Palaeodemography:
A New Hope

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Declaration

This thesis is my own original work. Contributions by co-authors to papers are listed before each chapter in authorship declarations.

Signed

Clare H McFadden

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To Pat, thank you for your unshakeable optimism, your unconditional love, your ferocious loyalty and your determined sense of humour.

To my parents, thank you for your endless support and patience, for talking through problems, encouraging and inspiring me, and for the highly effective reward-based upbringing that drove me to where I am today. To my in-laws, thank you for being proud of me, for being bright and generous. And to both parents and in-laws, thank you for always ensuring a steady flow of high quality wines.

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Abstract

Palaeodemography - the study of past human populations - is as much about studying ourselves as it is about our ancestors. The population as a biological entity has had persisting capacity for resilience, adaptivity and response to internal and external factors from past to present. As a social entity, populations can play a large role in our individual identity and have significant effects on how we relate to others within and outside of the population or populations we see ourselves belonging to (Chen and Li, 2009; Sökefeld, 1999). More than just the sum of individuals, populations take on their own identity and meaning, becoming defined by biological, social and cultural patterns. Past populations provide us the opportunity to zoom in and out on human experience, changing the resolution based on the research endeavour. Far from dismissing the individual, they provide a context within which to better understand the individual experience within past communities, particularly how their sociocultural, economic and environmental conditions shaped their life psychologically and physiologically.

This thesis aims to take a particularly pragmatic approach to palaeodemography (a move recommended by a number of prominent bioarchaeologists including Meindl and Russell (1998)). It has focused on identifying the most parsimonious solutions to existing issues and gaps in the discipline, relying more strongly on empiricism than theory to produce and test reliable tools for evaluating past population dynamics, specifically fertility and population growth. Shifting away from the traditional Western-centricism of palaeodemography, this thesis aims to provide new tools with increased accuracy for use in Asia and the Pacific where preservation conditions are often optimal. The new tools are then evaluated for robusticity and resilience against various sources of sample bias, including infant and elderly underenumeration and age estimation bias. The application of these tools to archaeological skeletal samples from Asia and the Pacific is used to demonstrate the utility and capability of the methods, particularly their temporospatial precision and accuracy, and the interpretive framework into which they can be integrated. Additionally, such applications may provide exciting new insights into population dynamics in Southeast Asia and the Pacific Islands, where previous palaeodemographic work has been limited. The methods and case studies showcased in this thesis indicate a bright future for palaeodemography in the Asia-Pacific region, and indeed the world. The accessibility and accuracy of these methods will hopefully re-establish palaeodemography as a cornerstone of bioarchaeological studies.

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1. Introduction and Thesis Outline

Studying past human populations is as much about studying ourselves as it is about our ancestors. Similar to the body itself, the population as a biological entity has had persisting capacity for resilience, adaptivity and response to internal and external factors from past to present. As a social entity, populations can play a large role in our individual identity and have significant effects on how we relate to others within and outside of the population or populations we see ourselves belonging to (Chen and Li, 2009; Sökefeld, 1999). More than just the sum of individuals, populations take on their own identity and meaning, becoming defined by biological, social and cultural patterns. For individuals, populations can be comforting and supportive, or hostile and exclusionary. It is near impossible to extricate ourselves from the population we come from and the ones we occupy throughout our lives (Brodwin, 2002; Tutton, 2004).

So, what can we learn from the study of past populations? They provide us the opportunity to zoom in and out on human experience, changing the resolution based on the research endeavour. They provide a context within which to better understand the individual experience within a community, particularly how their sociocultural, economic and environmental conditions shaped their life psychologically and physiologically. Lowering the resolution ever so slightly, they allow us to understand the specific conditions that impacted upon a community, and how that community responded to those conditions, including extrinsic changes such as availability of resources, territorial pressure and changes in subsistence, and intrinsic ones, for instance population pressure and social hierarchy. Conversely, we can learn how changes within the community led to impacts upon the environment in which they lived. Lowering the resolution further, we can compare these populations to learn something of the human capacity for adaptivity and resilience within geographic regions and periods of time. And lowering the resolution once more, we can gain a global perspective of population dynamics throughout the history of anatomically modern humans and a broad understanding of the adaptability and resilience of *Homo sapiens* populations as a biological entity.

Palaeodemography, like many disciplines, is most successful when it is integrated with other sources of information. Cross comparison with palaeoclimate data can provide opportunities to evaluate the impact of climate change on populations and their response to it (Turney et al., 2006; Turney and Brown, 2007). This is particularly pertinent given the predictions of future climate change: our lives may again depend on our adaptability and resilience in the near future. Whether driven by climate or other factors, changes in subsistence indicated in the archaeological record, including evidence from zooarchaeology (Munro et al., 2004; Oxenham et al., 2018; Stiner et al., 1999), geoarchaeology (Riehl et al., 2012), and bioarchaeology (Bocquet-Appel and Bar-Yosef, 2008; Pinhasi and Stock, 2011), and their relationship to population dynamics are also of great interest. The population response to the development, intensification and spread of agriculture has proven to be a particularly engrossing area of research. The Neolithic Demographic Transition (NDT) is a prominent model which hypothesises that the increased resource reserves and decreased mobility associated with agriculture caused high rates of population growth (Childe, 1936; Sussman, 1972; Hassan and Sengel, 1973; Cohen, 1977). In parallel, however, health may have been impacted by reduced nutrition and increased communicable diseases (Armelagos et al., 1991; Cohen, 1987; Cohen and Armelagos, 1984). While a consistent pattern of increasing fertility and declining health has been inferred in association with the NDT in Europe and the Americas, a divergent pattern is recognised in Asia (Bellwood and Oxenham, 2008; Bocquet-Appel and Bar-Yosef, 2008; Oxenham et al., 2018; Pinhasi and Stock, 2011). More research in this region is clearly needed to understand the driving forces behind this seeming contrast. The integration of palaeodemography into palaeopathological studies has great potential, with recent studies having improved our understanding of morbidity and mortality associated with the plague (DeWitte, 2014a, 2014b, 2014c, 2015, 2016; DeWitte et al., 2017). Incorporating palaeodemography into bioarchaeological studies that address socio-economic status (Miszkiewicz and Mahoney, 2016) and gender (Cave and Oxenham, 2017) may identify how these attributes impact upon past patterns of fertility and mortality.

Populations, throughout the relative brevity of modern human history, have experienced innumerable challenges. We have adapted to some, like changes to climate and environment, and built resilience to others, like disease. Populations have fluctuated and grown, grown, grown - to the brink of exhausting many of the earth's resources and creating their own ecological nightmares (Daily and Ehrlich, 1992). Now, the human population is entering new territory, where its continued growth could prove self-defeating and potentially catastrophic (Cohen, 1995a, 1995b), and at the very least significant innovation and adaptation will be needed to support it. Forward projections of population growth have become increasingly complex and, in many cases, have failed to achieve the desired accuracy (Appleby, 2014). Thus, studying past populations provides us with opportunity to learn about our ancestors, learn about ourselves, and learn about our future.

Noting the significance and value of such research, this thesis aims to improve and add to the palaeodemographic toolkit used for the study of past populations. It will evaluate the current status of the discipline of palaeodemography, its theory, methodologies and applications, in order to identify problems, challenges and gaps in the existing approaches. The thesis will then aim to address a number of these concerns through the development of new methodologies. To ensure the methodologies are rigorous, they will be tested against various forms of uncertainty and error. They will then be applied to a case study where the archaeological record indicates a relatively clear trend in population dynamics to cross-validate the methods. Finally, they will be applied to a further case study where a minimal narrative regarding population dynamics exists, to provide new insights into past population responses to change.

This thesis is presented through a series of published and/or in-review manuscripts, forming a thesis by compilation. Note that spelling and formatting conventions may differ between manuscripts due to the differing publishing requirements of the journals they have been published in/submitted to. The overall format of the thesis is that governed by the Australian National University thesis by compilation policy (Appendix 5).

Chapters 2-4 will provide a comprehensive review of the palaeodemographic literature and will identify the problems and gaps within the existing palaeodemographic methodological toolkit.

Chapter 5 outlines the research aims and hypotheses to be addressed within this thesis.

Chapter 6 describes the overarching methodological approach utilised within this thesis and the limitations of this approach.

Chapter 7 proposes a new method of estimating fertility from an age-at-death ratio derived from skeletal remains. Contrary to previous methods, it includes infants (0-4 years) due to their sensitivity to changes in population dynamics and their representation in samples in Southeast Asia and the Pacific. This paper is published:

> McFadden, C., and Oxenham, M. F. (2018a). The D0-14/D ratio: A new paleodemographic index and equation for estimating total fertility rates. *American Journal of Physical Anthropology*. 165, 471–479.

Chapter 8 builds on the previous chapter to provide a method of estimating a proxy for population growth: the rate of natural population increase (RNPI). The relationship between RNPI and migration is also evaluated. This paper is published:

> McFadden, C., and Oxenham, M. F. (2018b). Rate of natural population increase as a paleodemographic measure of growth. *Journal of Archaeological Science: Reports*, 19, 352-356.

Chapter 9 evaluates the potential impacts of various sources of sample bias on the proposed methods. Specifically, infant and elderly underenumeration and age-at-death estimation error are simulated to determine the robusticity of the methods. This paper is published:

> McFadden, C., and Oxenham, M. F. (2019a) The Impacts of Underenumeration and Age Estimation Error on the D0-14/D ratio and Palaeodemographic Measures. *Journal of Archaeological Science: Reports*, 23, 57-61.

Chapter 10 applies the RNPI method to samples in Southeast Asia, where an established archaeological trend of population growth exists, in order to cross-validate the method using the type of data and context that it is intended for. This paper is published:

> McFadden, C., Buckley, H. R., Halcrow, S., and Oxenham, M. F. (2018). Skeletal Evidence of Temporospatially Localized Growth in Ancient Southeast Asia. *Journal of Archaeological Science,* 98, 93-101.

Chapter 11 applies the RNPI and fertility methods to samples in the Pacific Islands to gain insights into population dynamics in the region following initial colonization ~5000 years ago. This paper is in review:

> McFadden, C., Walter, R., Buckley, H. R., and Oxenham, M. F. (in review). Temporal trends in the colonisation of the Pacific: Palaeodemographic insights. *Journal of World Prehistory.*

Chapter 12 discusses the success of the thesis in addressing its research aims and hypotheses.

Chapter 13 summaries the findings of the thesis, presents concluding remarks, and describes suggestions for future research.

2. Palaeodemographic Theory and Methods

2.1. Introduction

Palaeodemography is the study of the dynamics of past populations, typically those that are prehistorical or that lack historical census data. The study of past demography broadly aims to provide a greater understanding of the resilience, adaptivity, and responsiveness of human populations to both change and stability. Not solely the interest of archaeologists and historians, palaeodemography may provide insights into human evolution and ecology, and may even assist in anticipating and planning for population changes resulting from climate, environmental and subsistence change. Originally developed primarily as a subdiscipline of archaeology (though with demographic thinkers contributing too), palaeodemography was rather late to form with studies appearing in the late 1960s (Angel, 1969) and early 1970s (Acsádi and Nemeskéri, 1970; Bennett, 1973; Brothwell, 1972; Lovejoy, 1971; Weiss and Wobst, 1973). From the outset, it was perceived by some to have many more limitations than opportunities, both within its own methodological approaches and due to its dependence on error-prone bioarchaeological indicators of age-at-death. Thus, the discipline was born with an array of caveats at birth. Bocquet-Appel and Masset's (1982) paper, *Farewell to Paleodemography*, received a huge response from fellow palaeodemographers who considered the farewell premature. The paper was controversial, but a positive shift towards greater scrutiny and refinement of methods ensued. A rich field has grown with significant contributions from demographers and mathematicians in addition to bioarchaeologists, archaeologists and biological anthropologists. In parallel, palaeodemographic methods have been applied to skeletal samples spanning the existence of modern humans across the world, and even delving into some samples of hominins other than *Homo sapiens*. Palaeodemography has seen great expansion in the past two decades, with the potential of its contributions being more fully recognised. However, many of the problems raised as the field developed remain prevalent today. Those that have been addressed, have often been addressed using seemingly complex and timeconsuming (which has hindered their application) methods that have dependencies that are often challenging to fulfil.

