

From the Mouths of Babes: Dental Caries in Infants and Children and the Intensification of Agriculture in Mainland Southeast Asia

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ABSTRACT Many bioarchaeological studies have established a link between increased dental caries prevalence and the intensification of agriculture. However, research in Southeast Asia challenges the global application of this theory. Although often overlooked, dental health of infants and children can provide a sensitive source of information concerning health and subsistence change. This article investigates the prevalence and location of caries in the dentition of infants and children (less than 15 years of age) from eight prehistoric mainland Southeast Asian sites collectively spanning the Neolithic to late Iron Age, during which time rice agriculture became an increasingly important subsistence mode. Caries prevalence varied among the sites but there was no correlation with chronological change. The absence of evidence of a decline in dental health over time can be

attributed to the relative noncariogenicity of rice and retention of broad-spectrum subsistence strategies. No differences in caries type indicating differences in dental health were found between the sites, apart from the Iron Age site of Muang Sema. There was a higher prevalence of caries in the deciduous dentition than the permanent dentition, likely due to a cariogenic weaning diet and the higher sensitivity of deciduous teeth to decay. The level of caries in the permanent dentition suggests an increased reliance on less cariogenic foods during childhood, including rice. The absence of a temporal decline in dental health of infants and children strengthens the argument that the relationship between caries and agricultural intensification in Southeast Asia was more complex than the general model suggests. *Am J Phys Anthropol* 150:409–420, 2013. ©2013 Wiley Periodicals, Inc.

Researchers have found a relationship between aspects of dental health and changes in subsistence patterns over time, including through the advent and intensification of agriculture (Turner, 1979; Cohen and Armelagos, 1984; Molnar and Molnar, 1985; Larsen et al., 1991; Cohen and Crane-Kramer, 2007; Temple and Larsen, 2007). Dental caries in the permanent dentition of adults is a commonly assessed indicator of dental health in archaeological samples. However, the assessment of dental health in infants and children in the past is an underused, yet potentially sensitive source of information for understanding health consequences of subsistence change with the development of agriculture.

Bioarchaeological research in mainland Southeast Asia has shown that, unlike in maize or wheat dependant societies from other parts of the world, no systematic increase in dental caries and other dental pathologies resulted from the intensification of rice agriculture (Pietrusewsky and Douglas, 2002a,b; Oxenham et al., 2006; Tayles et al., 2000, 2009). Reasons suggested for this include the low cariogenicity of rice and the retention of a broad-spectrum subsistence base with agricultural intensification (Oxenham, 2006; Douglas and Pietrusewsky, 2007; Tayles et al., 2009). With the recent excavations of a number of skeletal samples from late prehistoric mainland Southeast Asia, we now have the opportunity to assess infant and child dental health across the time period of the intensification of agriculture in the region. Unfortunately there are no preagricultural samples available to test the effect of the advent of agriculture.

The aim of this study is to assess whether the intensification of rice agriculture had an effect on infant and child dental health in prehistoric mainland Southeast Asia. This will be done by assessing the comparative prevalence of dental caries in the deciduous and permanent teeth of children and the frequency of types of caries among the sites. When investigating dental health in adults from bioarchaeological samples a number of dental characteristics are investigated in addition to caries, including periodontal disease, calculus and antemortem tooth loss (Lukacs, 1989). However, as these conditions do not generally occur in infants and children, and were not present in the infant and child dental samples analyzed, dental health will be assessed

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primarily through dental caries prevalences and caries types. We hypothesize, based on previous research that has shown a retention of similar levels of dental health over the period of the intensification of rice agriculture, that there will be no decline in dental health over time, as evidenced by caries prevalence.

DENTAL CARIES AND SOUTHEAST ASIA

The most widely accepted theory on caries formation is that they result from acids produced by micro-organisms (principally *Streptococcus mutans*) in dental plaque, which can ultimately lead to the destruction of enamel, dentine and cementum (Leverett, 1982; Hillson, 1996; Caselitz, 1998; Soames and Southam, 1998). Although this theory is relevant, dental health and disease cannot be viewed as a single cause and effect model (Caselitz, 1998; Shearer et al., 2011). Other factors that influence the development of caries include the composition and flow of saliva and mix of oral flora of the individual, level of immunity, maternal oral health and the amount and periodicity of food consumed, especially carbohydrates (Newburn, 1982; Shearer et al., 2011).

It is well known that there is a relationship between caries and the consumption of sugar and other carbohydrates (Gustafson et al., 1954; Newburn, 1983; Sreenby, 1982; Hillson, 1996; Rugg-Gunn and Nunn, 1999). This relationship has been used as an indicator of dietary reconstruction with agricultural intensification (Turner, 1979; Cohen and Armelagos, 1984; Cohen and Crane-Kramer, 2007; Temple and Larsen, 2007). In fact, dental caries are regarded as one of the most important clues to reconstructing the diet of past populations, including the analysis of the transition from hunter-gatherer to agriculturalist food procurement (Molnar and Molnar, 1985; Lubell et al., 1994; Larsen, 1997). Unfortunately, this relationship is accepted in the literature to the extent that the increase in prevalence of caries is used as evidence for the adoption of agricultural practices (for example, Roosevelt, 1984). This is despite warnings of the circularity of the argument (Goodman et al., 1984; Tayles et al., 2000). Rather, the relationship between agricultural intensification and caries is more complex than traditional models suggest (Lukacs, 2008; Tayles et al., 2009; Lanfranco and Eggers, 2010; Cucina et al., 2011). Other influences need to be acknowledged, including carbohydrate type and geochemical factors, such as the availability of fluoride, both in the environment and consumed in the diet (Alfano, 1980; Hillson, 1996: 279).

