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Detection of temporospatially localized growth in ancient Southeast Asia using human skeletal remains

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ABSTRACT

Measures of population growth can provide significant insights into the health, adaptivity and resilience of ancient communities, particularly the way in which human populations respond to major changes, such as the transition to agriculture. To date, paleodemographic tools have facilitated the evaluation of long term, regional population growth, while identification of intraregional variability and short-term growth has been more challenging. This study reports on the application of a new method for estimating the rate of natural population increase (RNPI) from skeletal remains. We have applied the method to ancient Southeast Asian samples and, based on the LOESS fitting procedure, our preliminary results indicate a trend of temporal homogeneity and spatial heterogeneity. This trend is validated against the existing archaeological narrative for the region and, we argue, may indicate intraregional variability in population responses to major technological, economic and sociocultural events, consistent with the variable response observed at the regional level. Due to the critical importance of temporospatial specificity to a vast array of paleodemographic research questions, we have evaluated the precision, assumptions and limitations of this method in the context of other existing paleodemographic methods. Our RNPI measure, in isolation or in combination with existing methods, provides a promising tool that can be used to develop a deeper and more localized understanding of the conditions impacting on population dynamics and, conversely, community responses to change.

1. Introduction

Reconstructing the dynamics of past human population growth can provide insights into the health, adaptivity and resilience of ancient human communities. In particular, researchers have sought to evaluate population changes following major events, such as changes in subsistence and epidemics (Armelagos and Cohen, 1984; Johansson and Horowitz, 1986; Armelagos et al., 1991; Bocquet-Appel, 2002; Bocquet-Appel and Naji, 2006; DeWitte and Wood, 2008; Pinhasi and Stock, 2011; DeWitte, 2014, 2015). The most prominent example of this is the adoption and/or transition to and intensification of agriculture, and the concurrent major demographic event known as the Neolithic Demographic Transition (NDT). The transition occurred in different regions at different times, and there is growing evidence that not all populations responded in the same way (Armelagos and Cohen, 1984; Armelagos et al., 1991; Tayles et al., 2000; Domett, 2001; Oxenham, 2006; Domett and Tayles, 2007; Bellwood and Oxenham, 2008; Pinhasi and Stock, 2011; Willis and Oxenham, 2013). Nonetheless, the NDT has been commonly associated with substantial population increase due to increased and stabilized resources and reduced mobility permitting shorter inter-pregnancy intervals, as well as various health and social impacts resulting from ecological and economic changes (Armelagos and Cohen, 1984; Armelagos et al., 1991; Bocquet-Appel, 2002; Bocquet-Appel and Naji, 2006; Pinhasi and Stock, 2011).

Until now, estimates of population growth have been made based on biological sources, including DNA (Harpending, 1994), skeletal measures of fertility (Bocquet-Appel, 2002; Bocquet-Appel and Naji, 2006; Downey et al., 2014; Kohler and Reese, 2014), and archaeological sources, the most popular of which are demographic temporal frequency analyses (dTFA) (Collard et al., 2010; Peros et al., 2010; Shennan et al., 2013; Downey et al., 2014; Tallavaara et al., 2015; Zahid et al., 2016; Brown, 2017). Faith in paleodemographic findings based on skeletal remains has fluctuated over time. Efforts made in response to Bocquet-Appel and Masset's (1982) '*Farewell to Paleodemography*' produced a range of solutions to identified methodological issues (e.g. Van Gerven and Armelagos, 1983; Buikstra and Konigsberg, 1985; Gage, 1988; Konigsberg and Frankenberg, 1994), and work by Hoppa and Vaupel (2002) and the attendees of the Rostock workshop

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on age-at-death estimation offered elegant methods to reconstruct mortality profiles. Nonetheless, Gage and DeWitte (2009) observed that a gap has persisted between advancing theory and methodology, and application to real samples (work by DeWitte (2014, 2015) and DeWitte and Wood (2008) has exemplified the possibilities when improved techniques are applied). In this paper we report on the first application of a new method that has been developed for estimating the rate of natural population increase per annum (RNPI) (McFadden and Oxenham, 2018a), from skeletal remains, by quantifying the contribution of births and deaths to population growth.