The overarching aim of this chapter is to provide a comprehensive literature review of palaeodemographic theory and methodological research to date. Beginning with a definition of palaeodemography as a discipline, this chapter then provides an overview of the fundamentals that underpin it. It explores how demographic theory has been integrated into palaeodemography and will discuss the concepts developed within palaeodemography itself. The theory component of the literature review concentrates on the way theory has influenced palaeodemography, including the amalgamation of theoretical concepts into palaeodemographic methods and the interpretive framework in which analyses are contextualised. Informative as it may be, palaeodemography has sought to fit data to existing models and a poor fit has often been blamed on poor data quality, when perhaps the appropriateness of the model should be challenged too. This chapter then discusses at length the development of methods in palaeodemography and how methods have evolved over time and responded to criticisms from within and outside the field. This component of the review seeks to highlight the current status of methods and particularly the problems that have persisted. The chapter concludes with remarks on the significant progress made in palaeodemography to date, but noting that it is still constrained by several methodological flaws and that advancements in techniques have not been widely adopted, with traditional methods still prevailing in many cases. The focus of the review is on bioarchaeological based approaches to palaeodemography, although some further palaeodemographic research, including dates-as-data techniques, is touched on.

2.2. Defining Palaeodemography: where bioarchaeology, archaeology and demography meet

Palaeodemography is less a subdiscipline than a multidisciplinary paradigm. Human bioarchaeology, the study and interpretation of human biological remains within archaeological contexts, meets with archaeology, the study of the cultural and physical context, and demography, the study of populations. In many cases, biological anthropology is also highly relevant to palaeodemographic studies. The aims and potential of empirical palaeodemography are determined by the information that can be obtained through bioarchaeology and archaeology. Empirical palaeodemography relies heavily on the biological profile (sex, age, ancestry, etc.) for each individual in order to calculate census data. As such, the validity and accuracy of such data are of fundamental importance to palaeodemographic studies. Demographers have sought to overcome this issue through modelling, while bioarchaeologists have sought to improve their sex and age estimation methods, producing a tension between the theoretically-focussed and empirical streams of the discipline.

Regardless of approach, palaeodemography provides the greatest insights when combined with the examination of palaeopathology, evidence of diet, indicators of behaviour, and archaeological material. Through a multifaceted approach, important insights may be gained into how population dynamics are impacted by, or relate to internal and external factors including disease, health, diet and subsistence, gender, societal structures, environmental change, migration, and much more. In this way, the disciplines of archaeology, bioarchaeology, demography and palaeodemography interact dynamically. In isolation, palaeodemographic results are of little value.

As a social science, sitting very much on the border of social studies and the sciences, bioarchaeology has at times struggled to effectively reconcile the two paradigms. One of the greatest challenges for palaeodemography is the issue of empiricism. Many aspects of the past are fundamentally unverifiable. When demographic theory is applied to estimate past population dynamics, there is nothing against which to verify it. While empirical palaeodemography equally suffers the constraints of verifiability, analyses of raw data and cross-validation with the archaeological record offers some comfort. Palaeodemography is in many ways pushed and pulled between the various contributing disciplines and paradigms: demography vs archaeology, theory vs empiricism, social study vs science. It is little wonder then that the discipline, with relatively late origins, is still in a phase of maturation and arguably even definition.

2.3. Demographic and Palaeodemographic Theory

The study of demography in the past has not differed much in its concerns from its present form. Early demographers described and hypothesised the causes and consequences of population growth: the nature of humanity; the impacts on social systems and hierarchies; the demands on finite resources; and catastrophic consequences of unimpeded growth, such as population collapse. To briefly summarise, Malthusian theory suggested that the fundamental cause of population growth is the instinctual urge to reproduce, and that growth rates are managed by what he termed positive and preventive population checks, including resource limitations and birth control. The primary consequence of population growth is poverty, he argued, due to the inability of food production to keep up with the rate of population increase. The Malthusian theory (though notably more complex than articulated here) was almost immediately challenged by critics who argued, amongst other things, that food production could keep up with population growth and therefore that poverty was not an inevitable consequence (see Weeks (2011) for a summary).

Marx (1867) and Engels (1844) did not disagree with Malthus' fundamental cause of growth, but argued that the consequences of population growth depended on the structure of the population it occurs in, specifically whether that population is capitalist or socialist. A socialist society could absorb growth, with additional people providing additional capacity for production, they argued, however, the disorganised nature of capitalism would result in an increasing working class, from which the wealthy would derive increased profits. In turn, the wealthy class could automate and mechanise production, ultimately reducing the paid work available to the working class and increasing the prevalence of poverty (Marx, 1867). More modern theories have expanded the consequences of population growth with respect to other resources, including fuel and water (Weeks, 2011).

In contrast to Malthus, Boserup (1965) proposed that population growth was the driver behind the agricultural transition and indeed other types of economic change. In her model, population growth would increase population pressure and reduce the standard of living, with the community then responding by looking to new means of production and subsistence. Subsequently, the community would adapt to the economic change and improvements to living standards would follow. If population growth is independent of changes in subsistence, then the many millennia of seemingly slow population growth in modern human history require an alternative explanation, rather than simply being a matter of limitation by resource constraints (Boserup, 1965). Wood (1998) reconciled Malthus and Boserup to form his own pre-industrial population growth model, of population push-and-pull (where economic change can drive population growth and also respond to it) but excluded Boserup's treatment of growth as an independent variable.

The potentially catastrophic impact of population growth on human societies has been a concern for many researchers over the past several decades (Cohen, 1995a; Ehrlich and Ehrlich, 1990; Meadows and Meadows, 1972) and more recently the impacts on the environment and climate have become a particular focus. Whether consequences can be prevented, managed or absorbed is still hotly debated and is undoubtedly highly variable across the globe and based on socioeconomic inequalities, but we know for certain that population growth has significant and likely irrevocable detrimental impacts on the environment and natural resources and that, in turn, these impacts reach back to the population. With the potential for catastrophe in mind, palaeodemographic studies have often been used to better understand past populations and to utilise them as an empirical study of demographic concepts in action.

2.3.1. Population Growth Theory

Overwhelmingly, applications of palaeodemography have been focussed on the effects of the introduction and intensification of agriculture, or the Neolithic Demographic Transition (NDT). From a strictly demographic perspective, the NDT hypothesis suggests that the transition from hunting and gathering to agriculture and static living caused a significant increase in the birth rate and population growth. More broadly, the event is associated with increasing social complexity, spread of communicable disease, and changes to health and nutrition. The NDT has provided researchers with an opportunity to evaluate demographic concepts including Malthusian, Marxist and Boserupian ideas, and offers a comparison to the more recent industrial demographic transition. Furthermore, it may provide insights into human population responses to major changes in subsistence, an event which may occur again in the future following on from the depletion of some resources. Thus, much theorising has revolved around this model of demographic upheaval. The sustainability, or lack thereof, of high rates of population growth has been discussed in many palaeodemographic studies. Sussman (1972) was widely criticised for suggesting that NDT population growth could have amounted to a 50% increase in each generation and sceptics argued that growth would have been far more moderate as such a rate would not be viable (Hassan and Sengel, 1973; Coale, 1974; Cowgill, 1975). Coale (1974) used demographic theory and formulae to reverse engineer global population sizes and growth at various points in time and suggested most of human history involved a lack of growth, with only minimal growth resulting from the NDT. This homeostasis, he argued, could result from several drivers of fertility and mortality balancing each other.

While most researchers agree that Sussman's (1972) model of growth would not have been sustainable, the exact model of growth and the mechanisms of population control, have been keenly discussed and fiercely contested. The traditional NDT hypothesis was that increased food production resulted in improved nutrition, greater availability of resources, and subsequently population increase (Sussman, 1972). Based on observations from non-human primates, Sussman (1972) expanded this argument to include reduction in interpregnancy intervals resulting from sedentism as a driver of population growth. But Hassan countered that mobility is not the primary factor in determining the interpregnancy interval, but rather health of both mother and child, and that the relationship between mobility and population size is a result of a third factor and is not causal (Hassan and Sengel, 1973). Cowgill (1975) questioned the idea that agriculture developed out of the need for additional resources to support a growing population, arguing that humans have evidently not suffered from uncontrollable growth and that population growth "*is not an inherent (or inelastic) tendency of humans. Rather, it is a human possibility which is encouraged in some situations and discouraged in others.*" (p.521).

Many commentators advocated for more complex models with a multitude of contributing factors determining population growth in the Neolithic period, including changes in birth control practices, warfare, occupational and epidemic mortality, diet and disease. Sengel proposed that an increase in protein consumption and reduction in age of onset of menarche would increase the reproductive lifespan of females, resulting in increased fertility (Hassan and Sengel, 1973). Coale (1974) argued that any change in fertility would have been balanced by increased mortality through unforeseeable famines (later reiterated by Wood, 1998 amongst others) and the spread of infectious disease, which he believed were unavoidable hazards of agricultural life:

> *Village life, by bringing comparatively large numbers into proximity, may have provided a basis for the transmission of pathogens and may have created reservoirs of endemic disease. Moreover, the greater density of agricultural populations may have led to greater contamination of food, soil and water* (Coale, 1974: pp.47-48).

Armelagos et al. (1991) argued against the equilibrium hypothesis of the Neolithic Demographic Transition, suggesting that while both fertility and mortality would have increased, reduced birth-spacing would have counterbalanced mortality to permit continued population growth. They argued that the traditional view is dismissive of "*the potential dynamic activities of Paleolithic peoples… as well as population oscillation*" (p.20) and that it is neither supported by the archaeologically evident population growth, nor the relationships between disease, ecology and population growth. In contrast to increased mortality through disease, they argued for a growing resistance to infectious pathologies amongst early agriculturalists. Wood (1998) questioned whether population growth in the past was 'regulated', and concluded it likely was, but through the inability of communities to overcome the limits of resources, rather than through self-imposed controls (for example, birth control via abstinence). He suggested that a combination of theories proposed by Malthus and Boserup provide a more complete approach to palaeodemography. Population growth and economic change may temporarily increase the mean and range of individual well-being, however, in the long term has minimal effect (Wood, 1998). He also felt that past populations would have experienced a high risk of famine.

More recently, authors in *The Neolithic Demographic Transition and its Consequences* by Bocquet-Appel and Bar-Yosef (2008) argued that rising fertility, increased disease, and decreased nutrition associated with the transition to agriculture would have resulted in increased mortality. This, they suggested, would limit growth and prevent long term population expansion. Shennan (2009) discussed the way in which evolutionary demography and human behavioural ecology theories can inform our interpretations of patterns associated with the NDT. He noted that life history theory underpins demographic processes and argued that agriculture provided the resource stability for increased densities and a means of lower parental investment, and that increased infant mortality would have spurred the expected shift in reproduction strategy to producing more offspring. Gage and DeWitte (2009) provided a review of arguments against the traditional NDT hypothesis, and concluded that the traditional view was largely based on assumptions that do not fit the available data, particularly that there is little evidence for a dramatic shift in mortality after the NDT. They also observed that ethnographic evidence for changes in fertility in association with agriculture suggest a valid pattern, but with significant overlap between different types of subsistence. They argued for abandonment of such preconceptions, and a shift towards more rigorous empirical evidence.