The main factor that should be taken into consideration when investigating dental disease in relation to agriculture is the types of carbohydrates consumed (Hillson, 2001). Not all carbohydrates have the same cariogenicity (Soames and Southam, 1998). It is generally accepted that carbohydrates with low molecular weights, such as sucrose, are easily fermentable and therefore highly cariogenic (Newburn, 1982; Leach et al., 1983). Of particular relevance to the study of dental health in Southeast Asian populations is the relatively cariostatic nature of rice (Madsen and Edmonds, 1962). A clinical study has shown that parboiled rice resulted in one of the smallest increases in acidity when compared with sucrose and carbohydrate rich foods like potatoes and wheat bread (Lingström et al., 1993). The less cariostatic nature of rice and resultant levels of caries experienced

in children from modern Southeast Asian populations will be discussed in more detail in the following section.

As most of the research on dental health in bioarchaeological samples has been undertaken on adults, it is necessary to consider additional factors that affect the susceptibility of deciduous teeth to developing dental caries. These include other dental pathology, enamel defects and enamel structure. For example, as infants and children are less likely to develop periodontitis (Hillson, 1996), the argument for an increase in cervical caries with the intensification of agriculture may not be applicable. Instead, it is more common for fissure and interproximal caries to become the dominant types of caries when sugar is introduced into the diet of infants and children (Hillson, 1996). Also, there are numerous studies that have shown a strong relationship between caries and developmental enamel defects, including hypomineralizations and hypoplasias (Cook and Buikstra, 1979; Hanson, 1990; Duray, 1990, 1992; Caselitz, 1998). There are also structural differences between deciduous and permanent teeth, including differences in enamel thickness, microstructure, and microhardness that make deciduous teeth more susceptible to demineralization and therefore caries (Wilson and Beynon, 1989; Hunter et al., 2000; Johansson et al., 2001; Wang et al., 2006; Correr et al., 2007; Taji and Seow, 2010).

Caries and subsistence change

The favored model of agricultural change in Southeast Asia links the intensification of wet rice agriculture with the escalation of socio-political complexity towards hierarchical systems and the purposeful manipulation of waterways during the middle to late Iron Age (O'Reilly, 2000, 2008; Boyd and Chang, 2010; Higham, 2011). The intensification of rice production in the middle to late Iron Age is shown by the construction of water control measures (Boyd and Habberfield-Short, 2007; Boyd and Chang, 2010), indicating an increased emphasis in the effort expended for rice production regardless of whether this was driven by a hierarchical or heterarchical polity. Consequently, such a timeframe would suggest that any change in dental health would occur during the Iron Age (Oxenham et al., 2006), most likely late in its chronology.

Tayles et al. (2000) examined the adult dental health data from the prehistoric mainland Southeast Asian sites of Khok Phanom Di, Ban Lum Khao and Noen U-Loke (Fig. 1) to test the hypothesis that the transition to a rice-based agricultural subsistence mode resulted in an increase in dental caries. Contrary to the general bioarchaeological model of a decline in dental health with agricultural intensification, as seen in other parts of the world including the Americas and Europe, a diachronic decrease in caries rates was found (Tayles et al., 2000). The low prevalence of caries identified at the later sites of Ban Lum Khao and Noen U-Loke was consistent with studies of early modern Thai populations eating rice-based diets (Amatavakul et al., 1960).

Oxenham et al. (2006) have investigated evidence of oral disease in adults from the majority of prehistoric mainland Southeast Asian assemblages. Their aim was to investigate changes in adult oral health over time, focusing on carious lesions, alveolar defects of pulpal origin and antemortem tooth loss. Data from a total of 548 individuals from 10 different sites spanning 6,000 to 1,700 years BP were analyzed. Oxenham et al.

(2006:283) found a general homogeneity in the prevalence of caries and other indicators of dental health over time and state that:

“...the oral health profile for Southeast Asia is more complex than that described in the global literature, which demonstrates generally clear declines in oral health with the adoption or intensification of agricultur-

e...There is certainly no observable trend that could be interpreted as an improvement or decline in oral health from the mid Holocene through to early metal period in Southeast Asia.”

MATERIALS AND METHODS

The dental samples are from infants and children from eight sites, seven from Thailand and one from Cambodia (Table 1 and Fig. 1). Six of the sites are located in tributary valleys of the Mekong River on the Khorat Plateau in northeast Thailand, one is a coastal site in Southeast Thailand, and one on the lower Mekong Delta in southern Cambodia. Collectively, these sites span from c.4000 to 1500 BP. The chronological relationships of the sites are shown in Figure 2.

For all the Thai sites, age-at-death of the infants (defined here as less than one year of age) and children (1–14.9 years of age) was estimated using dental methods. Dental formation methods [Moorrees et al. (1963a), as tabulated in Harris and Buck (2002); and Moorrees et al. (1963b), as tabulated in Lewis (2002) with adjustments from Halcrow et al. (2007)]. Radiographs of all teeth held in their crypts were taken where possible to assist age estimation by dental formation. For dental eruption, Ubelaker's (1999) dental eruption charts were used, with modifications that incorporate the Thai dental eruption evidence from Kamalanathan et al. (1960a). For the Vat Komnou sample, Angkor Borei, Cambodia, estimation of the age-at-death of infant and child remains was based on dental eruption and formation criteria (Ubelaker, 1999; Scheuer and Black, 2000:160-161).