Both archaeological (Higham, 1989; Oxenham et al., 2011, 2015; Bellwood et al., 2011; Oxenham et al., 2018) and population mobility (Matsumura and Oxenham, 2014; Oxenham and Buckley, 2016; Lipson et al., 2018) research has tracked the timing of the emergence of the Mainland Southeast Asian (MSEA) Neolithic, which is characterized by the introduction of domestic plants and animals as well as a major increase in population size (as evidenced by the appearance of numerous sites and characteristic forms of material culture). Similarly, the emergence of the MSEA Bronze and Iron Ages, with attendant developments in social complexity and significant increases in population size, the latter evidenced by marked increases in the number of sites as well as the size of such sites, is well attested (Higham, 1996; O'Reilly, 2006; Higham and Higham, 2009; Rispoli et al., 2013). MSEA is clearly particularly well suited to paleodemographic hypothesis testing due to well-dated cultural sequences and a sophisticated understanding of major changes in the population structure and mobility in the region in antiquity. Indeed, the archaeological and population mobility data suggests a scenario whereby the region saw a major influx of people (a Neolithic demographic transition) and a new system of subsistence (farming), followed by the introduction of bronze and iron technologies in the context of ever increasing social complexity and population sizes. This begs the question: do the demographic data, derived from cemeteries associated with these major transitional events, match archaeological and population history data?

Two research aims are addressed in this study: first, we wanted to test whether the RNPI method could be used to identify a similar trend in population growth to that observed in the archaeological record in MSEA (thereby validating the results), and second, to evaluate the accuracy, precision, and limitations of the RNPI method identified through its application.

2. Materials

In order to evaluate the utility of our method for estimating the rate of natural increase, specifically its ability to identify an archaeologically observed trend in population dynamics, we sought to apply it to data from Southeast Asia where the recent application of Bayesian analyses of radiocarbon results has provided a firm chronological framework within which to consider changes in subsistence, technology, and social organization. Substantial evidence exists to indicate an overall trend in the region of high population growth during the Neolithic (the NDT) (e.g. see Matsumura and Oxenham, 2014; Oxenham et al., 2015), and continued growth through the Bronze and Iron Age (Higham, 1996; O'Reilly, 2006; Higham and Higham, 2009; Rispoli et al., 2013), although the exact rates and pattern of growth are unknown.

We obtained data from eleven sites in mainland Southeast Asia, three of which span multiple time periods. Table 1 provides the sites, sources of data, the time periods, and sample sizes. Data for eight sites were obtained from published sources, while some data for three sites were contributed by the authors. The time periods represented in the study range from pre-Neolithic to Iron Age. Eight sites are located in Thailand, two sites in Vietnam, and one site in southern China (Fig. 1). Age estimates, sample sizes, radiocarbon dates and technological period (e.g. Neolithic, Bronze Age) have been represented as reported in the cited sources unless otherwise stated below.

2.1. Huiyaotian

Huiyaotian is located in Qingxiu district in southern China, not far from Man Bac and Cong Co Ngua in northern Vietnam (Zhen et al., 2017). The site dates to 7000-6300BP and is characterized by shell middens, polished stone axes and adzes, and various bone and shell implements (Zhen et al., 2017). A total of 56 individuals were included in this sample (Zhen et al., 2017).

2.2. Cong Co Ngua

Cong Co Ngua is located in northern Vietnam, 30 km from the coast (Oxenham et al., 2018). The faunal remains indicate the dominant animals consumed were large bodied mammals, while the predominant plant material consumed was canarium nuts (Oxenham et al., 2018). Pottery, stone tools, and bone and shell artefacts are associated with the site, with the stone tools being notably different from those found at younger Neolithic sites such as Man Bac and An Son (Oxenham et al., 2018). The 2013 season assemblage is analysed here, which includes 172 individuals (Oxenham et al., 2018).

2.3. Khok Phanom Di

Khok Phanom Di is a large Neolithic site in Thailand. During the occupation period, the population transitioned from estuarine-based hunter-gathering to rice cultivation, and back again (Tayles, 1999). There are seven mortuary phases represented at the site. A total of 154 individuals were identified, all of which were able to be aged (Tayles, 1999).

2.4. Man Bac

The Neolithic site of Man Bac is located in northern Vietnam and was excavated in 1999, 2001, 2004–5, and 2007 (Oxenham et al., 2011). Faunal remains found at the site included domesticated pigs, representing the majority, and a small proportion of hunted wild mammals (Sawada et al., 2011). The 84 individuals (78 being assigned an age) from the 2004/5 and 2007 seasons are analysed here (Domett and Oxenham, 2011).