Due to the respective interests of palaeodemography and demography, the integration of demographic theory into palaeodemographic studies has largely related to the NDT, but this period represents only a small portion of modern human history. Furthermore, our focus in this area is arguably dismissive of non-agricultural technologies and subsistence strategies, despite their demonstrable success in many regions of the world and for various periods of time. An important consideration for paleodemographic research is integrating demographic theory into the broader study of past population dynamics, before and after the NDT, and in regions of the world where the NDT did not occur. Only then can we start to effectively integrate demographic theory into palaeodemographic practice.

2.3.2. Common Population Growth Models and Concepts

Population growth models and concepts, derived from mathematics, demography and ecology, are used to explain commonly observed trends in demography and palaeodemography, and are incorporated into and/or derived from demographic and ecological theory. There are a number of population growth models that frequently arise in palaeodemographic research. The key models are briefly outlined here.

a) Exponential Model

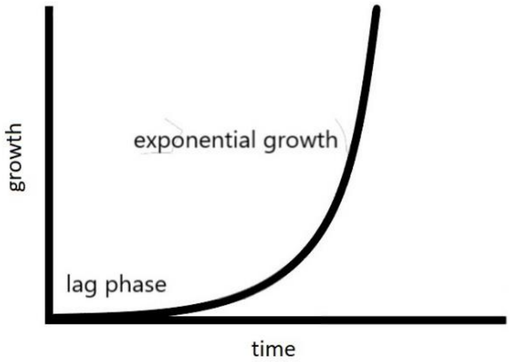

Figure 2.1 Exponential growth model

The exponential model of growth, where intrinsic growth occurs in an unconstrained manner, has largely been rejected by biologists and ecologists (Cohen, 1995b; Schacht, 1980), and indeed palaeodemographers (Wood, 1998) as a realistic model for population growth, as it does not fit the data except where it forms only the initial part of a larger model such as logistic growth or boom and bust scenario. In some cases, however, it still finds erroneous application. In palaeodemography, this is usually in the form of using relative measures of growth (e.g. changes in the size of settlements or frequency of radiocarbon dates) that use two or more points in time and applying an exponential model to determine the growth rate between those points (e.g. Zahid et al., 2016) or where population growth rates are mathematically estimated from either a starting point (in some cases two people) or from an end point (based on estimated population sizes in prehistory) (e.g. Carneiro and Hilse, 1968). Logically, exponential growth cannot be sustained indefinitely, as the consequence is unsustainable population sizes.

b) Logistic Growth Model and Carrying Capacity

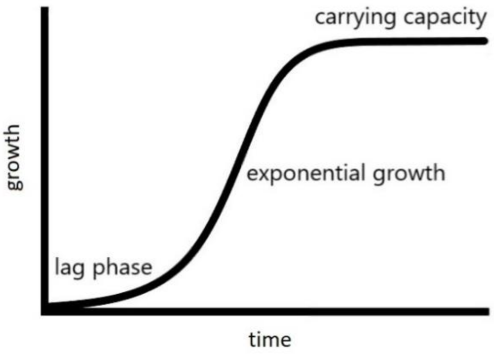

Figure 2.2 Logistic growth model

In 1838 Verhulst proposed the logistic growth model, which states that populations grow exponentially then growth slows towards an upper limit, known as carrying capacity or *K*, at which point growth plateaus (Tsoularis and Wallace, 2002) (a theory that aligns well with the Malthusian paradigm). Carrying capacity is an ecological concept which broadly stipulates that geographically delineated spaces (e.g. islands, deserts, etc.) have finite resources and thus a finite capacity to provide for populations. The concept is represented graphically by the logistic growth model. The model has been used for a range of growth applications. For human population growth it has been hypothesised that populations living in regions with restricted natural resources (e.g. deserts, islands, and migration into new uninhabited areas as per Diamond, 1977) will grow exponentially to the point that the resource limits are reached (i.e. population consumption and resources are at equilibrium), then growth will cease and the population size will stabilise before resources are irreparably diminished. Cohen (1995b) used the model in his interpretation of global human population growth, which he argued was approaching the earth's carrying capacity, if it had not already reached it. In palaeodemography, this model has been proposed for the Caribbean (Curet, 2005) and the Pacific Islands (Diamond, 1977; Kirch, 1984; Kirch and Rallu, 2007), where it is believed finite resources in an island context would impose limits on growth, though not without criticism (Sutton and Molloy, 1989).

c) Boom and Bust Model

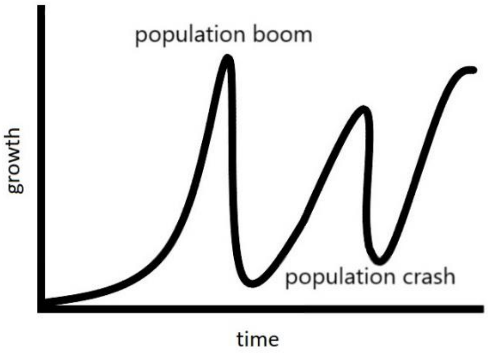

Figure 2.3 Boom and bust population growth model

The boom and bust model of population growth is less well defined and certainly less well studied. The model proposes that populations may grow exponentially until impacted upon by a growth-limiting, or even catastrophic, factor (such as resource limits or an epidemic), which then causes rapid population decline through increased mortality. Following the event, the population recovers and resumes exponential growth. The model has been used to explain growth rate patterns with significant peaks and troughs, including Holocene Fennoscandia (Tallavaara and Seppä, 2012) and Europe (Shennan et al., 2013).

d) Oscillating Growth

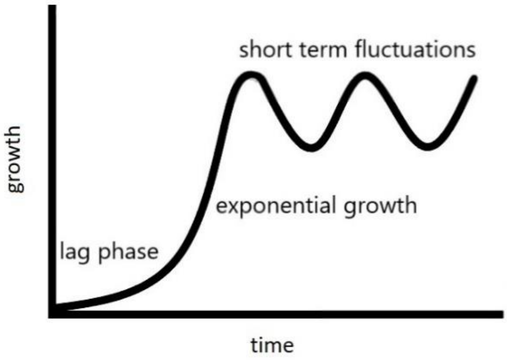

Figure 2.4 Oscillating population growth

Oscillations are widely accepted to occur in the above models (Gage and DeWitte, 2009; Wood, 1998). Populations experience short-term fluctuations which have a minimal impact on the long-term population growth rate. The pattern is similar to the boom and bust model but with less catastrophic and more common events resulting in smaller, regular oscillations. The oscillations can equally occur in a logistic model, where there are oscillations around the carrying capacity limit, or boom and bust models. Historically, oscillations have received little attention from palaeodemographers, with some even treating them as inconvenient noisiness around the trend of interest (e.g. Peros et al., 2010; Zahid et al., 2016).

e) Self-Regulation

The models outlined above incorporate various forms of involuntary regulation (e.g. resources limits, epidemics, etc.), however, some commentators have proposed that populations self-regulate. Self-regulation can involve various preventative (to use Malthusian terminology) measures such as birth control and infanticide (Angel, 1972b; Birdsell, 1968; Sussman, 1972). The theory has come under significant scrutiny, and many believe that the impact of these factors have been overstated and that active self-regulation to any substantial degree was unlikely (Cowgill, 1975; Gowland and Chamberlain, 2002; Gowland et al., 2014; Wood, 1998).

2.3.3. Uniformitarianism: The Fundamental Premise of Empirical Palaeodemography

Much of the discussion surrounding the NDT has incorporated demographic theory, but in parallel palaeodemography has developed or adopted its own theoretical foundations. Perhaps the most important of these is uniformitarian theory. The fundamental assumption of palaeodemography is that the mechanisms, causes and consequences impacting population dynamics today functioned in the same way in the past, producing the same or at least very similar effects on past populations (Howell, 1976). The theory was proposed by Howell (1976) who termed it uniformitarianism, borrowing from the discipline of geology where it refers to the depositional, transformational and erosive geological processes being the same throughout time. The key concept is very similar:

> *that the processes still respond in the same way to variations in environment; including the cultural and technological aspects of human society as part of the external environment... that the demographically relevant biological processes of our species are constant in our genetic composition, subject only to variation in response to environmental forces...* (Howell, 1976: 26).

She noted, however, exceptions to this, particularly the way in which individual's age, citing one example where males aged approximately 40 years looked to be at least 70 years in age based on appearance. Uniformitarianism has been generally accepted by the field (e.g. Hoppa and Vaupel, 2002, noting that the theory does not extend to age), though Milner et al. (2007) observed that while the relationship between population dynamics should not differ greatly between modern and past populations, there are likely to be some differences, constrained by a limited range of variation. The implications of uniformitarianism for this thesis are further discussed in Chapter 6.

2.3.4. Prevailing Assumptions

Early palaeodemographers were keen to place biological and mathematical limits on population dynamics. As previously discussed, a number of demographers have observed that average growth over millennia cannot significantly exceed 0%, or the result would be unfeasibly large population sizes (Hassan and Sengel, 1973; Coale, 1974; Cowgill, 1975). Certainly, for the most part population theory suggests equilibrium must be achieved over time, however, it is the fluctuations that should be specifically of interest to us. A general growth rate of 0% tells us nothing of the way populations respond to change, and merely reiterates historical theory in and essential rules that underpin population dynamics: it is a truism that is of little interest. This is the problem underpinning work by Zahid et al.'s (2016) claim to refute the NDT. In their study, Zahid et al. (2016) interpret the long term average growth rate, which is reported to be 0.04% per annum, to indicate no real change in population dynamics following the NDT, but they fail to explore the shorter-term fluctuations in growth. Similarly, some have believed that carrying capacity applies further constraints on population growth, though few have speculated on numerical limits.

Ethnographic accounts from modern hunter gatherer populations have been used as an indicator of uncontrolled fertility (Hassan and Sengel, 1973; Howell, 1976; Bentley, Goldberg and Jasieńska, 1993). Howell (1976) concluded that a total fertility rate of 8 was a reasonable maximum for past populations, and that 20-30 years was the probable life expectancy at birth for prehistoric people. However, the representativeness of modern hunter gatherer populations is debatable due to the often inescapable influences of modern neighbouring societies. Bentley, Goldberg, and Jasieńska (1993) used published fertility data from the demographic and anthropological literature to examine trends in agricultural and non-agricultural societies. They reported mean total fertility for foragers to be 5.6, for horticulturalists 5.4, and for agriculturalists 6.6. Maximum fertility, natural or uncontrolled fertility, and the fertility rates of non-agricultural societies have all been used to apply limitations to the estimated fertility rates of prehistoric populations. Jackes (2011) suggested that one way of identifying sample bias was by using biological limits of fertility to identify samples with unreasonable estimates and thus some type of bias: where the method produces a result outside of the expected range, bias is implied and various sources should be considered. The use of modern ethnographic data as a proxy for past populations has been criticised as reductive and unfounded (Schrire, 1980), and arguably these limits are not useful except to identify potentially erroneous estimates. The discipline should aim to achieve significant enough accuracy not to require the application of limits for the purpose of avoiding flawed analyses.