All deciduous and permanent teeth were examined macroscopically for carious lesions with the aid of a dental probe and their presence or absence and position were recorded. Caries type was scored following the method described by Moore and Corbett (1971) as modified in Buikstra and Ubelaker (1994: 55) (Table 2). The dentition was also examined for periodontal disease and

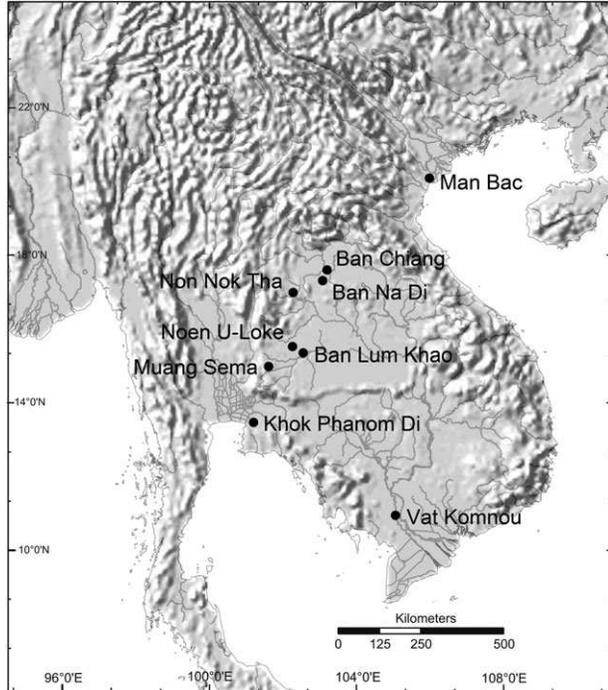


Fig. 1. Map of mainland Southeast Asia showing prehistoric sites mentioned in the text (map modified, courtesy of Dr. Kate Domett).

TABLE 1. The region and cemetery dates^a of the samples

Site and previous bioarchaeological research	Region	Cemetery dates
Khok Phanom Di (Domett, 2001; Tayles, 1999)	SE Thailand (Bang Pakong Region)	4000–3500 BP (Higham and Thosarat, 1994)
Non Nok Tha (Pietrusewsky 1974a,b; Douglas 1996, 2006)	NE Thailand (Chi River valley)	Varied dates 4800–1800 BP (Bayard, 1971; Douglas, 1996, 2006; Pietrusewsky and Douglas, 2002a). Higham (1996) prefers an initial occupation between 4000 and 3500 BP with the bulk of occupation from 3500 to 3000 BP.
Ban Lum Khao (Domett, 2001)	NE Thailand (Mun River valley)	3000–2500 BP (Higham and Thosarat, 2004)
Ban Chiang (Douglas, 1996; Pietrusewsky, 1978, 1982, 1984, 1997; Pietrusewsky and Douglas, 2002a,b)	NE Thailand (Songkhram River valley)	2950–1800 BP. Mostly from 2950–2300 BP (Pietrusewsky and Douglas, 2002a; Higham et al., 2011)
Ban Na Di (Houghton and Wiriyaromp, 1984; Domett, 2001)	NE Thailand (Pao River valley)	2900–2400 BP (Higham, 2002)
Noen U-Loke (Tayles et al., 1998; Nelsen, 1999; Tayles and Buckley, 2004)	NE Thailand (Mun River valley)	c.2300-c.1500 BP (Higham, 2002)
Vat Komnou (Pietrusewsky and Ikehara-Quebral, 2006; Ikehara-Quebral, 2010)	S Cambodia (Angkor Borei)	2150–1750 BP (Stark, 2001; Stark, 2004)
Muang Sema (Pureepatpong, 2001)	NE Thailand (Mun River valley)	c.2000–c.1500 BP ^b (Pureepatpong, 2001; Thosarat, pers. comm.)

^a There is considerable disagreement on the cemetery dates for the sites of Non Nok Tha (Bayard 1996; Higham 1996) and Ban Chiang (Glover and Syme, 1993; White, 1997).

^b No radiocarbon dates available, aged by material artifacts as late Iron Age (R. Thosarat, pers. comm.)

periapical inflammation, however none was identified. To reduce inter-observer error all data were collected by SH, apart from the Vat Komnou sample, collected by RI-Q.

Different researchers use different criteria to distinguish whether a lesion is carious or noncarious (Hillson, 2001). For example, most epidemiological surveys only

include cavities that extend into the dentine (Hillson, 2001). For this study a carious lesion was recorded if there was penetration of the enamel surface following the descriptions given by Buikstra and Ubelaker (1994) and Lukacs (1989). Penetration of the cavity into the dentine was not needed for a lesion to be classed as carious.

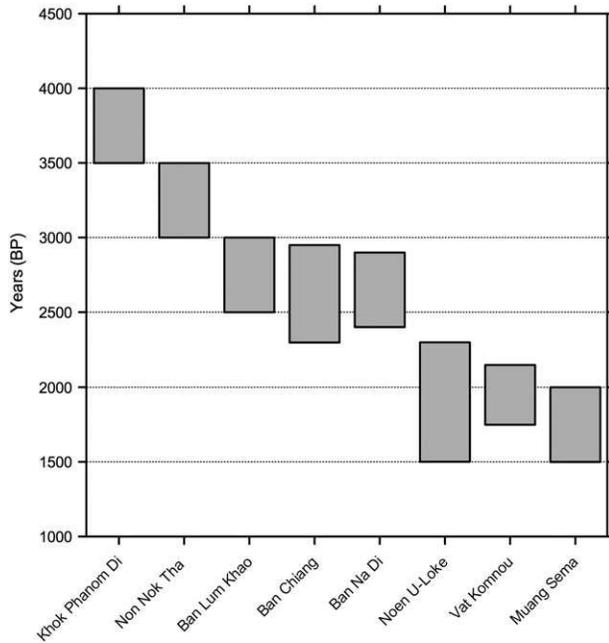


Fig. 2. General chronological relationships of the samples investigated. N.B: Non Nok Tha and Ban Chiang have longer chronologies than shown in the figure. Shown are the portions that correspond to the dates of the majority of the burials based on arguments from Higham (1996).

