky, M. (2013). From the mouths of babes: Dental caries in infants and children and the intensification of agriculture in Mainland Southeast Asia. *American Journal of Physical Anthropology*, *150*(3), 409–420.

Halcrow, S. E., Tayles, N., & King, C. L. (2016). Infant and child health and disease with agricultural intensification in Mainland Southeast Asia. In M. Oxenham & H. Buckley (Eds.), *The Routledge handbook of bioarchaeology in Southeast Asia and the Pacific Islands* (pp. 186–214). Routledge.

Hemilä, H. (2017). Vitamin C and infections. *Nutrients*, *9*(4), 339.

Hiep, T., & Phung, H. (2004). Man Bac location and its relationship through ceramic data (in Vietnamese). *Khao Co Hoc (Vietnamese Archaeology)*, *6*, 13–48.

Higham, C. (2007). *The Origins of the Civilization of Angkor: The excavation of Noen U-Loke and Non Muang Kao* (Vol. 2). Fine Arts Department of Thailand.

Higham, C. F., Cameron, J., Chang, N., Castillo, C., Halcrow, S., O'Reilly, D., & Shewan, L. (2014). The excavation of Non Ban Jak, Northeast Thailand-a report on the first three seasons. *Journal of Indo-Pacific Archaeology*, *34*, 1–41.

Higham, C., Guangmao, X., & Qiang, L. (2011). The prehistory of a friction zone: First farmers and hunters-gatherers in Southeast Asia. *Antiquity*, *85*(328), 529–543.

Higham, C., Higham, T., & Kijngam, A. (2011). Cutting a Gordian knot: The Bronze Age of Southeast Asia: Origins, timing and impact. *Antiquity*, *85*(328), 583–598.

Higham, C., Higham, T. F., & Douka, K. (2019). Dating the Bronze Age of Southeast Asia. Why does it matter? *Journal of Indo-Pacific Archaeology*, *43*, 43–67.

Higham, C., Manly, B., Thosarat, R., Buckley, H. R., Chang, N., Halcrow, S., Ward, S., O'Reilly, D., Shewan, L., & Domett, K. (2019). Environmental and social change in Northeast Thailand during the iron age. *Cambridge Archaeological Journal*, *29*(4), 549–569.

Higham, C., & Thosarat, R. (2005). *Excavation of Khok Phanom Di, 7: Summary and conclusions*. Fine Arts Department of Thailand.

Higham, T., Weiss, A., Pigott, V., Higham, C., Ramsey, C., D'Alpoim-Guedes, J., Hanson, S., Weber, S. A., Rispoli, F., Ciarla, R., & Pryce, T. O. (2022). A new chronology for a prehistoric copper production Centre in Central Thailand using kernel density estimates. *Antiquity*.

Hirschmann, J., & Raugi, G. J. (1999). Adult scurvy. *Journal of the American Academy of Dermatology*, *41*(6), 895–910.

Jaffe, H. L. (1972). *Metabolic, degenerative, and inflammatory diseases of bones and joints*. Lea and Febiger.

Jones, R. K. (2017). *Transitions to animal domestication in Southeast Asia: Zooarchaeological analysis of Cồn Cổ Ngựa and Mán Bạc, Vietnam* (PhD). Australian National University.

Jones, R. K., Piper, P. J., Groves, C. P., Anh, T. N., Thi, M. H. N., Thị, H. N., Hoang, T. H., & Oxenham, M. F. (2019). Shifting subsistence patterns from the terminal Pleistocene to Late Holocene: A regional southeast Asian analysis. *Quaternary International*, *529*, 47–56.

Keenan, S., Mitts, K. G., & Kurtz, C. A. (2002). Scurvy presenting as a medial head tear of the gastrocnemius. *Orthopedics*, *25*(6), 689–691.

Khaw, K.-T., & Woodhouse, P. (1995). Interrelation of vitamin C, infection, haemostatic factors, and cardiovascular disease. *BMJ*, *310*(6994), 1559–1563.

Kinaston, R. L., Buckley, H. R., Halcrow, S. E., Spriggs, M. J., Bedford, S., Neal, K., & Gray, A. (2009). Investigating foetal and perinatal mortality in prehistoric skeletal samples: A case study from a 3000-year-old Pacific Island cemetery site. *Journal of Archaeological Science*, *36*(12), 2780–2787.