Underenumeration of infants (which will be discussed in greater detail in the review of palaeodemographic methods) has also fallen prey to flawed theoretical assumptions. The way in which preservational and depositional bias may impact upon the representativeness of skeletal samples has been of significant concern for palaeodemographers, particularly where apparent infant underenumeration is concerned (Angel, 1969; Brothwell, 1972; Djurić et al., 2011; Gordon and Buikstra, 1981; Jackes, 2011; Konigsberg and Frankenberg, 1994). This valid concern, however, has given rise to the assumption that all samples with lower than anticipated numbers of infants have been subject to bias. One of the major issues seems to be conflation of high rates of infant mortality as a proportion of all infants born with high infant mortality as a proportion of the total population. The latter requires a large number of infants to be birthed and die in order to make a significant contribution to the total sample, whereas if few infants are born, even if all die they may make a smaller contribution to the total sample. There is also the long-held belief that modern populations living traditional lifeways, in addition to historical populations, are suitable proxies for ancient populations and that observations of high infant mortality in the former groups necessitate high infant mortality in the latter (Bocquet-Appel and Masset, 1982; Brothwell, 1972; Guy et al., 1997; Moore et al., 1975; Weiss and Wobst, 1973). But such an assumption is at odds with other widely held views in palaeodemography, such as that the age-at-death distribution is more representative of changes in fertility than mortality (Sattenspiel and Harpending, 1983). If we take this to be true, then the expectation of high infant mortality would in fact be an assumption of consistently high fertility, which arguably contradicts many accepted growth models (including the oscillating and boom and bust models of periods of high growth spliced with significant mortality events, including famine and natural disasters).

2.3.5. Integrating Demographic Theory into Palaeodemographic Research

This discussion of population theory has outlined the way in which it is used to understand palaeodemographic findings, the theory which has developed within palaeodemography itself, and the theoretical assumptions that have arisen from within the discipline, however, there is still much work to be done to better integrate theory into palaeodemography. Some key areas warranting further attention include the integration of population theory in studies outside of the NDT, the application of suitable models and consideration of demographic and ecological discussion relating to these, and abandonment, or at least challenge, of assumptions which may limit our understanding of past populations. Additionally, there is a much greater breadth of biological and sociocultural theory that has yet to be explored. Theoretical concepts from a range of disciplines guide our research interests and should inform our interpretations of palaeodemographic results.

2.4. Palaeodemographic Methods

Palaeodemographic methods were originally derived from demographic approaches but have evolved to meet the requirements and challenges of working with bioarchaeological data. Despite significant efforts, palaeodemographers have not always been able to overcome the limitations of the discipline, though some clever workarounds have been devised. In many cases, despite the availability of methodological advancements, traditional approaches have prevailed due to their greater simplicity and ease of use. Palaeodemographic methods therefore represent a mix of old and new tools, formal demography and palaeodemographic pragmatism, and often inaccessible complexity and inaccurate simplicity.

2.4.1. Life Tables

Life tables have been used by demographers as a means of estimating survivorship and mortality. Historical demographers and anthropologists have applied life table methods to census and ethnographically-derived data in order to profile communities of interest and compare them to each other and modern populations. In doing so, a wealth of data has been collected with, at times, valuable contextual information regarding the conditions and dynamics which may impact upon mortality and survivorship. These data have been used to calculate model life tables: a set of life tables that estimate the mortality schedule based on specific conditions (e.g. fertility, child mortality, growth, etc.) (United Nations, 1955; Coale and Demeny, 1966). Such tables are based on real population data, but represent the average mortality curve of several populations with similar characteristics: this has a smoothing effect on the life table data. Model life tables, particularly those developed by Coale and Demeny (1966), have been adopted by palaeodemographers who saw the opportunity to calculate the age-at-death distribution (comparable to the mortality schedule or D_x: the number of people who died at each age) for past populations based on skeletal remains, then compare the tables to model life tables to identify a best fit scenario (a method that was refined by Paine (1989)). They could then apply the conditions of the fitted model life table to their past population. This led many palaeodemographers to believe that it was necessary to identify proxy populations such as modern hunter-gatherer populations, for example the Ju/'hoansi (formerly referred to as !Kung) (Howell, 1976), and pre-industrial populations (Weiss and Wobst, 1973), in order for the model life tables to be an accurate reflection of prehistoric mortality and fertility.

In '*The Bases of Paleodemography*' Angel (1969) outlined the key types of evidence available to the palaeodemographer, and the potential interpretations that could be made. From bioarchaeological information such as sex, age, ancestry, health and disease, and archaeological context such as grave type and goods, Angel (1969) suggested that we may be able to learn much about population dynamics. If the biological profile of each individual skeleton was accurately described, Angel (1969) believed an equally accurate demographic profile and mortality curve could be constructed and compared to those from modern "*simpler societies*" (pp.427). He noted, however, that the life table method assumed the cemetery represents a single cohort, and that the population and mortality rates are stable.

Acsádi and Nemeskéri (1970) provided a comprehensive guide to studying the *History of Human Life Span and Mortality*, with a focus on palaeodemographic techniques. They described the life table methods and the means of acquiring the biological data (age, sex, etc.) that are necessary to undertake a palaeodemographic analysis. Noting migration as a potentially confounding factor, Acsádi and Nemeskéri (1970) argued that in its absence, skeletally-derived age-at-death data could be used to calculate the d_x value of life tables. Weiss and Wobst (1973) set out to better bridge the gap between demography and archaeology, by explaining the relevant theory and assumptions for palaeodemographic analyses and providing model life tables for past populations. To address the latter, they used data from what they termed 'anthropological populations', comprised of "*primitive, pre-industrial, and non-industrial*" (p.4) populations. Weiss and Wobst (1973) described the way in which they calculated their model life tables and demographic parameters: importantly, they note:

> *The model life tables possess a great deal of internal connectedness since all elements ultimately derive from the mortality rates and from the stationary population equations. The crude death rate,* d, *and the life expectancy both reflect the total experience of a cohort... The model life tables are also connected internally by the fertility schedule. Fertility has been calculated as the dependent variable given mortality as the independent variable... A model table should not be used as a series of independent elements.* (Weiss and Wobst, 1973: pp.45-46).

They noted that these tables were still underpinned by assumptions of stability (closed to migration, and with age-specific fertility and mortality rates that remain constant over time), and stationarity (a type of stable population which, in addition to the factors noted for stable populations, experiences 0% growth). There has been much discussion regarding the problems with the use of life table methods. These concerns can be divided into two broad categories, those relating to the accuracy of individual and population data (i.e. the suitability of life table methods to the data they are applied to) and those relating to the assumptions imposed by the use of life tables, with early critics focussing more closely on the former.

The accuracy of the outputs of life table approaches in large part depends on the accuracy of the data inputs. Lovejoy (1971) suggested caution in the application of palaeodemographic techniques, noting the limits of accuracy when estimating sex and age. He observed that similar errors apply to demography and that the techniques employed by demographers to address these could be applied to palaeodemography's own sources of error. Similarly, Bennett (1973) was concerned with the inability to accurately estimate sex for juveniles and the upper age limit for elderly individuals. He suggested a means of overcoming the former issue by applying a 1:1 sex ratio to juveniles, though he noted that this is an arbitrary application and that it fails to account for potential sources of bias, such as sex-preferential infanticide. Bennett (1973) suggested the issue of estimating the maximum age limit could be addressed by assuming the final age-specific mortality rate in the source life table is equal to the final observed mortality rate. Like Lovejoy (1971), he proposed that demographic work, specifically by Carrier (1958), may be used to improve the accuracy of life table calculations. Brothwell (1972) and Moore et al. (1975) discussed the issue of representativeness, specifically through preservation and differential burial, with Moore et al. (1975) simulating the negative impacts of infant underenumeration on palaeodemographic estimators.

2.4.2. Farewell to Palaeodemography…and Hello Again

Bocquet-Appel and Masset's critique of palaeodemography, originally published in French (1977), was largely overlooked by Anglophone bioarchaeologists until they published a similar paper in English (1982). The 1982 paper was more comprehensive in its assault on palaeodemographic method and inference while capturing the specific focus of the 1977 paper, which was the issue of infant underenumeration and the potential impact of this on palaeodemographic estimates.

Attention is paid here to the 1982 paper. Bocquet-Appel and Masset (1982) articulated a number of criticisms of palaeodemography, specifically: that using reference samples for age-at-death estimation imposes the mortality distribution of that sample onto the population of interest; that bias is inherent and multi-faceted in age-at-death estimation methods; and that such methods lack the accuracy to confidently place individuals in small (e.g. 5 year – the standard in many life tables) age categories. They demonstrated that age-at-death estimation techniques with less than 90% accuracy result in an unacceptably high error rates of demographic estimates. Bocquet-Appel and Masset (1982) proposed the use of age-at-death ratios as a means of overcoming, or at the very least reducing, the error associated with age-at-death estimation. They introduced the D5-14/D20+ ratio: the ratio of juveniles to adults, as a resilient and accurate estimator of population dynamics. Whilst it is not entirely clear why they selected these age groups ("*After a few trials, we selected a proportion that we could calculate without undue risk of error...*" p.326), they achieved strong correlations (most in excess of $r^2=0.9$) between their ratio and various demographic parameters, including life expectancy at birth, birth rate and mortality rate, using polynomial regression based on historical life table data. However, such correlations are hardly surprising when we consider that high order polynomial regression overfits the curve to the data. Further, they did not provide access or references to the life tables used, so it is not possible to re-test their analyses or evaluate the tables for the type of circularity observed by Weiss and Wobst (1973). Notwithstanding, Bocquet-Appel and Masset's (1982) '*Farewell to Paleodemography*' reinvigorated the discussion, and indeed controversy, surrounding palaeodemographic methods.

The response to the paper was significant. Van Gerven and Armelagos (1983) stated that Bocquet-Appel and Masset's argument to bid farewell to palaeodemography was exaggerated, given the problems they raised. Specifically, Van Gerven and Armelagos (1983) argued that skeletal samples are not merely a reflection of the reference population, demonstrated by differences between a Nubian sample and the Todd reference collection (a point later reiterated by Buikstra and Konigsberg (1985)). They were more optimistic regarding age-at-death estimation and suggested that Bocquet-Appel and Masset's theoretical concerns were not empirically demonstrated. Finally, they criticised the exclusion of infants due to the sensitivity and importance of this age group. Buikstra and Konigsberg (1985) described the criticisms as extreme and, in addition to the points made by Van Gerven and Armelagos (1983), argued that age estimation varies by population by only a minimal degree, and that bioarchaeologists are wholly aware of the limitations of the field, and seek to address such limitations through methodological improvements and analytical approaches. They concluded that, while problems persist and require attention, palaeodemography remains a promising field. Konigsberg and Frankenberg (1994) similarly argued that the criticisms of palaeodemography had in fact strengthened the discipline, but that substantial work lay ahead to improve the accuracy of methods.

In contrast to other responses, the demographers Piontek and Weber (1990) argued that Bocquet-Appel and Masset's (1982) objections didn't go far enough, stating that palaeodemography operates under "*an erroneous conviction that palaeodemography can be treated as demography of prehistoric populations*" (p.71), but that their suggestion the palaeodemography should be farewelled is unjustified. They echoed earlier views of Petersen et al. (1975), that before proceeding with technological improvements in palaeodemography researchers should first evaluate biological, cultural and ecological evolution, and that a failure to do so has led to scepticism and erroneous interpretations in the field. If methodological improvements could be made, they believed that palaeodemography could make a significant contribution to our understanding of biological and cultural adaptation and resilience.