TABLE 2. Caries type and code

Code	Caries type
–	No tooth present, tooth not erupted or unobservable
0	No lesion present
1	Occlusal surface: all grooves, pits, cusps, dentine exposures, and the buccal and lingual grooves of the molars
2	Interproximal surfaces: includes the mesial and distal cervical regions
3	Smooth surfaces: buccal (labial) and lingual surfaces other than grooves
4	Cervical caries: originates at any CEJ, except the interproximal regions
5	Root caries: below the CEJ
6	Large caries: cavities that have destroyed so much of the tooth that they cannot be assigned a surface of origin.

RESULTS

The mean prevalence of caries by tooth count at all sites was 9.9% ($n = 96/972$) in deciduous teeth and 5.5% ($n = 24/435$) in permanent teeth. Because there is a general hierarchy of tooth involvement of caries dependent on tooth type, a general comparison was carried out between the anterior and posterior dentition to check that differences in prevalences of caries were not the result of differences in proportions of these teeth present. There were no statistically significant differences among the sites in the proportion of anterior and posterior teeth present in the deciduous ($\chi^2 = 1.705$, P -value=0.8884) or the permanent dentition ($\chi^2 = 1.603$, P -value = 0.9524). There appears to have been a relatively high prevalence of carious lesions in the deciduous dentition by tooth count in the Ban Na Di sample, moderate prevalences at Muang Sema, Vat Komnou, and Ban Chiang and low prevalences at Noen U-Loke, Ban Lum Khao, Khok Phanom Di and Non Nok Tha (Table 3), but the prevalence of caries at Ban Na Di was not statistically significantly higher than Muang Sema, Vat Komnou, and Ban Chiang (Supporting Information S1). It should be noted, however, that one individual from the Ban Na Di sample had 10 carious lesions, skewing the data. Muang Sema had a statistically significant higher prevalence of deciduous caries by tooth count than Khok Phanom Di, Non Nok Tha, Ban Lum Khao, and Noen U-Loke (S1). Ban Chiang had a statistically significant higher prevalence than Noen U-Loke. There were no statistically significant differences among the samples by individual count ($\chi^2 = 9.689$, P -value = 0.2069), but this could be the effect of the small sample size when this denominator is used. As caries formation is partially dependent on the time for which teeth are present in the mouth, we tested for differences in mean ages among the samples, to determine whether the caries prevalences were a product of the different age structures of the samples. No statistically significant differences were found (Supporting Information S2). Although there was heterogeneity among the samples in the prevalence of caries in the deciduous dentition, there is no correlation with the chronology of the sites (Table 3).

For the permanent dentition there were no statistically significant differences in caries prevalence among the sites (Supporting Information S3). The age structure of the samples is not a factor as there again were no

TABLE 3. Caries prevalences in the deciduous and permanent teeth for the infant and child samples by individual and tooth count

		Khok Phanom Di		Non Nok Tha		Ban Lum Khao		Ban Chiang		Ban Na Di		Noen U-Loke		Vat Komnou		Muang Sema	
		tth	ind	tth	ind	tth	ind	tth	ind	tth	ind	tth	ind	tth	ind	tth	ind
Deciduous teeth	a/n	9/152	6/16	5/103	2/13	11/168	6/18	20/159	7/17	17/77	5/9	2/66	1/9	9/80	6/11	23/167	7/13
	%	5.9	37.5	4.9	15.4	6.5	33.3	12.6	41.2	22.1	55.5	3.0	11.1	11.3	54.5	13.8	53.8
Permanent teeth	a/n	13/183	5/10	0/3	0/2	1/47	1/7	2/66	1/7	1/64	1/5	5/54	2/4	2/83	2/9	1/38	1/7
	%	7.1	50.0	0.0	0.0	2.1	14.3	3.0	14.3	1.6	20.0	9.3	50.0	2.4	22.2	2.6	14.3

tth, tooth count; ind, individual count; a/n, number affected/number present.

TABLE 4. Caries type frequency and percentage (in parentheses) of the total number of caries at each site in the deciduous teeth for the infant and child samples

Caries types	Khok Phanom Di	Non Nok Tha	Ban Lum Khao	Ban Chiang	Ban Na Di	Noen U-Loke	Vat Komnou	Muang Sema	Total frequency
1	2 (28.6)	2 (28.6)	3 ^a (21.4)	5 (23.8)	7 (23.3)	0 (0.0)	5 (55.6)	15 ^d (65.2)	39 (34.5)
2	2 (28.6)	0 (0.0)	6 ^b (42.9)	8 (38.1)	11 (36.6)	2 (100.0)	3 (33.3)	4 (17.4)	36 (31.9)
3	3 (42.9)	5 (71.4)	5 ^c (35.7)	8 (38.1)	12 (40.0)	0 (0.0)	1 (11.1)	3 ^e (13.0)	37 (32.7)
4	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (4.3)	1 (0.9)

^a Includes one classed as 1 and 3.

^b Includes one classed as 2 and 3.

^c Includes one classed as 1 and 3 and one classed as 2 and 3.

^d Includes two classed as 1 and 3.

^e Includes two classed as 1 and 3.