King, C. L., Bentley, R. A., Higham, C., Tayles, N., Viðarsdóttir, U. S., Layton, R., Macpherson, C. G., & Nowell, G. (2014). Economic change after the agricultural revolution in Southeast Asia? *Antiquity*, *88*(339), 112–125.

King, C. L., Halcrow, S. E., Tayles, N., & Shkrum, S. (2017). Considering the palaeoepidemiological implications of socioeconomic and environmental change in Southeast Asia. *Archaeological Research in Asia*, *11*, 27–37.

Klaus, H. D. (2017). Paleopathological rigor and differential diagnosis: Case studies involving terminology, description, and diagnostic frameworks for scurvy in skeletal remains. *International Journal of Paleopathology*, *19*, 96–110.

Larsen, C. S. (2006). The agricultural revolution as environmental catastrophe: Implications for health and lifestyle in the Holocene. *Quaternary International*, *150*(1), 12–20. https://doi.org/10.1016/j.quaint.2006.01.004

Larsen, C. S., Hillson, S. W., Boz, B., Pilloud, M. A., Sadvari, J. W., Agarwal, S. C., Glencross, B., Beauchesne, P., Pearson, J., Garofalo, E. M., Hager, L. D., Haddow, S. D., Knüsel, C. J., & Ruff, C. B. (2015). Bioarchaeology of Neolithic Çatalhöyük: Lives and lifestyles of an early farming society in transition. *Journal of World Prehistory*, *28*(1), 27–68.

Lewis, M. E. (2017). *Paleopathology of children: Identification of pathological conditions in the human skeletal remains of non-adults*. Academic Press.

Lewis, S. J., Mcdowell, I., & Hawthorne, A. B. (1998). Vitamin C deficiency in Asian women. *Nutrition (Burbank, Los Angeles County, Calif.)*, *14*(2), 231–232.

Linster, C. L., & Van Schaftingen, E. (2007). Vitamin C. *The FEBS Journal*, *274*(1), 1–22.

Maat, G. (2004). Scurvy in adults and youngsters: The Dutch experience. A review of the history and pathology of a disregarded disease. *International Journal of Osteoarchaeology*, *14*(2), 77–81.

Maher, B. A., & Hu, M. (2006). A high-resolution record of Holocene rainfall variations from the western Chinese Loess Plateau: Antiphase behaviour of the African/Indian and East Asian summer monsoons. *The Holocene*, *16*(3), 309–319.

Mai Huong, N. T. (2013). Neolithic vegetation in Northern Vietnam: An indication of early agricultural activities. *Journal of Austronesian Studies*, *4*, 1.

Mai Huong, N. T. (2016). Burnt rice from four archaeological sites in Northern Vietnam. *Vietnam Social Sciences*, *179*(3), 64–77.

Mays, S. (2013). A discussion of some recent methodological developments in the osteoarchaeology of childhood. *Childhood in the Past*, *6*(1), 4–21.

Mays, S. (2018). How should we diagnose disease in palaeopathology? Some epistemological considerations. *International Journal of Paleopathology*, *20*, 12–19.

McFadden, C., Buckley, H., Halcrow, S. E., & Oxenham, M. F. (2018). Detection of temporospatially localized growth in ancient Southeast Asia using human skeletal remains. *Journal of Archaeological Science*, *98*, 93–101. https://doi.org/10.1016/j.jas.2018.08.010

McFadden, C., & Oxenham, M. F. (2018). The D0-14/D ratio: A new paleodemographic index and equation for estimating total fertility rates. *American Journal of Physical Anthropology*, *165*(3), 471–479. https://doi.org/10.1002/ajpa.23365

McGrath, R., & Boyd, W. E. (2001). The chronology of the iron age 'moats' of Northeast Thailand. *Antiquity*, *75*(288), 349–360.

McKinley, J. (2004). Compiling a skeletal inventory: Disarticulated and co-mingled remains. In M. Brickley & J. McKinley (Eds.), *Guidelines to the standards for recording human remains* (Vol. IfA Paper no.7). BABAO/Institute of Field Archaeologists.