2.5. Ban Non Wat

Ban Non Wat is a large site located in northeast Thailand. Excavations between 2002 and 2007 revealed burials and cultural material dating to the Neolithic, Bronze Age and Iron Age have been found at the site (Higham, 2011a; Higham, 2011b; Higham and Kijngam, 2011). Remains of domesticated pigs and cattle are found at the site, as well as evidence of domesticated dogs and rice cultivation (Higham, 2011a). Tayles et al. (2015) reported 83 individuals for the Neolithic population, 317 individuals for the Bronze Age, and 224 for the Iron Age. There are three mortuary phases in the Iron Age occupation which correspond to periods at Noen U-Loke, though notably one of four periods is not represented at Ban Non Wat (Higham and Kijngam, 2011). There is evidence that shell ornaments, clay goods, woven and fabric items, and iron, bronze and lead objects were produced at the site during the Iron Age occupation (Iseppy, 2011).

2.6. Non Nok Tha

Non Nok Tha is located in northeast Thailand and was excavated in 1965–1966 and 1968 (Pietrusewsky, 1974). Three periods are represented at Non Nok Tha: the Early pre-metal period, the Middle Bronze working period, and the Late Iron working period (Pietrusewsky, 1974). The burials at Non Nok Tha span the Early and Middle periods, and Pietrusewsky (1974) divided these into Phase I, including the two Early phase and the first Middle phase, and Phase II

Table 1
Sample information and descriptive statistics.

Sample	Site	Primary Source	Time Period	Mortuary Phase	Sample Source	Skeletal Sample n =	Radiocarbon Dates Source	Years BP	D0-14/D	CI 95%	RNPI (% per annum)
Huiyaotian	China	Zhen et al. (2017)	pre-Neolithic		Author's own	56	Zhen et al. (2017)	7000-6300BP	0.07	0.07–0.08	−0.89
Cong Co Ngua	Vietnam	Oxenham et al. (2018)	pre-Neolithic		Author's own	172	Oxenham et al. (2018)	6700-6200BP	0.30	0.28–0.32	1.37
Khok Phanom Di	Thailand	Tayles (1999)	Neolithic		Tayles (1999), p.39	154	Tayles (1999)	4000-3500BP	0.56	0.51–0.60	4.01
Man Bac	Vietnam	Oxenham et al. (2011)	Neolithic		Author's own	78	Oxenham et al. (2011)	3800-3500BP	0.59	0.53–0.65	4.32
Ban Non Wat (Early)	Thailand	Higham (2011a)	Neolithic - Early Bronze	Neolithic 1b-1c	Tayles et al. (2015), Table 2	83	Higham and Higham (2009)	3500-3050BP	0.37	0.33–0.41	2.15
Non Nok Tha (Early-Middle)	Thailand	Pietrusewsky (1974)	Neolithic - Early Bronze	EP1-3 + MP1-3	Pietrusewsky (1974), p.127	86	Higham et al. (2015)	3500-3000BP	0.30	0.27–0.33	1.43
Ban Chiang (Early)	Thailand	Pietrusewsky and Douglas (2002)	Neolithic - Early Bronze	Early period (I-V)	Pietrusewsky and Douglas (2002), p.161	93	Higham et al. (2015)	3600-2700BP	0.28	0.25–0.31	1.23
Nong Nor	Thailand	Domett (2001)	Bronze		Domett (2001), p.39	155	Domett (2001)	2800-2650BP	0.21	0.20–0.23	0.53
Ban Lum Khao	Thailand	Domett (2004)	Bronze	MP1-3	Domett (2001), p.41	110	Higham et al. (2015)	3200-2600BP	0.46	0.42–0.51	3.05
Non Nok Tha (Middle)	Thailand	Pietrusewsky (1974)	Bronze	MP2-MP8	Pietrusewsky (1974), p.127	102	Higham et al. (2015)	3000-2500BP	0.21	0.19–0.22	0.46
Ban Non Wat (Mid)	Thailand	Higham and Kijngam (2012)	Bronze	BA1-BA5	Tayles et al. (2015), Table 2	317	Higham and Higham (2009)	3050-2450BP	0.33	0.31–0.35	1.71
Ban Na Di	Thailand	Domett (2001)	Bronze	MP1-MP3	Domett (2001), p.42	78	Higham et al. (2015)	2800-2450BP	0.36	0.32–0.40	2.00
Ban Non Wat (Late)	Thailand	Higham and Kijngam (2011)	Iron	IA1-IA2	Tayles et al. (2015), Table 2	224	Higham and Higham (2009)	2450-1850BP	0.29	0.27–0.31	1.26
Ban Chiang (Mid - Late)	Thailand	Pietrusewsky and Douglas (2002)	Iron	Mid-late period (VI-X)	Pietrusewsky and Douglas (2002), p.161	46	Higham et al. (2015)	2450-1500BP	0.24	0.21–0.27	0.79
Noen U-Loke	Thailand	Tayles et al. (2007)	Iron	MP2-MP5	Tayles et al. (2007), p.251	120	Tayles et al. (2007)	2450-1450BP	0.44	0.39–0.47	2.83