TABLE 5. Caries type frequency and percentage (in parentheses) of the total number of caries at each site in the permanent teeth for the child samples

Caries types	Khok Phanom Di	Non Nok Tha	Ban Lum Khao	Ban Chiang	Ban Na Di	Noen U-Loke	Vat Komnou	Muang Sema	Total frequency
1	6 (46.1)	0 (0.0)	3 ^a (100.0)	0 (0.0)	1 (100.0)	0 (0.0)	1 (50.0)	1 (100.0)	12 (44.4)
2	3 (23.1)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	4 (80.0)	0 (0.0)	0 (0.0)	7 (25.9)
3	4 (50.1)	0 (0.0)	0 (0.0)	2 (100.0)	0 (0.0)	0 (0.0)	1 (50.0)	0 (0.0)	7 (25.9)
4	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (20.0)	0 (0.0)	0 (0.0)	1 (3.7)

^a Includes one classed as 1 and 3.

statistically significant differences among the mean ages in the samples with permanent dentition, apart from Khok Phanom Di having a higher mean age compared with Ban Lum Khao (Supporting Information S4). Khok Phanom Di and Noen U-Loke both had high prevalences of caries in the permanent dentition, despite having low prevalences in the deciduous dentition. (Table 3). Ban Na Di had the lowest prevalence of caries in permanent teeth, yet it had one of the highest prevalences in deciduous teeth.

The frequencies of the various types of caries in the deciduous and permanent dentition are given in Tables 4 and 5. In the combined deciduous tooth sample, interproximal, smooth surface and occlusal surface caries occurred at a very similar frequency. However, Muang Sema had a high number of occlusal caries and a comparatively low number of interproximal and smooth surface caries. There was only one occurrence of CEJ caries in the deciduous teeth. For the permanent dentition, there was a higher proportion of occlusal caries. Because of the small sample size ($n = 27$) inter-site statistical comparisons of caries types were not carried out. There is no apparent relationship between the relative prevalence of caries and caries types within sites. For example, the deciduous dentition of Ban Na Di had a very high prevalence of caries compared with Ban Lum Khao, which had a low prevalence, but both had a high percentage of smooth surface and interproximal caries.

DISCUSSION

The prevalence of caries by tooth count in the deciduous teeth in our samples ranged from 3.0 to 22.1%. Table 6 shows the prevalence of caries in deciduous teeth from archaeological samples of differing time periods and different geographical regions in the world. This table shows that generally the more recent samples with increased agricultural dependency have higher caries prevalences than preagricultural populations. However, even though the data are worldwide, this statement is based on a small number of sites and, as discussed, the

relationship between caries and agricultural dependence is far from simple. There is a large range of prevalence among the sites listed in Table 6, with Ban Chiang, Ban Na Di, Muang Sema, and Vat Komnou having high caries prevalences compared with other sites around the world, with the exception of some North American sites. In contrast, the permanent teeth caries prevalences by tooth count range from 0 to 9.3%, most falling within the lower end of the range of caries prevalences in other archaeological sites (Table 7). This is likely a reflection of the lower susceptibility of permanent teeth to carious decay (Wilson and Beynon, 1989) combined with a possibly cariogenic weaning diet, discussed further below.

The permanent teeth had a lower prevalence of dental caries than the deciduous dentition among children recovered from all sites, except Khok Phanom Di and Noen U-Loke (Table 8). The higher prevalence of caries in deciduous compared with permanent teeth is similar to the comparative prevalence of caries found in the deciduous and permanent teeth at the late Neolithic site (3800–3400BP) of Man Bac in Viet Nam (Oxenham and Domett, 2011) (Fig. 1), where 3.7% of deciduous teeth were affected with caries ($n = 10/270$) involving 27.8% of individuals with deciduous dentition ($n = 5/18$). None of the 11 children with 163 permanent teeth showed evidence of caries. These values are similar to the contemporary sites of Khok Phanom Di and Non Nok Tha, with relatively low levels of caries. The small sample sizes of permanent teeth limit any definitive conclusions from the permanent tooth data.

Information on infant and child feeding practices from historical works and ethnographic studies on Southeast Asian populations is useful for interpreting feeding practices in the past and their possible effects on dental caries. Breastfeeding was probably carried out well into the third year of a baby's life in prehistory in mainland Southeast Asia, with literature from the latter 20th century reporting that the normal cessation age is about two years in Thailand (Jelliffe, 1968; Van Esterik, 1985). In contemporary Cambodia infants are usually weaned by three years of age (National Institute of Statistics,

TABLE 6. Deciduous dental caries prevalences (tooth count) from a range of archaeological sites in addition to those reported in this paper

Site/population	Subsistence mode	Caries <i>a/n</i> (%)	Source
Khok Phanom Di	Agricultural	9/152 (5.9%)	–
Non Nok Tha	Agricultural	5/103 (4.9%)	–
Ban Lum Khao	Agricultural	11/168 (6.5%)	–
Ban Chiang	Agricultural	20/159 (12.6%)	–
Ban Na Di	Agricultural	17/77 (22.1%)	–
Noen U-Loke	Agricultural	2/66 (3.0%)	–
Vat Komnou	Agricultural	9/80 (11.3%)	–
Muang Sema	Agricultural	23/167 (13.8%)	–
Neolithic Man Bac, Vietnam	Agricultural/ hunter-gatherer	10/270 (3.7%)	Oxenham and Domett (2011)
Precontact Hawaiian	Agricultural	50/1855 (2.7%)	Keene and Keene (1985)
Prehistoric Inuit, Greenland	Hunter-gatherer	2/146 (1.4%)	Pederson (1938)
Pre-Inca Peruvian Coast	Agricultural	34/619 (4.5%)	Adapted from Lanfranco and Eggers (2010)
Californian Prehistoric Amerindian	Hunter-gatherer	60/976 (6.1%)	Schulz (1992)
Late Archaic Amerindian, Ohio	Hunter-gatherer	6/414 (1.4%)	Sciulli (1990)
Late Archaic Amerindian, Ohio	Hunter-gatherer	7/793 (0.9%)	Sciulli (1997)
Early-Late Woodlands Amerindian, Ohio	Hunter-gatherer	6/228 (2.6%)	Sciulli (1997)
Late Woodlands Amerindian, Ohio	Hunter-gatherer	109/596 (18.3)	Duray (1990)
Late Prehistoric Amerindian, Ohio	Agricultural	356/2237 (15.9%)	Sciulli (1997)
Roman Period Kellis, Egypt	Agricultural	99/1116 (8.9%)	Shkrum (2008)
Smörkullen Early Iron Age, Sweden	Agricultural	23/221 (10.4%)	Liebe-Harkort (2010)
Early Middle Age Great Moravian Empire and Frankish Empire sites	Agricultural	67/2712 (2.5%)	Adapted from Garcin et al. (2010)
Prehistoric to 18 th century Britain	Agricultural	Average 227/1974 ^a (11.4%)	O'Sullivan et al. (1993)