Moorrees, C. F., Fanning, E. A., & Hunt, E. E. (1963). Formation and resorption of three deciduous teeth in children. *American Journal of Physical Anthropology*, *21*(2), 205–213.

Ortner, D. J. (1992). Skeletal paleopathology; probabilities, possibilities and impossibilities. In J. Verano & D. Ubelaker (Eds.), *Demography in the Americas* (pp. 5–13). Smithsonian Institution Press.

Ortner, D. J. (2003). *Identification of pathological conditions in human skeletal remains*. Academic Press.

Ortner, D. J., Butler, W., Cafarella, J., & Milligan, L. (2001). Evidence of probable scurvy in subadults from archeological sites in North America. *American Journal of Physical Anthropology*, *114*(4), 343–351.

Ortner, D. J., & Ericksen, M. F. (1997). Bone changes in the human skull probably resulting from scurvy in infancy and childhood. *International Journal of Osteoarchaeology*, *7*(3), 212–220.

Oxenham, M. F. (2006). Biological responses to change in prehistoric Viet Nam. *Asian Perspectives*, *45*(2), 212–239.

Oxenham, M. F. (2015). Mainland Southeast Asia: Towards a new theoretical approach. *Antiquity*, *89*(347), 1221–1223.

Oxenham, M. F. (2016). *Bioarchaeology of ancient northern Vietnam* (Vol. 2781). Archaeopress.

Oxenham, M. F., & Buckley, H. (2016). The population history of mainland and Island Southeast Asia. In M. F. Oxenham & H. Buckley (Eds.), *The Routledge handbook of bioarchaeology in Southeast Asia and the Pacific* (pp. 9–23). Routledge.

Oxenham, M. F., & Domett, K. M. (2011). Palaeohealth at Man Bac. In M. F. Oxenham, H. Matsumura, & N. Kim Dung (Eds.), *Man Bac: The excavation of a Neolithic site in Northern Vietnam. The biology* (Vol. 33, pp. 77–93). ANU ePress.

Oxenham, M. F., Matsumura, H., Domett, K., Thuy, N. K., Dung, N. K., Cuong, N. L., Huffer, D., & Muller, S. (2008). Health and the experience of childhood in Late Neolithic Viet Nam. *Asian Perspectives*, *47*(2), 190–209.

Oxenham, M. F., Matsumura, H., & Kim Dung, N. (2011). *Man Bac: The excavation of a Neolithic site in Northern Vietnam: The biology*. *Terra Australis 33*. ANU ePress.

Oxenham, M. F., & Tayles, N. (2006). Synthesising Southeast Asian population history and Palaeohealth. In M. Oxenham & N. Tayles (Eds.), *Bioarchaeology of Southeast Asia* (pp. 335–349). Cambridge University Press.

Oxenham, M. F., Trinh, H., Willis, A., Jones, R., Domett, K., Castillo, C., Wood, R., Bellwood, P., Tromp, M., Kells, A., Piper, P., Pham, S., Matsumura, H., & Buckley, H. (2018). Between foraging and farming: Strategic responses to the Holocene thermal maximum in Southeast Asia. *Antiquity*, *92*(364), 940–957.

Oxenham, M. F., & Willis, A. (2017). Towards a bioarchaeology of care of children. In L. Tilley & A. Schrenk (Eds.), *New developments in the bioarchaeology of care* (pp. 219–236). Springer.

Pettifor, J. M. (2004). Nutritional rickets: Deficiency of vitamin D, calcium, or both? *The American Journal of Clinical Nutrition*, *80*(6), 1725 S–1729 S.

Pietrusewsky, M., & Douglas, M. T. (2002). *Ban Chiang, a prehistoric village site in Northeast Thailand, Vol. 1: The human skeletal remains*. University of Pennsylvania Museum of Archaeology.

Piper, P., Campos, F., Ngoc Kinh, D., Amano, N., Oxenham, M. F., Chi Hoang, B., Bellwood, P., & Willis, A. (2014). Early evidence for pig and dog husbandry from the Neolithic site of an son, Southern Vietnam. *International Journal of Osteoarchaeology*, *24*(1), 68–78.

Renssen, H. (2022). Climate model experiments on the 4.2 ka event: The impact of tropical sea-surface temperature anomalies and desertification. *The Holocene*, *32*(5), 378–389.