Bocquet-Appel and Masset (1996) revisited the core points of their earlier paper, expanding the suite of demographic measures (again using polynomial regression and life tables), reinforcing their criticisms of age-at-death distribution estimates, and suggesting average age-at-death as a more robust estimate which is reasonably representative of the age-at-death distribution. While the work of Bocquet-Appel and Masset (1982, 1996) was controversial and drew a substantial response from bioarchaeologists and demographers, it undoubtedly turned the attention of many to fleshing out and addressing the issues raised, as well as applying greater scrutiny to the discipline in general. Konigsberg and Frankenberg (2002) criticised some researchers in the field for being too adversarial, observing "*the emphasis in paleodemography should be on "we," not "me," "I," "one," or "us" (as vs. "them"). There have been too many fractious statements made concerning paleodemography (Bocquet-Appel and Masset, 1982, 1996; Petersen, 1975), and rarely do these comments provide suggestions on how to improve the field.*" (p.308). They advocated collaborative and multidisciplinary approaches.

2.4.3. Persistent Issues

Age-at-death estimation techniques remain far from perfect, but significant work has been undertaken to identify new (Cave and Oxenham, 2016; Couoh, 2017; Lanteri et al., 2018), and fine tune existing (AlQahtani et al., 2014; Savall et al., 2016; Wittwer-Backofen et al., 2008), methods of estimating individual age, as well as approaches to modelling the age-at-death distribution (discussed in greater detail below). The latter, in particular, along with the use of age-at-death categories that minimise age-estimation error, have overcome some of the limitations of skeletal data. This leaves two broad issues: assumptions of stability and stationarity, and the problem of underrepresentation.

a) Stability and Stationarity

The assumed stability and stationarity of life tables methods were recognised as problematic early on in the history of palaeodemography (Angel, 1969; Moore et al., 1975), but stationarity became a more prominent matter in the 1980s. Corruccini et al. (1989) noted that model life tables do not necessarily represent real populations, particularly in regard to stability. Importantly, they note:

> *When inferring fertility from mortality, the theoretical underpinning is the stable model life table. The incorporated stability assumption allows life tables to be computer generated by balancing fertility and mortality rates (hence creating a strong correlation) such that no growth or small, constant growth occurs. Thus the negative relation between fertility and relative adult mortality is automatic in creating stable models; as longevity increases, fertility must decline mathematically to keep resulting model populations from changing. In other words, in stable or stationary closed model life tables, the predictive correlation between fertility and mortality is a fixed feature, neither a necessarily real biological feature nor a generalization justifying fertility estimation from real population data.* (Corruccini et al., 1989: p.612).

Assumed stability was regarded by many to be less problematic, including Milner et al. (2007) who dismissed the problem of stable populations stating that stability is usually resumed after demographic disturbances.

In contrast, the issue of assumed stationarity has been recognised as a prevailing one. Sattenspiel and Harpending (1983) demonstrated the impacts of assuming stationarity in the common palaeodemographic practice of estimating life expectancy at birth from mean age-at-death. Using census data for non-stationary populations (which, they note, most real populations are), they showed that mean age-at-death was more an indicator of birth rate than of life expectancy. Only for stationary population data (e.g. life table data) did they find mean age-at-death and life expectancy to be the same. Their re-evaluations of previously reported palaeodemographic analyses, including those by Angel (1972b) and Green et al. (1974), highlighted the misinterpretations that may result from using mean-age-at-death to estimate life expectancy, and Sattenspiel and Harpending (1983) remarked that "*conclusions about the general level of mortality of a skeletal population derived from mean age at death are unreliable and meaningless*." (p.495). Horowitz et al. (1988) agreed with the assertion that life expectancy cannot readily be calculated from age-at-death, but disagreed that mean age-at-death was an inverse of birth rate, using Coale and Demeny life tables to illustrate their point. They suggested that focus should not shift away from life table methods, but rather that multiple approaches should be integrated to provide as much information as possible. Johansson and Horowitz (1986) evaluated the influence of growth rate on life table methods. They reported that when a population is growing but is assumed to be stationary, the mean age-at-death will be estimated to be lower than the actual. They concluded that this assumption has likely resulted in "*distorted reconstructions of the demographic history of human populations in transition to agriculture*." (p.249). These concerns pertaining to stationarity have been echoed by many over the years (Gage, 1985; Milner et al., 2007; Wood et al., 1992).

b) Underenumeration and Representativeness

Guy et al. (1997) reported rates per 1000 births of infant mortality based on historical data and primate infant mortality rates from a number of studies and stated that "*[i]n almost all living creatures…a high infant mortality is the rule*" (p.221). Acknowledging the seeming prevalence of infant underrepresentation in skeletal samples, Guy et al. (1997) examined infant taphonomy and differential preservation as contributors. They discussed the composition of infant bone, noting that it undergoes low mineralisation and irregular mineral distribution, both of which (they believed) would make it more susceptible to decomposition. Turning to the archaeological evidence, they argued low proportions of infants and juveniles for several sites reinforced the issue of underrepresentation. They concluded that infant preservation bias is such a prevalent issue that palaeodemographic "*calculations of life expectancy at birth…are considered illegitimate*" (p.227) and that "*[p]alaeodemography can expect a bright future if only it becomes aware of its restrictions*."

(p.227). However, their study conflates the proportion of infants born that die in the first year of life, with deaths that occur in the first year of life as a proportion of all deaths at all ages. The two measures are very different, and we should not expect that the proportions will be the same or even correlated. Furthermore, they failed to explore potentially favourable conditions for preservation. Pokines and De La Paz (2016) found that that not only preservation but archaeological recovery, in the form of mesh size, contributed significantly to infant underenumeration, with the largest mesh size in the study, 6.4mm, resulting in a 63.2% loss of remains and 1.0mm mesh resulting in only a 0.2% loss.

Gordon and Buikstra (1981) took an experimental approach to the issue, reporting a significant correlation between soil pH level and bone preservation in both adults and subadults. There was more variability in the subadult response to pH, but this was believed to be due to the wide range in bone density in subadults, which encompasses individuals age 0-14.9 years (Gordon and Buikstra, 1981). They found that preservation declined more rapidly for subadults than adults, and reiterated concerns for infant underenumeration. Djurić et al. (2011) reported similar results when they evaluated a church cemetery in northern Serbia to identify the degree to poorly preservation and underrepresentation. The minimum number of individuals at the site was 951, with 327 being subadults. A subsample of 155 subadults with good contextual information were identified for analysis. They found the skeletal remains belonging to individuals aged 0-3 years were underrepresented, likely due to small size. They also determined additional intrinsic factors, such as bone mineral density and structure, caused subadult underrepresentation. In contrast, Stojanowski et al. (2002) found no age or sex specific differences in preservation, but determined vertical depth of burial was a significant predictor. Gowland and Chamberlain (2002) used a Bayesian approach to re-estimate age for over 400 infants from Roman Britain sites, and found that the previously identified peak in neonatal deaths (interpreted as indicating infanticide) was an artefact of age estimation procedures used.

At the other end of the spectrum, Willey and Mann (1986) provided evidence for elderly under-ageing or underenumeration at a site in South Dakota. They believed that an elderly woman from Crow Creek Village was the most elderly individual amongst 2000 skeletons in the region. The burial context indicated differential mortuary treatment of the elderly and, in addition to the widely acknowledged inaccuracy of elderly age-estimation, Willey and Mann (1986) saw this as impetus to consider the impacts of elderly underenumeration and under-ageing. Using data from two samples from South Dakota, they simulated a range of elderly underenumeration and under-ageing scenarios and found that while under-ageing had a relatively limited impact on the age-at-death distribution, underenumeration had serious ramifications.

Walker et al. (1988) sought to evaluate age and sex biases in skeletal preservation by studying skeletal remains from a 19th century cemetery site in California, with accompanying historical records. They found minimal differences in sex ratios, but age bias was determined to be a significant factor. Both infants and the elderly were under-represented relative to young and middle aged adults. They reported that 32% of the individuals interred were under the age of 18 years based on historical records, but only 6% of the skeletal remains belonged to this age group. Similarly, individuals over 45 years of age represented 36% of those interred based on historical records, and only 4% of the skeletal remains. Interestingly, this indicated that preservational bias may impact infants and the elderly to a similar degree. Hoppa and Saunders (1998) similarly evaluated the impacts of poor representation of skeletal samples compared to their parent populations. They simulated various scenarios of bias by removing individuals from the samples and undertaking bootstrapping procedures, using three well-documented 19th century Canadian cemetery samples as the basis. They compared the effects of bias on the estimated mean age-at-death and found that samples with under 100 individuals presented a high degree of variability in the age-at-death profile when compared to their parent population. They noted that sample bias was of particular concern, as both infant and elderly underenumeration was found to skew estimates of mean age-at-death. Their concerns added to those of Sattenspiel and Harpending (1983) and they concluded mean age-at-death was a poor indicator of premature mortality and that representativeness is the greatest hurdle faced by palaeodemography.

Paine and Harpending (1998) evaluated the impact of infant and elderly underenumeration on the estimation of fertility rates. For the elderly, they used known rates of age-estimate bias (noting that this does not acknowledge regional differences in such bias) and for infants they removed 50% of the sample to replicate the impacts of commensurate underenumeration. They then applied Paine's (1989) model life table fitting procedure and examined the impact on crude birth rate estimates. In contrast to Willey and Mann (1986), Paine and Harpending (1998) reported that elderly underenumeration inflated crude birth rate estimates significantly, by 10-20%, but that as such ageing biases are known to researchers it is possible to account for this. Infant underenumeration was found to decrease crude birth rate estimates by 20-25%, but they noted that it is not possible to compensate for this error due to the inability to accurately estimate the degree to which infants are underrepresented in an archaeological sample. As such, they concluded that infant underrepresentation was a more significant issue than elderly underrepresentation for palaeodemography.

The broader question of how well cemetery populations represent living populations from which they derive has also proved difficult to resolve. Many have commented on the issue (Brothwell, 1972; Moore et al., 1975; Wood et al., 1992), but it has been difficult to evaluate and to quantify. Contributing factors include differential preservation, sample size, socioeconomic status and differential burial practices, as well as sampling bias.

2.4.4. Current Methods

Current methods have sought to address the limitations of bioarchaeological data, particularly scarce data, underrepresentation of infants and the elderly, and inability accurately estimate age, and the issues with model life table methods, specifically assumptions of stationarity and stability, and the requirement for large datasets. While traditional bioarchaeological methods have continued to be popular due to the multitude of research questions they can inform both about the individual and the population, alternative approaches including modelling of the age-at-death distribution (which allows for palaeodemographic analyses, but imposes some limitations on integrating individual data such as pathology, burial context, etc.) and dates as data techniques (which solely aim to provide estimates of population growth) have also gained momentum.

a) Age-at-death Ratios as Palaeodemographic Estimators

Age-at-death ratios seek to use a proportion of the total deceased population to estimate population dynamics. The chief advantage of age-at-death ratios is that they are not greatly affected by individual age-at-death estimation errors, in that such approaches can combine individuals into large age-range groups. Such ratios also minimise age estimation error to certain individuals within range of the ratio demarcation points (e.g. for the ratio d5-14/d20+, the age estimation error is minimised to individuals within the error range for 5 years, 14 years and 20 years). Bocquet-Appel and Masset (1982) proposed the first age-at-death ratio (d5-14/d20+) for estimating population dynamics, but, later amended and refined this, presenting the $_{15}P_5$ ratio (or d5-19/d5+) (Bocquet-Appel (2002)). The latter ratio (or juvenility index) was more broadly applied both by Bocquet-Appel himself (Bocquet-Appel, 2009; Bocquet-Appel and Naji, 2006; Bocquet-Appel, 2002) and others (Downey et al., 2014; Hershkovitz and Gopher, 2008; Kohler et al., 2008; Kohler and Reese, 2014). Buikstra et al. (1986) developed the D30+/D5+ using Coale and Demeny's model life tables, apparently missing the caution by Weiss and Wobst (1973) that variables within these tables are not independent. Since this is the case, we would expect age-at-death ratios derived from these tables to correlate strongly with attributes of the very population used to calculate them. Jackes (2011) used a combination of the Bocquet-Appel and Masset (1982) original juvenility index and mean childhood mortality (MCM) (the mean age-at-death between 5 and 20 years of age) to estimate fertility. To test the accuracy of her methods she used quadratic regression of model life tables, finding them predictive of fertility.