a/n, number affected/number observable.

^a First molars only.

TABLE 7. Permanent child dental caries prevalences (tooth count) from a range of archaeological sites in addition to those reported in this paper^a

Site/population	Subsistence mode	Caries <i>a/n</i> (%)	Source
Khok Phanom Di	Agricultural	13/183 (7.1%)	–
Non Nok Tha	Agricultural	0.3 (0.0%)	–
Ban Lum Khao	Agricultural	1/47 (2.1%)	–
Ban Chiang	Agricultural	2/66 (3.0%)	–
Ban Na Di	Agricultural	1/64 (1.6%)	–
Noen U-Loke	Agricultural	5/54 (9.3%)	–
Vat Komnou	Agricultural	2/83 (2.4%)	–
Muang Sema	Agricultural	1/38 (2.6%)	–
Neolithic Man Bac, Vietnam	Agricultural/ hunter-gatherer	0/163 (0.0%)	Oxenham and Domett (2011)
Southern Honshu Yayoi, Japan	Agricultural	21/200 (10.5%)	Temple and Larsen (2007)
Northern Honshu Yayoi, Japan	Agricultural	7/121 (5.8%)	Temple and Larsen (2007)
Tanegashima Yayoi, Japan	Agricultural	5/119 (4.2%)	Temple and Larsen (2007)
Late to final Jomon, Japan	Hunter-gatherer	28/427 (6.5%)	Temple and Larsen (2007)
Shih-san-hang Iron Age, Taiwan	Agricultural	19/2871 (0.7%)	Liu et al. (In Press)
Precontact Amerindian, Georgia	Hunter-gatherer	0/180 (0.0%)	Larsen et al. (1991)
Roman Period Kellis, Egypt	Agricultural	21/551 (3.8%)	Shkrum (2008)
Smörkullen Early Iron Age, Sweden	Agricultural	82/468 (17.5%)	Adapted from Liebe-Harkort (2010)
Early Middle Age Great Moravian Empire and Frankish Empire sites	Agricultural	88/3011 (2.9%)	Adapted from Garcin et al. (2010)

a/n, number affected/number observable.

2001). There is ongoing debate concerning the role prolonged breastfeeding may play in the development of early childhood caries (ECC). Although some researchers claim lengthened breastfeeding significantly increases a child's risk of developing ECC (van Palenstein Helderma et al., 2006), others argue that prolonged breastfeeding does not appear to have these negative consequences (Mohebbi et al., 2008).

The breastmilk diet of contemporary Thai infants is gradually supplemented with weaning foods such as banana and rice gruel followed by solid foods from the adult diet (Kunstadter, 1985). Mashed banana of a par-

ticular kind known as *nem lavar*, eaten either ripe or roasted, is a common form of baby food (Jelliffe, 1968). Wild and cultivated taro and yams were probably used as weaning foods as they have shown to be in ethnographic studies, as they are easy to mash (King, 2008; Van Esterick, 2011). The starch-rich composition and sticky consistency of such root crops contribute to their high cariogenicity.

Historically rice has been a mainstay of mainland Southeast Asia and it is likely that this cereal was a staple crop in prehistoric times and perhaps a common weaning food. The traditional rice type in mainland

TABLE 8. Dental caries prevalence for the infant and child deciduous, permanent (child) dentition and the adult dentition from prehistoric sites^a

	Khok Phanom Di: Neolithic	Non Nok Tha: Neolithic-early Iron Age	Ban Lum Khao: Bronze Age	Ban Chiang: Neolithic-Iron Age	Ban Na Di: late Bronze Age	Noen U-Loke: Iron Age	Vat Komnou: Iron Age	Muang Sema: Iron Age
Deciduous	Prevalence Age data	Low (5.9%) 5.0 ± 3.9 (1.0–10.0)	Low (4.9%) 4.9 ± 2.3 (1.0–9.0)	Low (6.5%) 4.4 ± 2.5 (1.5–8.0)	Moderate (12.6%) 4.5 ± 2.8 (0.75–9.0)	Very high (22.1%) 3.3 ± 2.6 (0.75–8.0)	Moderate (11.3%) 5.9 ± 3.3 (0.75–11.0)	Moderate-high (13.8%) 5.3 ± 2.8 (2.0–11.0)
Permanent (child)	Prevalence Age data	High (7.1%) 10.7 ± 1.6 (8.0–12.5)	Low (0.0%) Low 8 ± 1.4 (7.0–9.0)	Low (0.0%) Low (0.0%) 8.1 ± 1.8 (7.0–12.0)	Moderate (3.0%) Moderate 9.3 ± 3.0 (7.0–14.75)	High (9.3%) High 10.9 ± 2.7 (7.25–13.5)	Low-moderate (2.4%) Low-moderate 11.9 ± 2.8 (5.5–13.5)	Low-moderate (2.6%) Low-moderate 9.0 ± 2.8 (5.0–13.0)
Adult	Prevalence	Very high (10.8%) ^b	Low (2.8%) ^c	Moderate (4.5%) ^d	Moderate (4.7%) ^e	Moderate (4.8%) ^f	Moderate (5.0%)	Data not available

The deciduous and permanent (child) categories include age data for each category expressed as mean age ± standard deviation (minimum age-maximum age). Age data was not available for the adult samples.
^a Terms low, moderate and high are relative and only appropriate to the samples used and tooth types (deciduous or permanent).
^b Data from Tayles (1999).
^c Data from Douglas (1996).
^d Data from Pietrusewsky and Douglas (2002a).
^e Data from Domett (2001).
^f Data from Domett and Tayles (2006).