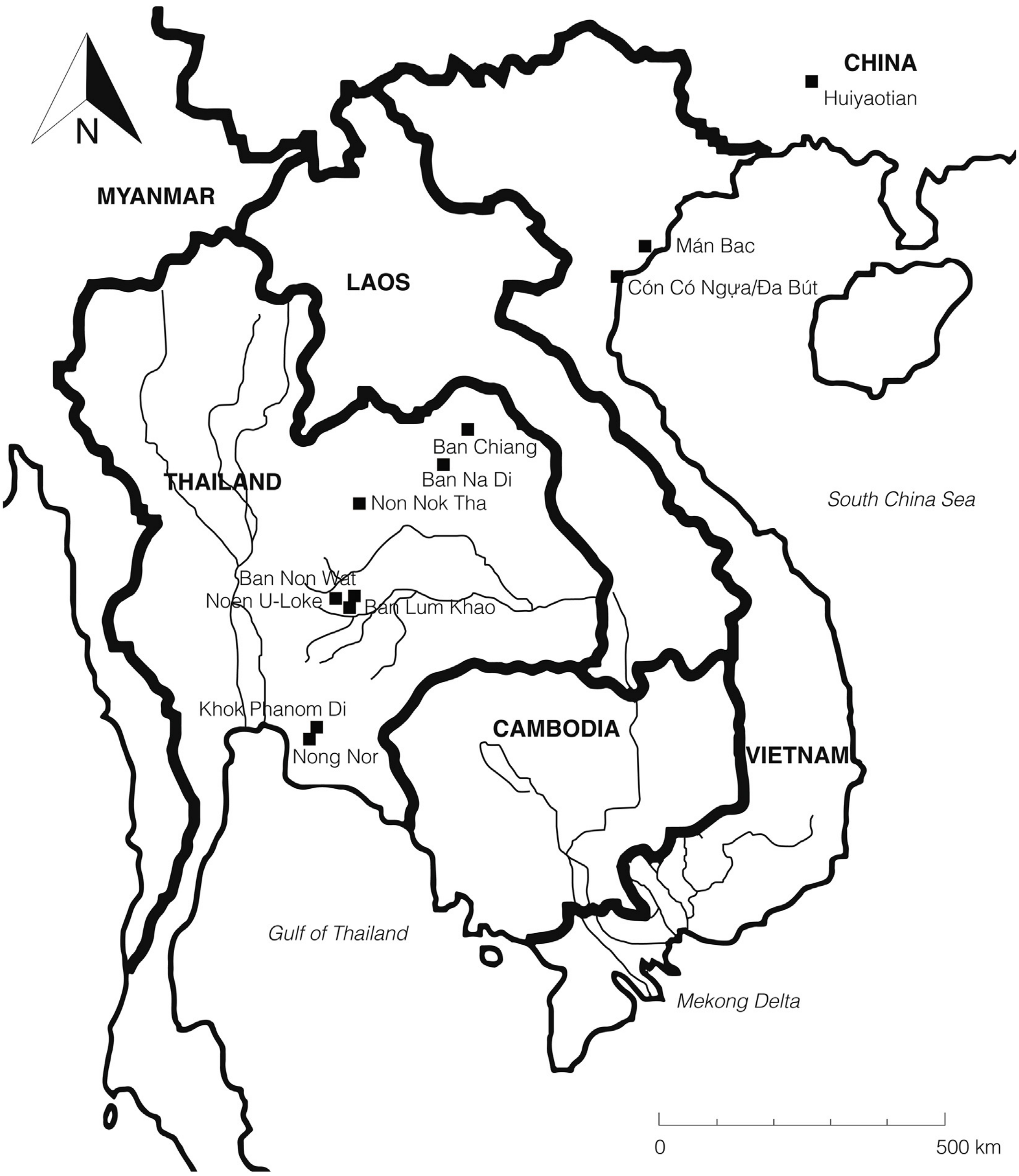

Fig. 1. Map of Sites in Southeast Asia, adapted from Sarjeant (2017).

which included the remainder of the Middle period. Phase I included 86 individuals and Phase II comprised 102 individuals (Pietrusewsky, 1974).