Corruccini et al. (1989) evaluated the accuracy of estimating fertility from juvenile age-at-death ratios on a cemetery with historical records. They reported a standard error of between 0.24% and 0.61% when using the Bocquet-Appel and Masset (1982) and Buikstra et al. (1986) juvenile ratios to calculate birth rate, compared to the historically recorded crude birth rate of 3.7%. Paine and Harpending (1996) examined the accuracy of palaeodemographic estimators of fertility, using simulated age-at-death distributions and a cemetery sample with known birth rates. They used the juvenile ratios proposed by Bocquet-Appel and Masset (1982) and Buikstra and Konigsberg (1985), as well as Paine's (1989) model life table fitting procedure. They found both the juvenile ratios to be problematic for small samples, which they noted could particularly be an issue with declining populations.

Age-at-death ratios, particularly the $_{15}P_5$ and d30+/d5+ ratios, continue to be a cornerstone of palaeodemographic studies. Their benefits are that they are simple to use and provide estimates which in many cases reflect the expected (based on other archaeological sources) trend. They can be used for small samples (noting the implications for accuracy) and are suitable for those with varying degrees of preservation and potentially challenges in estimating age-at-death accurately for all individuals in the sample. However, in both cases the exclusion of infants come as at a cost, as we may anticipate that infants and young children are the age groups most sensitive to changes in fertility and growth.

b) Palaeodemographic Modelling

While this thesis is concerned with the estimation of population dynamics such as fertility and population growth, methods for estimating the age-at-death distribution are also of great value to palaeodemography. A number of researchers have used modelling to estimate the age-at-death distribution, recognising patterns in the mammal and human mortality curve. Gage (1988) used a five-parameter competing hazard model, originally developed for animal populations, and based on subadult mortality, decreasing risk of subadult mortality with increasing age, and increasing risk of adult mortality with age. The method requires inputs of survivorship rates, age-specific death rates or an age structure. He found that the model compared well with life tables for Late Woodland, Nubian and Yanomama populations. Konigsberg and Frankenberg (1992, 2002) proposed and then refined Bayesian methods for modelling age-at-death distributions. They reported issues with the application of iterated age length key (IALK) methods, which use a reference age-at-death structure to develop maximum likelihood estimates for a target population, by Bocquet-Appel and Bacro (1997), and Jackes (2000), though Jackes (2003) responded to their criticism of her work stating that she had oversimplified the methods under editor guidance. Broadly similar and iterative approaches have been proposed by Wood et al. (2002) and Bonneuil (2005), Caussinus et al. (2010) and Sasaki and Kondo (2016).

In terms of progressing the field of palaeodemography, there has been much work devoted to modelling the age-at-death distribution. These methods provide sophisticated solutions to the counterintuitively problematic matter of understanding mortality from the dead. Why then have these methods seen such limited application (Gage and DeWitte, 2009)? For bioarchaeologists whose training is focussed more so on anatomy and physiology, practical techniques, and empirical research, such theoretically focussed and statistically-based methods are seemingly complex and cumbersome. As observed by Buikstra and Konigsberg (1985) "*We are dealing with a composite field* *where forensic anthropology, physical anthropology, archeology, and demography interface. It would be surprising if tensions did not develop…*" (p.316). It has indeed proven difficult to reconcile the theory and methods of demographers, with the wants, skills, and data of bioarchaeologists. More importantly, however, there are some notable limitations to these methods. In many cases, modelling the age-at-death distribution relies on selection of a suitable proxy distribution, often based on historical or ethnographic data; the suitability of these proxies is inherently unverifiable. Any subsequent calculation of population dynamics such as fertility or growth rate is then potentially undermined by the reference selection process. Modelling of the age-at-death distribution imposes some limitations on the integration of individual data, including pathology and status, into further analyses as it only provides the distribution, not individual estimates of age-at-death. Noting these limitations, such methods appear to provide the most accurate approach to estimation of the age-at-death distribution.

c) Non-bioarchaeological Approaches to Palaeodemography

Turning away from bioarchaeological methods, Nelson (1981) used ethnographic research to test the hypothesis that cooking vessel capacity indicated household size, based on observations from a Highland Mayan village. He concluded that significant variation existed as a result of, not only household size, but socio-economic status. Stiner et al. (1999) examined faunal remains from Italy and Israel for changes in frequencies of small prey. They found that the species consumed changed dramatically between the Upper Palaeolithic and Epi-Palaeolithic. Further, the mean size of slow-growing prey decreased over a period of time that included climate and environmental oscillations, therefore the authors concluded that this was driven by hunting. They suggested that pulses in species representation and mean size of small prey indicated dips and troughs in population growth.

Dates as data techniques, or demographic temporal frequency analyses (dTFA), initially appeared in the 1980s as a method of estimating population growth, with work by Rick (1987) which used radiocarbon dates from coastal and inland sites in Peru to indicate occupation and population size. Such methods have become significantly more popular in the past two decades, with work being undertaken in the Americas (Axtell et al., 2002; Hill et al., 2004), Europe (Collard et al., 2010; Shennan et al., 2013; Turney et al., 2006; Turney and Brown, 2007), Australia (Dortch and Smith, 2001; Johnson and Brook, 2011; Smith et al., 2008; Williams, 2013; Williams et al., 2015), New

Zealand (Dye and Komori, 1992) and on a global-scale (Chaput and Gajewski, 2016; Goldewijk et al., 2011), and resultant interpretations ranging from the impacts of agriculture to population responses to climate change. The methods have seen significant refinement with various adjustments to account for taphonomic and other sources of bias. Of particular interest to this thesis is the study by Downey et al. (2014) that compared the results of summed calibrated radiocarbon date probability distribution (SCDPD) analysis and the ${}_{15}P_5$ juvenility index, in order to validate the former method. They included 67 cemetery datasets from Bocquet-Appel (2008a) and additional samples from other published sources, for a total of 212 samples. Some 8023 radiocarbon dates were analysed with controls for settlement size. The juvenility indices for many sites were found to have broad confidence ranges, however, SCDPD reinforced several trends with the correlation between the juvenility index and SCDPD being r=0.855 unscaled and 0.883 scaled. The agreement between the two methods, which derived from different sources of evidence, are indicative of a valid pattern. They concluded that agriculture had introduced demographic instability and that demographic collapse occurred across Europe around 1200 years after the spread of agriculture, shortly followed by recovery and population growth. García et al. (2015) undertook a similarly multi-faceted approach to the palaeodemography of Late Holocene hunter-gatherer populations in Patagonia, but were limited by small skeletal samples.

Dates-as-data techniques have not been accepted as credible by all in the field. Attenbrow and Hiscock (2015) took aim at the application of such methods in the Australian context, arguing that there has been no demonstrated relationship between the number of radiocarbon dates and number of people. They noted bias in radiocarbon dates, both due to differences in preservation and research goals, and the complexities associated with interpreting behaviour and activity from charcoal evidence. French and Collins (2015) compared results of a variety of palaeodemographic methods for an upper Palaeolithic site in southwestern France and, in contrast to Shennan et al. (2013), found the results of the multiple population growth indicators (including number of archaeological sites, site size, and occupation intensity) to be conflicting. They noted that "*there still remains a need for the empirical assessment of archaeological data in the investigation of palaeodemography*" (p.204).

Another source of controversy is work by Zahid et al. (2016) which reported on the summed probability distribution (SPD) for sites in Wyoming and Colorado between 6000 and 13000 years

BP. They found long term exponential growth, with medium-term (a few hundred to a thousand years in length) fluctuations. They calculated a long-term growth rate of 0.04% per annum and found this to be similar to growth rate estimates (also based on dTFA methods) during the same period in other parts of the world, despite different subsistence strategies in some regions. They concluded that this indicates that agriculture is not directly linked to an increase in the long-term annual rate of population growth, and that global climate and inherent biological factors may have greater effects on growth. But the calculation of an average, per annum growth rate based on the difference between points in time is underpinned by the assumption that growth is constant and exponential, and does not account for periods of decline. While the results reported by Zahid et al. (2016) are not erroneous (as the rate they report is indeed the annual average over the course of several thousands of years), their interpretations are flawed and suggest a lack of understanding of the nature of population dynamics. This study highlights the need for care when interpreting dTFA results.

dTFA only seeks to evaluate population growth, and therefore does not, in itself, provide a holistic tool for evaluating palaeodemography. For its intended purpose, it appears to provide an accurate estimate, but such results may prove difficult to integrate with other data sources particularly those of high resolution (e.g. pathological and cultural data). Similar to age-at-death distribution modelling, it also removes the potential to examine information about individuals from the population of interest. dTFA relies on relatively large numbers of radiocarbon dates, which can be problematic particularly for regions or time periods with limited data.

2.5. Current Palaeodemographic Methodologies

As outlined above, not all current palaeodemographic methods have the same goals. Age-at-death ratios strive to provide proxy information for the calculation of population dynamics, such as fertility and growth rate. Modelling of the age-at-death distribution seeks to tell us more about survivorship, life expectancy, and other matters of mortality. The most popular of non-bioarchaeological methods, dTFA, aims to estimate population growth more broadly. Even noting the limited scope of what each method seeks to inform, there are further limitations to their accuracy and applicability. Furthermore, while no single method can inform all palaeodemographic questions, the ability to integrate analyses and results provides the greatest opportunity for insights into past populations, and such this capacity for integration should be a priority.

3. Applying Bioarchaeological Palaeodemographic Methods

To understand the value and contribution of palaeodemography, it is essential to consider the depth and breadth of research that it has been applied to. Here, applications of palaeodemographic techniques to skeletal samples from across the globe are considered, identifying inter- and intra-regional patterns and divergences in population dynamics. Evidence has been found in support of the Neolithic Demographic Transition, in particular, in North America, Europe, the Middle East, and Southeast Asia. The concentration of research in particular areas reflects both the availability and accessibility of skeletal remains, the suitability of available palaeodemographic tools to evaluate them, and the research goals of those undertaking the research. In Australia, for example, research on skeletal remains is highly limited due to the significance of Aboriginal and Torres Strait Islander burials to living populations. In Southeast Asia, interpretations have been limited by the unavailability of existing palaeodemographic tools suitable to the remains identified. In North America, research has focussed on the known phenomenon of the Hohokam disappearance, and more broadly, population collapse in the southwest. As such, palaeodemographic research in some parts of the world has been prolific, and less so in others. This has resulted in a set of palaeodemographic methodologies that are not well suited to all regions and periods. Due to its prominence, the Neolithic Demographic Transition is discussed in its own section below. The discussion is limited to bioarchaeologically based studies, since they are the basis of this thesis. The aim of this chapter is to demonstrate how the application of methods identifies different issues to strictly methodological studies, to show where gaps exist in the temporal and geographic application of methods, and highlight what this means for the applicability and accuracy of methods to neglected regions of the world and periods of time. The focus of this thesis is on anatomically modern humans, and therefore reference to studies of other hominins and other animals is limited.