Southeast Asia is glutinous or “sticky” rice (Golomb, 1976). Sticky rice reduces the drop in oral pH through the stimulation of the salivary flow rate (Kedjarune et al., 1997; Moynihan, 2000). Also, because of the method of preparation it is not fully decorticated and as a result does not adhere to the teeth (Techanitiswad, 1994). Such unrefined foods can also contain organic phosphates that can protect the teeth from dissolution (Moynihan, 2000).
 The results from the skeletal samples generally follow the patterns seen in dental health surveys in rural and traditional Thai and Southeast Asian communities. Comparatively better dental health was found in the permanent dentition of children in all sites apart from Khok Phanom Di and Noen U-Loke (discussed below), with a higher prevalence of caries in the deciduous dentition. The high rates of caries in deciduous teeth is also consistent with previous research findings, as mentioned, which show that deciduous teeth are structurally more susceptible to carious decay (Wilson and Beynon, 1989).
 There is a lack of other comparative prevalence data on deciduous and child permanent dental caries prevalence from prehistoric and historic samples of populations reliant on rice-based diets, necessitating comparisons with modern caries prevalence rates (Supporting Information S5). Studies on modern Thai communities with rice as the main carbohydrate in the diet show low caries prevalences (Laband, 1941; Kridakara et al., 1956; Kedjarune et al., 1997), while the data on deciduous dental health surveys generally show a higher prevalence of dental caries (Kamalanathan et al., 1960a,b).
 Although the deciduous tooth caries prevalences are generally higher than the permanent tooth prevalences, there were disparities in the relative levels of caries prevalences between the permanent child and the deciduous dentitions within sites, e.g., Khok Phanom Di had one of the lowest levels of caries prevalence in the deciduous teeth among all the sites, but the highest level of caries in the permanent dentition of the children. This indicates the importance of considering the differences in food consumed by children and infants at sites. The results could mean that the weaning diet at Khok Phanom Di may have been less cariogenic than the childhood diet, compared with the other sites that may have had more cariogenic weaning foods. As the effect that prolonged breastfeeding had on dental health is unclear (van Palenstein Helderma et al., 2006; Mohebbi et al., 2008), we cannot state whether a lengthened period of breastfeeding in prehistoric Southeast Asia increased the chances of developing caries in the deciduous dentition.
 The argument of foodstuffs contributing to the comparative prevalences of caries between deciduous dentition and child permanent dentition (i.e., comparatively more cariogenic weaning diets and/or cariostatic or less cariogenic childhood diets) is also supported. Previous dental health research in other parts of the world has shown that agricultural intensification of cariogenic foodstuffs, such as maize, results in a higher prevalence of caries in permanent compared with deciduous teeth (Larsen et al., 1991). However, in the case of Southeast Asian populations, an increase in rice within the diet from infancy to childhood may have had a less cariogenic effect on the permanent dentition, compared with the deciduous dentition.
 Apart from Muang Sema there were no differences in the types of caries in deciduous teeth that would indicate differences in dental health among the sites. There was only one carious lesion located in the CEJ from the

deciduous dentition. This may suggest good periodontal health of the infants and children, as CEJ caries arise after the exposure of the CEJ from periodontitis (Fejerskov et al., 2009). There are limited comparative data on caries types in deciduous teeth from past populations. O'Sullivan et al.'s (1993) research on sites spanning from prehistoric times to 18th century Britain found that 35.0 percent of all deciduous caries formed at the CEJ and is explained as the result of food being impacted adjacent to the gingival margin. For the permanent teeth little can be said about comparisons of caries types among the sites because of the small sample. Khok Phanom Di had a higher prevalence of occlusal caries compared with the sites of Noen U-Loke and Ban Chiang. The permanent teeth had more occlusal caries than the deciduous teeth, but still had a low proportion of CEJ caries suggesting good periodontal health of the infants and children, as is consistent with the lack of evidence for periodontal infection from the bone observed in the samples and with the effects of lightly processed sticky rice.

Deciduous caries can also be attributed to enamel defects present in the dentition. There are a number of cases of "smooth surface" carious lesions on the mid-labial surface of the crowns of deciduous canines in the infants and children from the Thai samples associated with localized hypoplastic enamel defects (LHPC) of these teeth (9/33 teeth affected with LHPC) (Halcrow and Tayles, 2008). The reason for the association of these developmental defects and caries is because of the imperfect enamel structure of the defect and/or that the defects are more prone to harboring plaque, which made these areas particularly vulnerable to carious decay. Although not quantified in this paper, it was also observed that the deciduous caries were associated with other enamel defects including hypomineralizations. Certainly, a strong relationship between enamel defects and caries has been found in bioarchaeological research and clinical studies (Infante and Gillespie, 1977; Duray, 1990; Techanitiswad, 1994; Kanchanakamol et al., 1996). This is so much so, that 'circular' caries, which form on the smooth surfaces of the deciduous dentition, have been used in bioarchaeological studies as indicators of stress due to their recognized relationship with dental enamel defects (Cook and Buikstra, 1979; Katzenberg et al., 1993; Buckley, 2001).