2.7. Ban Chiang

Ban Chiang is a late Neolithic to Iron Age site located in northeast Thailand and was excavated in 1974 and 1975 (Pietrusewsky and Douglas, 2002). The Early Period population at Ban Chiang was believed to have had a hunter-gatherer and cultivator subsistence, and evidence of bronze casting and animal domestication was found belonging to this period (Pietrusewsky and Douglas, 2002). Remains of water buffalo and evidence of further environmental manipulation (forest clearing) and iron were found in the Middle period, and indicators of wet rice agriculture were observed in the Late period (Pietrusewsky and Douglas, 2002). The Early (Neolithic to Early Bronze) period included phases I-V, with a sample size of 9, and the Middle to Late (Iron Age) period included phases VI-X, with a sample size of 46 (Pietrusewsky and Douglas, 2002). Our proportion of subadults differs from that reported by Pietrusewsky and Douglas (2002) as they used 20 years of age as the adult cut-off point.

2.8. Ban Lum Khao

Ban Lum Khao is a site in northeast Thailand, with three phases of occupation: Late Neolithic, early and late Bronze Age (Higham et al., 2004). A variety of stone, clay, bronze, shell and bone artefacts and ornaments were found at the site (Higham and O'Reilly, 2004). A small number of individuals were found in the late Neolithic phase. 110 individuals were identified for the early Bronze Age and age was estimated for all individuals (Domett, 2004).

2.9. Ban Na Di

Ban Na Di is located in northeast Thailand and was excavated in 1980 and 1981. The site dates to the Bronze Age and early Iron Age (Domett, 2001). The original reports on human skeletal remains from the site stated there were 73 individuals, but subsequent analysis by

Domett (2001) identified 78, all of which were assigned to ages or age categories. This study utilised the age-estimates from Domett (2001).

2.10. Noen U-Loke

Noen U-Loke is located in northeast Thailand, with the major excavation occurring from 1996 to 1998 (Higham and Thosarat, 2007). It spans 400 BC to AD 500. Industrial activity evidenced at the site included salt processing, metal working, textiles and pottery making (Higham, 2007). Higham (2007, p. 160) concluded that the Noen U-Loke population was likely experiencing "*cultural change that also involved growing social friction, expressed in conflict*". One hundred and twenty individuals were identified and age or age categories were assigned to all of these (Tayles et al., 2007).

2.11. Nong Nor

Nong Nor is located in Thailand near Khok Phanom Di (Domett, 2001). The Nong Nor cemetery is dated to the Bronze Age and was cut into a hunter-gatherer shell midden (Domett, 2001). Bronze artefacts were found at the site but there was no evidence of manufacturing (Domett, 2001). The sample includes 155 individuals with estimated age (Domett, 2001).

3. Methods

3.1. Age estimation

The published sources used a variety of age estimation methods and readers are referred to the original sources for further information. In the case of Cong Co Ngua and Man Bac, refer to Oxenham et al. (2018) and Domett and Oxenham (2011) respectively.

3.2. Paleodemographic analyses

We employed the methods outlined in McFadden and Oxenham (2018a) for the rate of natural increase. In summary, the D0-14/D ratio was calculated by dividing the number of individuals aged 0–14 years at the time of death, by the total number of individuals in the sample. The ratio was then used in the regression equation developed by McFadden and Oxenham (2018a) to estimate the rate of natural increase. We applied the method to 15 chronologically distinct skeletal samples from 11 sites in Southeast Asia (three sites spanning multiple time periods). Descriptive statistics were performed in Microsoft Excel (2016).

Data were plotted using the mean radiocarbon date for each sample (earliest date + latest date/2) and the LOESS fitting procedure (95% confidence interval) with a span of 0.75 and polynomial degree of 2 in StatsDirect (2017). The LOESS fitting procedure is a flexible, non-parametric method that uses local regression and is well suited to modelling processes that occur in complex environments (StatsDirect, 2017). We ran the LOESS analysis with varying parameters (span = 0.50, 0.75, 1.00, polynomial = 1,2) and found the results were consistent with the original analysis.

3.3. Absolute population size models

We calculated the resulting population per individual in a hypothetical community using four models of population growth over a period of 1000 years. The years and rates of growth in Supplementary Table 1 were used to calculate the number of individuals per original community member.

4. Results and discussion

4.1. Detecting temporospatially localized growth in ancient Southeast Asia

We generated estimates of short-term growth in Southeast Asian populations dating from prior to the Neolithic through to the Iron Age (Table 1). The LOESS fitting procedure was used to fit a smooth curve to the RNPI over time (span = 0.75, polynomial degree = 2). The LOESS curve has identified the same trend observed in the archaeological record, of high growth in the Neolithic and continued growth in the Bronze and Iron Ages. However, the method has also ascertained a seemingly more nuanced trend of slowing rate of increase and steadier absolute population growth in the Bronze Age, followed by increasing rates and more rapid absolute growth in the Iron Age. Further validation of the accuracy of the method and investigation of the specific conditions that may have produced such a trend may serve to further reinforce and explain these results. The results for the NDT samples indicate that this was the period of highest growth experienced by populations in this region, which is consistent with the archaeological narrative. This validation against the archaeological record provides assurance that our method is estimating the RNPI trend with a substantial degree of accuracy. The archaeological evidence has a close relationship with the skeletal samples but is, nonetheless, an independent source. This provides the RNPI estimator a unique opportunity to validate temporally (short-term) and spatially (specific to a site) localized hypotheses, as well as broader trends as informed by the archaeology.