Renssen, H., Seppä, H., Crosta, X., Goosse, H., & Roche, D. M. (2012). Global characterization of the Holocene thermal maximum. *Quaternary Science Reviews*, *48*, 7–19.

Resnick, D. (1995). *Diagnosis of bone and joint disorders*. Saunders.

Roberts, C. A., & Connell, B. (2004). *Guidance on recording palaeopathology*. British Association for Biological Anthropology and Osteoarchaeology.

Rokkas, T., Papatheodorou, G., Karameris, A., Mavrogeorgis, A., Kalogeropoulos, N., & Giannikos, N. (1995). Helicobacter pylori infection and gastric juice vitamin C levels. *Digestive Diseases and Sciences*, *40*(3), 615–621.

Rumm-Kreuter, D., & Demmel, I. (1990). Comparison of vitamin losses in vegetables due to various cooking methods. *Journal of Nutritional Science and Vitaminology*, *36*(4), S7–S15.

Sawada, J., Thuy, N. K., & Tuan, N. A. (2011). Faunal remains at Man Bac. In M. F. Oxenham, H. Matsumura, & N. Kim Dung (Eds.), *Man Bac: The excavation of a Neolithic site in Northern Vietnam: The biology*. *Terra Australis 33* (pp. 105–116). ANU ePress.

Schattmann, A., Bertrand, B., Vatteoni, S., & Brickley, M. (2016). Approaches to co-occurrence: Scurvy and rickets in infants and young children of 16–18th century Douai, France. *International Journal of Paleopathology*, *12*, 63–75.

Scheuer, L., & Black, S. (2000). *Developmental juvenile osteology*. Academic Press.

Scott, R. M., Buckley, H. R., Domett, K., Tromp, M., Trinh, H. H., Willis, A., Matsumura, H., & Oxenham, M. F. (2019). Domestication and large animal interactions: Skeletal trauma in northern Vietnam during the hunter-gatherer Da But period. *PLoS One*, *14*(9), e0218777.

Shoocongdej, R. (2000). Forager mobility organization in seasonal tropical environments of western Thailand. *World Archaeology*, *32*(1), 14–40.

Smith, R. J. (2020). P > .05: The incorrect interpretation of "not significant" results is a significant problem. *American Journal of Physical Anthropology*, *172*(4), 521–527.

Snoddy, A. M. E., Buckley, H. R., Elliott, G. E., Standen, V. G., Arriaza, B. T., & Halcrow, S. E. (2018). Macroscopic features of scurvy in human skeletal remains: A literature synthesis and diagnostic guide. *American Journal of Physical Anthropology*, *167*(4), 876–895. https://doi.org/10.1002/ajpa.23699

Snoddy, A. M. E., Halcrow, S. E., Buckley, H. R., Standen, V. G., & Arriaza, B. T. (2017). Scurvy at the agricultural transition in the Atacama Desert (ca 3600–3200 BP): Nutritional stress at the maternal-foetal interface? *International Journal of Paleopathology*, *18*, 108–120. https://doi.org/10.1016/j.ijpp.2017.05.011

Tanabe, S., Saito, Y., Vu, Q. L., Hanebuth, T. J., Ngo, Q. L., & Kitamura, A. (2006). Holocene evolution of the Song Hong (Red River) delta system, northern Vietnam. *Sedimentary Geology*, *187*(1–2), 29–61.

Tayles, N. (1996). Anemia, genetic diseases, and malaria in prehistoric mainland Southeast Asia. *American Journal of Physical Anthropology*, *101*(1), 11–27.

Tayles, N. (1999). *The excavation of Khok Phanom Di a prehistoric site in Central Thailand, Vol. V: The people*. Reports-Research Committee Society of Antiquaries London.

Tayles, N., Domett, K., & Nelsen, K. (2000). Agriculture and dental caries? The case of rice in prehistoric Southeast Asia. *World Archaeology*, *32*(1), 68–83.

Temple, D. H., & Larsen, C. S. (2013). Bioarchaeological perspectives on systemic stress during the agricultural transition in prehistoric Japan. In K. Pechenkina & M. Oxenham (Eds.), *Bioarchaeology of East Asia: Movement, contact, health* (pp. 344–367). University Press of Florida.