Although some sites had comparatively high caries prevalences in the deciduous dentition and others relatively low prevalences, these differences were not related to temporal change. There was heterogeneity in the prevalence of caries in the child permanent dentition, with most of the sites having low levels of caries, apart from Khok Phanom Di and Noen U-Loke. Both sites have higher mean ages for individuals with child permanent teeth (third and second highest, respectively, out of eight) and greater mean age discrepancies between individuals with deciduous and child permanent teeth (fourth and first, respectively, out of eight). Even so, the differences in prevalences among the sites are not statistically significant, and again, the differences in caries prevalence is not related to chronology. As there were no statistically significant differences among the sites in mean ages of infants and children with deciduous and permanent dentition, this cannot be used to explain the differences in prevalences. Because the results do not indicate a temporal pattern of change for the deciduous and permanent dentition they support the hypothesis that there would be no change in dental health with the intensification of rice agriculture.

The heterogeneity in caries prevalence among the sites may be related to localized environments of the sites, such as differing geochemistry. For example, large salt deposits high in fluoride ions exist in parts of northeast Thailand (Rivett and Higham, 2007). Fluoride has a negative impact on caries formation and the proximity of sites to such deposits may account for the differing prevalences in caries (Alfano, 1980; Hillson, 1996:279). In addition, White et al.'s (2004) research on vegetation changes in Thailand from the late Pleistocene through the Holocene shows region-specific environmental changes. Such vegetation differences likely had an effect on the foods consumed at different sites, which could have contributed to the heterogeneity in caries prevalence between sites separated both spatially and temporally, perhaps best exemplified by Khok Phanom Di, the only coastal site in the sample.

The overall low caries prevalence in the child permanent teeth, and absence of temporal patterns of changes in caries frequency and types of caries among the sites can also be interpreted in the context of past bioarchaeological evidence of dental health and agricultural development in Southeast Asia as showing neither a clear increase or decrease in dental health with the intensification of agriculture (Douglas, 1996; Tayles et al., 2000; Oxenham et al., 2006). As previously mentioned, this can be explained by the cariostatic nature of rice as well as the retention of a broad spectrum subsistence base. The retention of a broad spectrum subsistence base rather than forming a large part of the diet is also a compelling argument. Such a scenario views the intensification of rice agriculture as a response to increasing population numbers and deteriorating environmental conditions (for the production of wet rice), rather than an increase in individual rice consumption. Geoarchaeological studies have shown that during the mid to late Iron Age environmental conditions became drier, necessitating the need for water management (Boyd and Habberfield-Short, 2007; Boyd and Chang, 2010). This, combined with the lack of a decline in dental health suggests that rather than an increase in individual rice consumption, the intensification of rice agriculture was necessary to keep the individual *status quo* in a deteriorating milieu of increasing population size.

For interpretive purposes the dental health results from the infants and children from our sample can be compared with the adult prevalences of caries at the sites (Table 8). The Non Nok Tha adults had a low caries prevalence, Ban Lum Khao, Ban Na Di, Vat Komnou, and Noen U-Loke all had moderate prevalences, Ban Chiang had a moderate to high caries prevalence and Khok Phanom Di had a comparatively very high prevalence of caries (Tayles, 1999). Dental caries prevalence data were not available for the Muang Sema adults. The relative prevalences of caries in the deciduous dentition among the sites do not follow the patterns seen in the adult data (Table 8). For example, although the Ban Na Di adults had comparatively moderate level of caries, the infants and children from this site with deciduous dentition had a very high prevalence of caries compared with infants and children from the other sites. Like the differences in levels of caries between deciduous and child permanent teeth within a site, these findings suggest that there were probably differences in diet between the children and adults within a site, and emphasize the importance of considering weaning foods and children's diets in the interpretation of caries rates in deciduous dentition.

Although the levels of caries in the deciduous teeth are not similar to the adult prevalences, the prevalences in the deciduous teeth compared with those in adults at the same sites are all considerably higher, except for Noen U-Loke and Khok Phanom Di (Table 8). As discussed in the comparison of caries prevalence between the child permanent dentition and the deciduous teeth, this can be explained, in part, by the higher susceptibility of deciduous teeth to caries. At all sites, apart from Noen U-Loke, the prevalences of carious permanent teeth were higher in the adults than in the children, as would be expected because of the longer time in which they are exposed to the potentially cariogenic oral environment. The higher prevalence of dental caries in the permanent teeth of the infants and children compared with adults at Noen U-Loke and the deciduous dentition at the site may be the result of sampling bias, with a very small sample.

CONCLUSIONS

This article assessed whether there is evidence for a change in dental health with the intensification of agriculture in mainland Southeast Asia by comparing dental caries prevalence rates and caries types in infants and children recovered from eight sites that collectively span from the early to late agricultural periods. The deciduous dentition generally had a higher prevalence of caries than the permanent dentition of the children, which is interpreted as a result of the sticky consistency and/or cariogenic properties of infant weaning foods, such as banana and other sticky root crops, as well as the susceptibility of deciduous dental enamel and dental defects to carious decay. Overall, however, the level of caries in the permanent teeth indicate a less cariogenic diet, probably as a result of the increased reliance on rice during childhood. There is no relationship between the levels of caries prevalence in the deciduous, child permanent and adult dentition within the sites, perhaps indicating differing diets through stages of life. The results show heterogeneity in caries prevalence that does not correlate with the chronology of the sites, supporting the hypothesis that there was no decline in dental health with the intensification of agriculture in this region of the world. The evidence is consistent with comparative bioarchaeological research that has shown no clear change in dental health with the intensification of agriculture in Southeast Asia.

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