A great advantage of our method is that it can be applied to small samples, allowing the potential identification of intraregional, community-based differences in population dynamics, in addition to illustrating fine temporal fluctuations. In MSEA, sites that are temporally close were found to have more similar rates of population increase (Fig. 2), while spatial proximity seems to be less of a predictor of likeness (Fig. 1). The Neolithic sites Khok Phanom Di and Man Bac, are geographically distant but are highly consistent in occupation dates and RNPI, indicating that both populations experienced similar rates of growth during this period of agricultural intensification. Similarly, Nong Nor and Non Nok Tha show strikingly similar rates of growth in the Bronze Age despite the physical distance between sites (Fig. 1), while Ban Non Wat, geographically located at the midpoint between the two, is estimated to have had higher growth during the same period. In contrast, Ban Lum Khao, a site in use during the Neolithic-Bronze Age transition, appears to have experienced significantly different growth to the neighboring sites of Ban Non Wat and, more distantly, Non Nok Tha and Ban Chiang. Despite some cases of variability, the similarity in rates of many temporally proximal sites in this sample is striking.

Our results appear to be in agreement with those reported by Kohler and Reese (2014), who detected intraregional variability in the NDT response in the North American Southwest, with an overall temporal trend. The variability observed in this study is not solely driven by time. Recently, it has been argued that Southeast Asian archaeological samples do not necessarily indicate a decline in health after the introduction and intensification of agriculture (Tayles et al., 2000; Domett, 2001; Oxenham, 2006; Domett and Tayles, 2007; Bellwood and Oxenham, 2008; Willis and Oxenham, 2013; Clark et al., 2014; Halcrow et al., 2016), contrary to the pattern of relatively poorer health observed throughout Europe and North America (Armelagos and Cohen, 1984; Armelagos et al., 1991; Pinhasi and Stock, 2011; Cohen, 2008). We suggest that the spatial variability in our results with close temporal proximity may represent intraregional variation in how ancient Southeast Asian populations responded to major transitional events such as the introduction of agriculture by migrants, the spread of new technologies, and social change, consequently producing highly localized (or community-specific) population dynamics and health responses. Indeed, Matsumura and Oxenham (2014) have demonstrated the spatial and temporal complexity of the population history