3.1. Middle East

The Middle East has long been an area of great interest to archaeologists due to its association with the earliest evidence for agriculture, the Mesopotamian civilisation and the birth of a number of religions. Angel (1972b) examined the ecology and demography of the Eastern Mediterranean, discussing the impacts of each on the other (e.g. changes of climate on demography, impacts of human deforestation on ecology). Angel (1972b) used a combination of historical sources and mathematical models to develop estimates of population size. Parturition scarring (not associated with childbirth after all as summarised by McFadden and Oxenham (2017)) was used to estimate birth rates and age-at-death was estimated using "*all available criteria*" (p.97). He also examined palaeopathology, including porotic hyperostosis which he believed to be largely indicative of malarial anaemia, as a result of farmers occupying land near open water sources. Angel (1972b) reported a rate of natural increase of 0.3-0.4% annually in the Late Bronze Age, with an equilibrium achieved in the Hellenistic period. In the Byzantine period, Angel (1972b) found decreased longevity to be indicative of population decline. He also noted that the mutual feedback system of ecology and population dynamics is subtle and slow.

Green et al. (1974) calculated composite life tables based on skeletal remains from a cemetery on the island of Meinarti in Nubia, representing several distinct time periods. They aimed to identify whether sex or age were determinants of status, based on whether individuals were buried within or outside a burial superstructure. Using the life table method, they reasoned that both age and sex had some relationship to status, but that an additional unknown, biological factor associated with average age-at-death seemed to be more influential. Additionally, they concluded that the population fertility decreased in 1100-1150AD when compared to preceding years, based on low juvenile mortality.

Van Gerven et al. (1981) investigated the demography of a Nubian population known as Batn el Hajar. The site dated to approximately 1400AD: the terminal Christian period in Nubia. Some 214 individuals were recovered from an island cemetery and 185 individuals from a mainland cemetery, with ages from seven foetal months to over 51 years being represented. Van Gerven et al. (1981) created a life table for the population, examining the usual parameters such as life expectancy and mortality, and sex-based differences and evaluated mortality in the context of cribra orbitalia, finding a high correlation between these lesions and mortality in subadults and the elderly. They concluded that there had been a decrease in subadult mortality from earlier Nubian Christian sites to the Batn el Hajar population, which they suggest resulted from improvements in health.

Rathbun (1982) examined the palaeodemography of nine archaeological sites in Iran and Iraq. Sex and age were estimated for individuals at each site, however, Rathbun (1982) noted that due to fragmentation the latter could only be estimated in categories rather than specific ages. He concluded that the populations studied were young and relatively stable, and that females experienced shorter life expectancy than males. Based on average age-at-death, Rathbun (1982) suggested there was little improvement in health with the intensification of agriculture during this period.

Further work from the Middle East is discussed under the NDT section of this chapter. Notably, much of the work in the Middle East has relied on methods that have since been largely abandoned, and there has been little discussion of the issues (such as underrepresentation) and assumptions (for example stationarity) that underpin the methods used. Outside of the NDT, both isolated and regional studies have been undertaken but no overarching trend has been discussed. Today, archaeological work in the region is limited due to political unrest and the destruction of many sites.

3.2. Europe

In Europe, diverse palaeodemographic research has been undertaken, spanning the Pleistocene (Bermúdez de Castro and Nicolás, 1997) through to 18th century cemetery populations. Again, interests have focussed on the NDT, but studies outside of this have provide interesting insights into site-specific and regional population dynamics.

Jackes (1988) examined demographic changes during the Mesolithic-Neolithic transition in Portugal. She evaluated evidence from six archaeological sites (two Mesolithic and four Neolithic), with a total of 176 Mesolithic individuals and 314 Neolithic individuals. Jackes (1988) calculated mean child mortality and, for the largest of the sites (Casa da Moura) a life table. She concluded that the Mesolithic was a period of population stability and relatively low mortality, while the Neolithic, conversely, was one of high fertility and high mortality. While the sample size from Casa da Moura was relatively suitable for the life table method applied, Jackes (1988) noted herself that it was possible that the population was neither stable nor stationary and that this would impact the interpretations made from the age-at-death distribution. More weight was placed on the results of the child mortality rates.

Macchiarelli and Salvadei (1994) provided evidence for selective funerary practices in Middle-Tyrrhenian Italy. In a sample of 545 individuals, they found the palaeodemographic measures deviated from a "*realistic protohistoric demographic model*" (p.37). They found just 4 individuals aged 0-1 years, indicating severe infant underrepresentation which they believed to indicate differential burial practices. They also found a greater number of females in the young adult age group, and suggested this may be due to a combination of maternal mortality and the cremation of young adult and adult males. They highlighted the impacts of cultural practices on the burial distribution.

Lynnerup (1996) reported on the palaeodemography of a Greenland Norse population. Population size was calculated using two different approaches: a mathematical model and estimation of the total number of interred individuals in Norse graveyards. He found both methodologies produced similar results and estimated a peak population of 2250, with a cumulative population over the entire settlement period of 25,000. Lynnerup (1996) suggested that emigration to Iceland may have caused the population to decline. However, the approach of Lynnerup (1996) to burial data involved significant extrapolation of burial density from excavations to unexcavated burial sites.

Alesan et al. (1999) evaluated the demography of an Iron Age necropolis in Majorca. The skeletal sample contained 285 individuals (93 subadults and 192 adults). They constructed an abridged life table for comparison with the Coale and Demeny life tables, following the methods of Weiss and Wobst (1973). They reported infant underenumeration for the site, with infants aged 0-5 being underrepresented, and suggested a range of taphonomic factors as likely implicated. They calculated the Bocquet-Appel and Masset D5-14/D20+ ratio and found the results to be consistent with high infant mortality and low life expectancy.

Zarina (2006) evaluated skeletal remains for 3304 individuals, from Latvian sites dating between the 7th and 18th century and employed a standard life table approach to palaeodemography. Evidence for maternal mortality was identified, with life expectancy at age 20 being approximately 6 years shorter in females than males. Overall life expectancy was reported to increase over time, with a decrease in crude mortality.

Fernández-Crespo and de-La-Rua (2015) evaluated the demographic evidence of selective burial practices at a megalithic site in northern Spain, dating to 3700-1500BCE. Some 248 individuals from the megalithic graves were examined: the authors found infants to be underrepresented, with only 3 individuals aged under one year old in the sample. Subadults aged 1-4 years also appeared in low frequencies (n=7). Fernández-Crespo and de-La-Rua (2015) suggested they did not find the differential preservation hypothesis of infant underenumeration compelling, as they believed dental elements and long bones diaphyses should preserve well, and that there is not a large enough difference in size and composition of some bones in subadults aged 0-4 years and those aged 5-14 years. They also found an overrepresentation of individuals aged 5-14 years but interpreted this to indicate adult underrepresentation. They concluded both infant and adult underrepresentation was the result of differential burial rites, where infants were not considered full members of the community, and adults experienced socio-cultural discrimination.

Bermúdez de Castro and Nicolás (1997) reported on the application of palaeodemography to a Pleistocene hominin sample from Sima de los Huesos (300-200kya). They identified 32 individuals for inclusion and estimated sex and age. There were low numbers of infants, but due to the presence of some infant remains the authors argued against broad spectrum differential preservation and suggested scavenger activity as a potential alternative. 52.6% of the sample were adolescents based on the modern definition, though it is notable that they reported the presence of individuals up to 30-35 years in age. They also examined the number of individuals of childbearing age in order to crudely estimate age-based birth rates. Bocquet-Appel and Arsuaga (1999) reanalysed the sample, along with a younger sample (~130kya) from Krapina, Croatia. They evaluated the age-at-death distribution to determine whether it reflected an attritional or catastrophic mortality model, finding evidence in favour of the latter.

Palaeodemographic research in Europe has increased in rigour over time, with greater awareness of potential sources of underrepresentation. Broadly, infant underrepresentation has been observed at many sites (though the cause is argued to vary from preservation to differential burial) and this makes current bioarchaeological methods including the ${}_{15}P_5$ ratio well suited to the region.

3.3. Africa

Limited studies have been undertaken in Africa. Henneberg and Steyn (1994) provided a palaeodemographic account of the K2 and Mapungubwe populations in South Africa, dating to approximately 970-1200 AD. A total of 109 individuals (K2 n=97, Mapungubwe n=12) were recovered from the sites, with 81 being subadults. They concluded that the site represented either specific burial practices, high subadult mortality, or significant population growth produced such a distribution. Henneberg and Steyn (1994) constructed a life table on the basis of 2.5% population growth, and found this to account for the observed age-at-death structure. Morongwa and Steyn (2004) similarly reported high infant mortality for an early Iron Age site in Botswana (n=84), and L'abbe (2005) found high infant mortality and good juvenile survivorship for a rural 20th century site in Venda, South Africa. Pfeiffer et al. (2014) reported on a Later Stone Age (LSA) sample from South Africa, consisting of 246 individuals. They estimated age for each individual and found in the young adult category an overrepresentation of females, with 26 women and 14 men. They believed that maternal mortality was a likely cause of the disproportionate number of young female deaths. Martinez et al. (2004) undertook a qualitative palaeodemographic analysis of *Homo habilis* in East Africa, noting the limitations of sample size (n=26). The survivorship curve was compared to those of other human ancestors, including *Homo heidelbergensis* and *Homo neanderthalensis* (both also impacted by small samples), and all three were found to represent similar mortality profiles.

3.4. Americas

In North America a significant amount of research has been devoted to the population dynamics of indigenous Americans over three pre-European contact, periods: the Archaic period (from 8000-1000BCE), the Woodland period (1000BCE-1000CE) and the Mississippian period (1000CE to European contact). An early example of such studies is Blakely (1971), who constructed and compared mortality profiles for four indigenous American populations with significant sample sizes (ranging n=101 to n=844), dating to three periods: Archaic, Middle Woodland, and Middle Mississippian. He evaluated sex and age-at-death frequencies in 10-year brackets for each population and compared the distributions. He found the sex ratios to be seemingly accurate, ranging from 50% to 53%, which he considered an indicator of good representation. He noted that there were significantly higher mortality rates in females aged 20-29 years than in males and suggested two possible interpretations: the females experienced higher mortality due to childbirth; or that males in this age group were more likely to be involved in, and to die during, activities away from home. Blakely (1971) provided other insights based on changes in mortality frequencies, for example, he suggested that an increase in mortality between 3 and 4 years of age may indicate the hazards of weaning, or potentially multiparity. The evidence of maternal and weaning associated mortality was corroborated by Clarke (1977) who reported very similar trends based on 1724 individuals from Late Woodland and Middle Mississippian populations. Further support came from Owsley and Bass (1979) who observed 41% of deaths occurred in the first year of life and a significantly higher mortality rate in females aged 15-19 years in their sample, and Owsley and Bradtmiller (1983) who reported high infant mortality and greater female than male deaths between the ages of 15 and 30 years (with the greatest difference between 15 and 19 years of age) in Arikara period villages in South Dakota. Arriaza et al. (1988) reported on maternal mortality amongst Pre-Columbian indigenous Chileans. Some 187 mummified females were studied for evidence of childbirth-related complications that may have ultimately resulted in death, including foetal remains within the uterus or pelvic cavity, separation of the pubic symphysis, evidence of placenta and umbilical cord, and uterine prolapse. They believed 14% (12/128) of females aged between 12 and 45 years (considered to be the childbearing years) had died during or as a result of childbirth.