Toizumi, T., Thuy, N. K., & Sawada, J. (2011). Fish remains at Man Bac. In M. F. Oxenham, H. Matsumura, & N. Kim Dung (Eds.), *Man Bac: The excavation of a Neolithic site in northern Vietnam. The biology, Terra Australis* (Vol. 33, pp. 117–126). ANU ePress.

Ubelaker, D. H. (1989). *Human skeletal remains: Excavation, analysis, interpretation* (3rd ed.). Taraxacum Press.

Vlok, M., Buckley, H. R., Domett, K., Willis, A., Tromp, M., Trinh, H. H., Minh, T. T., Mai Hương, N. T., Nguyễn, L. C., Matsumura, H., Huu, N., & Oxenham, M. F. (2022). Hydatid disease (*Echinococcosis granulosis*) diagnosis from skeletal osteolytic lesions in an early seventh-millennium BP forager community from preagricultural northern Vietnam. *American Journal of Biological Anthropology*, *177*(1), 100–115.

Vlok, M., Buckley, H. R., Miszkiewicz, J. J., Walker, M., Domett, K., Matsumura, H., Wang, T., Nghia, H. T., & Oxenham, M. F. (2021). Forager and farmer evolutionary adaptations to malaria evidenced by 7000 years of thalassemia in Southeast Asia. *Scientific Reports*, *11*, 5677.

Vlok, M., Oxenham, M. F., Domett, K., Tran, M. T., Mai Huong, N. T., Matsumura, H., Trinh, H., Higham, T., Higham, C., Huu, N., & Buckley, H. R. (2020). Two probable cases of infection with *Treponema pallidum* during the Neolithic period in northern Vietnam (ca. 2000-1500B.C.). *Bioarchaeology International*, *4*(1), 15–39.

Vlok, M., Oxenham, M. F., McFadden, C., Domett, K., Minh, T. T., Mai Huong, N. T., Matsumura, H., & Buckley, H. (forthcoming). *Nutritional Rickets in Tropical Southeast Asia during the Agricultural Revolution: Analysis of Morbidity and Mortality*. Sydney Southeast Asia Centre, The University of Sydney.

Weber, S., Lehman, H., Barela, T., Hawks, S., & Harriman, D. (2010). Rice or millets: Early farming strategies in prehistoric Central Thailand. *Archaeological and Anthropological Sciences*, *2*(2), 79–88.

White, T. D., Black, M. T., & Folkens, P. A. (2000). *Human osteology* (3rd ed.). Academic Press.

Willis, A., & Oxenham, M. F. (2013). The Neolithic demographic transition and oral health: The Southeast Asian experience. *American Journal of Physical Anthropology*, *152*(2), 197–208.

Wintergerst, E. S., Maggini, S., & Hornig, D. H. (2006). Immune-enhancing role of vitamin C and zinc and effect on clinical conditions. *Annals of Nutrition and Metabolism*, *50*(2), 85–94.

Woodruff, C. (1956). Infantile scurvy: The increasing incidence of scurvy in the Nashville area. *Journal of the American Medical Association*, *161*(5), 448–456.

World Health Organization. (1999). *Scurvy and its prevention and control in major emergencies (No. WHO/NHD/99.11)*. World Health Organization. Retrieved from https://apps.who.int/iris/bitstream/handle/10665/66962/?sequence=1

World Health Organization. (2016). *WHO guideline: use of multiple micronutrient powders for point-of-use fortification of foods consumed by infants and young children aged 6–23 months and children aged 2–12 years*. World Health Organization.

Yoneda, M. (2008). *Dietary reconstruction of ancient Vietnamese based on carbon and nitrogen isotopes*. Paper presented at the Man Bac Symposium, Institute of Archaeology, Hanoi, Vietnam.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Vlok, M., Oxenham, M. F., Domett, K., Trinh, H. H., Minh, T. T., Mai Huong, N. T., Matsumura, H., Huu, N. T., Nguyen, L. C., Willis, A., & Buckley, H. (2023). Scurvy in the tropics: Evidence for increasing non-adult micronutrient deficiency with the transition to agriculture in northern Vietnam. *American Journal of Biological Anthropology*, 1–18. https://doi.org/10.1002/ajpa.24698