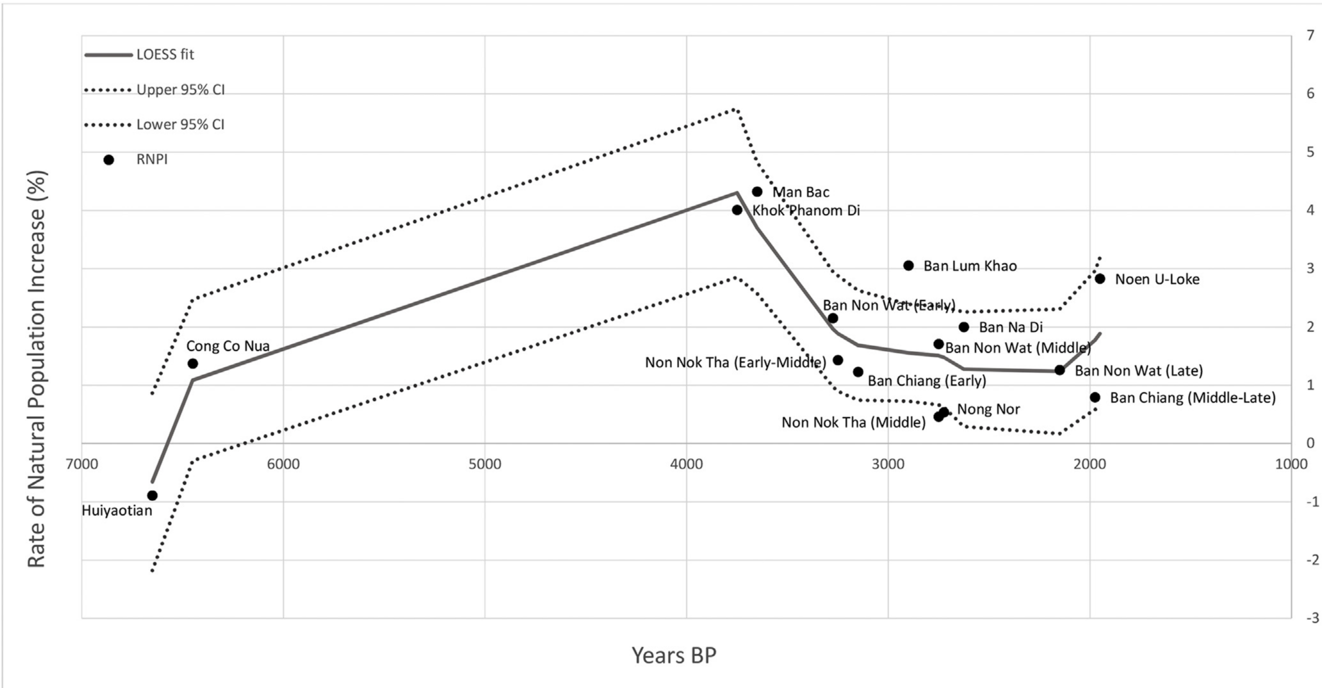

Fig. 2. Rate of natural population increase (per annum) for 15 ancient Southeast Asian samples (LOESS fit with 95% CI).

(movement, interaction) of this region, particularly in the context of the diffusion of genes and farming from the Neolithic onward. Alternatively, growth-rate disparity between temporospatially proximal samples could indicate the gradual abandonment of one site and absorption by another. Finally, there is the potential that such instances are the product of sample bias or error, however, due to the consistency with the archaeological narrative both at the regional and intraregional level, we do not believe this to be the case. Additional hypothesis testing and the analysis of further skeletal samples from the region (should they be found) and of other regions may provide greater clarity as to the cause of this variability. Importantly, the meaning of temporal and spatial proximity (and distance) each represent a range of attributes that warrant more detailed consideration. Temporal trends may result from changes in technology (that may occur within a short timeframe) and regional climate change, while spatial trends or lack thereof may result from similarities or differences in local ecology, diet, and culture. As such, trends in temporospatially localized growth are only meaningful if the relevant associated and contributing factors are investigated.

4.2. Precision, assumptions and limitations

The validation of the trend produced by the RNPI analysis and the existing archaeological narrative for Southeast Asia has indicated a significant level of precision of the RNPI method, however, further methodological validation and trend contextualisation is anticipated to provide greater confidence in the results reported here. Previous methods based on skeletal remains have produced estimates of fertility that conflict with archaeological evidence of population expansion, due to the methodological exclusion of infants in samples where subadults (aged 5–14 years) appear to experience reasonably good survivorship (Bellwood and Oxenham, 2008; Domett and Tayles, 2006; Domett and Oxenham, 2011). By including infants, we believe we have significantly increased the accuracy of such estimates in MSEA (McFadden and Oxenham, 2018b).

The process of comparing archaeologically and skeletally derived trends provides a unique opportunity for validation of independent, but sufficiently associated, evidence. This process could be extended to include comparison with dTFA trends (as per Downey et al., 2014), though no such analysis is presently available for the Southeast Asia region. dTFA methods essentially quantify archaeological material and, as such, the ability to validate with biological material is a significant benefit of skeletally-based methods.

As previously noted, the RNPI method has afforded the opportunity to analyze small samples and produce high precision estimates. Even for samples where a limited archaeological record exists, the method may provide new insights regarding populations. By comparison, the availability of data may determine whether dTFA techniques have the capacity to identify temporally localized changes, for example, where datasets are large enough to permit short-term (e.g. 10-year) data bins (Downey et al., 2014; Shennan et al., 2013). Conversely, where data are limited they may be combined on a larger temporospatial scale, thereby glossing over both temporally and spatially localized variability (although noting that methods by Timpson et al. (2014) have made progress in improving the resolution of small sample dTFA studies). The RNPI method may provide a useful tool where small datasets exist, or intraregional variability is suspected, by making excellent use of the data available and producing high precision estimates.

Reports of very low, long-term average growth rates are essentially a truism: averaged over several thousands of years, population growth cannot greatly exceed 0.00% as the consequence would be impossible absolute population sizes. The issue is that in many cases it is the short-term fluctuations that are of the greatest interest, particularly in terms of backdrops to differential health and resilience outcomes. Indeed, we would expect that many of the events that impact upon populations will produce results in a more immediate manner, with population dynamics being directly impacted for decades or centuries, rather than millennia. A number of authors have argued that the rapid growth resulting from the transition to agriculture would have been counterbalanced by increasing mortality (Armelagos and Cohen, 1984; Bocquet-Appel, 2002, 2008; Bocquet-Appel and Naji, 2006; Cohen, 2008; Pinhasi and Stock, 2011): this scenario would produce a low average growth rate for the period, thus greater temporal specificity is needed to detect or validate the hypothesis of a NDT.

Table 2
Three models of fluctuating population growth.

Model	Scenario	Estimated No. Individuals per Original Community Member
Armageddon	The community is almost wiped out twice in 1000 years, with only a 1% survival rate for these events.	15 individuals per 1 original community member
Occasional Catastrophe	90% of the community is eliminated on five occasions in 1000 years.	18 individuals per 1 original community member
Regular Adverse Conditions	There is a 20% decrease of the community for one year in each decade.	1335 individuals per 1 original community member

At the Neolithic sites of Khok Phanom Di and Man Bac, the highest rates of population increase of 4.01% and 4.32% respectively (Fig. 2) are reported. With the exception of Ban Lum Khao, which experienced a high enough rate of population increase to deviate from the LOESS trend, growth then remained below 2.00% up until the Iron Age. In agreement with Kohler and Reese (2014), we believe these rates represent growth for short periods of time (decades or one to two centuries), and most likely shorter than the occupation period for each site. Just as 0.04% stable annual growth over thousands of years is not feasible, equally, our maximum estimates of ~4% every year over thousands of years simply cannot have occurred as the outcome would be astronomical population sizes. However, there are a variety of models of growth between these two extremes that are more plausible than a highly stable system of annual checks and balances.

We calculated the resulting population per individual in a hypothetical community assuming an average annual rate of increase of 1% and a period of 1000 years. It is clear that if the rate of increase is applied as fixed for each of 1000 years, the result is extreme: after 1000 years it is estimated that there will be approximately 21,000 individuals for every member of the original community. This is the Constant Growth model. We outline three alternative hypothesized models that assume fluctuating growth: the Armageddon model, the Occasional Catastrophe model, and the Regular Adverse Conditions model (Table 2).

These models provide different absolute estimates of population size over the same period of time. Again, this is a very limited representation of the various scenarios that may impact upon population size, but it demonstrates the significant difference between constant and fluctuating growth rates. It is therefore an assumption of this method that the short-term growth detected fits into a longer-term fluctuating growth model.

There are limitations to this method. The first, though not explicitly demonstrated by this study, is that the method does not account for a number of sources of uncertainty. The degree to which skeletal samples represent the living population from which they are derived has been the overarching concern of paleodemography to date. Representation has significant implications for the accuracy of paleodemographic methods, therefore, noting the inherent uncertainty surrounding skeletal samples, we have sought to implement other controls for error such as the inclusion of infants (the age group most sensitive to changes in fertility and population increase as noted in McFadden and Oxenham (2018b)) and the use of a ratio which reduces the potential for age-estimation error to a single demarcation point. Nonetheless, it is important to acknowledge that some sources of error are likely to persist.

In this study, the mid-point for the estimated usage period of each cemetery has been used to evaluate the temporal trend. Best efforts have been made to use sites with a well-established chronology, however, there is potential that the mid-point of the date range does not accurately reflect the mid-point of cemetery usage, as the site may have experienced more or less usage at various points in time or the skeletal sample may have been deposited over a very short period. As such, it is important to note that the estimates of RNPI are an average for the period the cemetery was in use. Depending on the period, this may reduce the temporal precision of the method. It is therefore imperative to evaluate the cemetery context.

5. Conclusion

We have demonstrated that our skeletally based method is capable of detecting intraregional, short-term population changes within communities, and has produced a trend consistent with the archaeological narrative for mainland Southeast Asia. The inclusion of infants in the RNPI method has produced estimates that align far more closely with the archaeological evidence than previous methods which excluded infants and relied on individuals aged 5–14 years, a category that often shows robust survivorship in Southeast Asia. We have demonstrated the method's applicability to small samples (noting the implications for confidence). Community-level growth allows us to investigate the specific, localized conditions impacting on population dynamics and, conversely, provides insights into population responses to change and significant (e.g. climatic, cultural, technological etc.) events. Indeed, we hope that future work will evaluate these relationships between RNPI and impact factors, both those that are similar (e.g. Man Bac and Khok Phanom Di) and those that are different (e.g. Ban Lum Khao), in greater detail. The RNPI method, whilst noting its limitations, provides a great number of advantages and opportunities in the evaluation of temporospatially localized ancient population growth.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jas.2018.08.010.

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