The work by Lovejoy et al. (1977) on the Libben site in North America proved to be one of the most contentious applications of palaeodemography, and remains controversial to this day. In 1967 and 1968 the Libben site in Ohio was excavated, with radiocarbon analysis revealing dates of 800-1100AD (Lovejoy et al., 1977). In total, 1327 individuals were carefully excavated from the site, with age estimation identifying an age range of 16 weeks in utero to 70+ years. Lovejoy et al. (1977) produced an abridged life table for the Libben site and, considering the demographic parameters, determined it to be representative of a robust and successful population with low infant mortality. They noted that underenumeration of infants was unlikely the cause due to the care taken during excavation and the presence of very young infants in the sample. Further, for the Libben site to align with modern 'anthropological populations', underenumeration would have to be in the vicinity of 225 juveniles, which the authors believed to be unlikely. Howell (1982) revisited the palaeodemographic findings and argued that a population with the age-at-death distribution presented by Lovejoy et al. (1977) would see adults bear a significant workload, and where there would be very high rates of orphanage. Howell (1982) proposed two hypotheses: either the Libben site represents a far more difficult way of life than that observed in early ethnographic accounts, or the Libben sample has experienced some kind of bias in its composition.

Sciulli and Aument (1987) provided a palaeodemographic analysis of a terminal Late Archaic site: the Duff cemetery in north western Ohio. They used life table techniques as outlined by Weiss and Wobst (1973). They found that the age-at-death structure of the population was similar to other prehistoric populations including the Libben site. They reported a high rate of adult mortality, with 45% of the population dying between 15 and 45 years of age, and a comparatively lower rate of subadult mortality.

Duray (1996) evaluated dental enamel defects in the context of average age-at-death for the Libben site. He analysed 143 individuals for enamel defects and used the palaeodemographic analyses performed by Lovejoy et al. (1977). Duray (1996) found that individuals with enamel defects had a lower mean age-at-death than individuals without. He did not report any sex differences in frequencies and believed the earlier mortality to be the result of early childhood or even prenatal biological damage weakening the immune system.

Sutton (1988) raised concerns about much of the work to date in North America. He used ethnographic and archaeological evidence to argue that palaeodemographers had made erroneous assumptions about such sites in the past, including representativeness, stationarity, stability and consistency in burial deposition periods. He suggested that the active period of burial sites varied significantly by community, that the populations were not fully sedentary nor isolated, and that significant proportions of populations were likely placed in non-ossuary burials. These concerns were further illustrated by Mensforth (1990) who observed deviations in sex ratio and adult age distribution of a late hunter-gatherer population from Kentucky (n=354), which he believed to indicate sample bias. Additionally, Sciulli et al. (1996) provided a palaeodemographic account of an Eiden Phase (approximately 1100-1200AD) cemetery from the Pearson Complex in Ohio (n=475) and found the age-at-death distribution to be biased. They suggested that infants and the elderly were significantly underrepresented, but that this did not result from excavation or preservation biases: rather interment bias caused the skewed age-at-death distribution, with infants and the elderly being more likely to die whilst the population was mobilised during the winter. Milner et al. (1989) were more optimistic, comparing the age-at-death distribution for an archaeological skeletal series from Oneota to model age-at-death distributions from two modern "*traditional human societies*" (p.49), with different subsistence cultures: modern hunter-gatherers, and horticulturalists. The Oneota population was found to closely resemble the distribution of the Yanomamo, which the authors reported was consistent with previous interpretations.

Similar concerns have been raised for South America. Storey (1992) reported on the palaeodemography of a Pre-Columbian site in Copan, Honduras. Age-at-death and sex were estimated, and dental pathologies examined for 264 individuals belonging to a single occupation period; a subset of the broader skeletal sample which consisted of 600 individuals. She compared the age-at-death distribution for the sample with Coale and Demeny's model life table distributions and found that whilst it had significant subadult mortality, deaths between birth and 1 year of age deviated from the expected range. Storey (1992) suggested that infant underrepresentation may have caused the difference from the expected pattern. Similarly, Guraieb et al. (2015) evaluated the ratio of juveniles to adults and mean child mortality for a Late Holocene sample from Santa Cruz in Argentina. Based on comparison with other datasets, they suggested their samples experienced both infant and adult underrepresentation.

Kohler and Reese (2014) used the ${}_{15}P_5$ ratio to evaluate population changes in North America and found the evidence from skeletal samples supported the archaeological narrative of population decline pre-contact. McClelland (2015) observed the same trend, examining the palaeodemographic profile of a population in the Hohokam region of Southern Arizona. Using the life table method, McClelland (2015) concluded that population growth occurred through an increase in fertility in the Early Classic period and population declined via decreased fertility in the Late Classic period. Dates-as-data (dTFA) studies have reported the same pattern (Peros et al., 2010).

Research in the Americas has served to highlight the importance of cultural considerations in undertaking palaeodemographic studies. In particular, assumptions of sedentism for populations which were arguably mobile have been challenged based on the representativeness of skeletal samples, where more fragile individuals (infants and the elderly) are less common in cemeteries. Many early studies would benefit from re-analysis with improved methodologies and greater awareness of potential sources of bias and methodological flaws.

3.5. Australia

In Australia, bioarchaeological work has been limited due to the cultural significance of skeletal remains to living Aboriginal and Torres Strait Islander populations. Some skeletal studies have incorporated basic palaeodemographic profiles (e.g. Webb (1989)) but have not been subject to further analysis. Most population history research in Australia has utilised dTFA techniques (Dortch and Smith, 2001; Johnson and Brook, 2011; Smith et al., 2008; Williams, 2013; Williams et al., 2015) and mitogenomes (Tobler et al., 2017), but much remains unknown about the past population dynamics of the continent.

3.6. Asia and the Pacific

Work in Asia and the Pacific has been limited by the availability of suitable palaeodemographic tools. Nonetheless, a number of authors have applied existing methods to evaluate population dynamics in the region. Pietrusewsky (1974) applied the composite life table method to the site of Non Nok Tha in northeastern Thailand. Two distinct periods are represented at the site and Pietrusewsky (1974) reported that the earlier Neolithic-Bronze period experienced shorter life expectancy and higher juvenile mortality than the later Bronze period. Pietrusewsky and Douglas (2002) undertook a similar demographic analysis for Ban Chiang, finding very similar dynamics between the two groups. Pietrusewsky (1976) and Pietrusewsky et al. (1991) also provided life tables for archaeological populations from Papua New Guinea and the Marquesas, and Honokahua in Hawaii respectively.

Nagaoka and co-authors have undertaken several palaeodemographic analyses in Japan. Nagaoka et al. (2006) used data from a medieval Japanese population to create an abridged life-table, using the Siler competing-risk mortality model. The results estimated a life expectancy at birth of 24 years. This was compared with data from a Mesolithic-Neolithic Jomon population and a modern Edo population: the medieval population was found to have a life expectancy more similar to the Mesolithic-Neolithic period than the modern one. The authors noted that infants appeared to be underrepresented and that this may impact upon the results. Nagaoka et al. (2008) reanalysed the available demographic data for the Jomon period. They found that with improved techniques of estimating individual age and the age-at-death distribution, the life expectancy was greatly increased (from 16 years to 32 years life expectancy at the age of 15) and that a large portion of the population lived to 65 years or more. Nagaoka et al. (2013; 2016) identified further differences in mortality in sites from medieval Yuigahama-minami and early modern Okinawa. In all studies, longevity and the conditions that influence it are a key focus.

Kirch (1984) applied the life table method to skeletal samples from the Marquesas Islands, Tonga and Hawaii but was unable to contextualise the results due to unconfirmed chronologies for many sites. He argued that population dynamics in the Pacific Islands would follow a logistic curve due to the limited carrying capacity of each island. Kirch (1984) used Hawaii as an example of this, but quickly came under criticism by Clark (1988) and Sutton and Molloy (1989) who felt the model was outdated and that there was insufficient evidence to support it.

Numerous bioarchaeologists have recorded demographic data for samples throughout Asia and the Pacific and have undertaken preliminary analyses such as the ${}_{15}P_5$ ratio and mean child mortality, however, many have commented on the inability of the ${}_{15}P_5$ ratio to capture the large numbers of infants observed and have therefore questioned the validity of such measures in the Asia-Pacific context (Domett, 2004; Domett and Oxenham, 2011; Oxenham et al., 2008; Tayles, Halcrow, and Domett, 2007; Tayles, 1999).

3.7. Testing the Neolithic Demographic Transition (NDT) Hypothesis

The NDT, and specifically the population response to agriculture and sedentism, has been a core focus of modern palaeodemographic interest. Researchers have sought to identify the NDT signal in the Americas, Europe, the Middle East, and Asia. This work has been integrated with a range of archaeological and palaeopathological data to draw conclusions about the impact of agriculture on human populations. Broadly, the NDT has been associated with increased fertility and growth. In the Americas, Europe and the Middle East, a decline in health is also indicated, whilst in Southeast Asia the trends are much more complex.

In the Americas, Buikstra et al. (1986) evaluated skeletal collections from eight Woodland and Mississippian sites and found evidence for a shift in diet to high carbohydrate content at the same time as fertility increased, as indicated by the juvenile/adult ratio. From this they concluded that the population was responding to the change in subsistence. Bocquet-Appel and Naji (2006) used the 15P5 ratio to evaluate the NDT using published data from North America. They observed high variability in the response and small pre-NDT numbers. Nonetheless, the only sites with a juvenile-adult ratio over 0.3 occurred after the NDT, and there were many of them, indicative of high rates of population growth post-NDT. They noted that high growth could not have been maintained for long, and thus fertility must have been quickly counterbalanced by mortality, producing "*stationary equilibrium*" (p.348). Bocquet-Appel (2009) repeated his previous assertions that fertility must have been counterbalanced rapidly by mortality, as even growth of an additional single person per year would result in implausible growth over thousands of years. Kohler et al. (2008) identified evidence for the NDT in the North American Southwest. Based on birth rate estimates using the Bocquet-Appel (2002) $_{15}P_5$ method, they found that the transition occurred much later than the introduction of maize to the area, indicating the earliest maize use was by hunter-gatherers. Kohler and Reese (2014) continued the earlier work, again applying the $_{15}P_5$ method to samples from the NDT period in the North American Southwest. A total of 194 sites and 10,199 individuals were included in this study. They concluded that the NDT caused gradual, rather than rapid, growth in the Southwest. They found evidence for stabilisation, and possibly decline, after 1100CE, and rapid decline from 1300CE.

Bocquet-Appel (2002) used European cemetery data for populations that lived around the time of the NDT to estimate birth and growth rates. He observed an overall trend towards an increased ratio of juveniles to adults following the transition to agriculture, although it should be noted that the model exhibits a high rate of variability and the pre-NDT sample size is small. He concluded that only a reduction in interpregnancy interval could cause such growth, and that social factors associated with agriculture and sedentism, such as both division of labour and resource availability permitting earlier weaning, would permit this reduction.

Eshed et al. (2004) evaluated the impacts of the transition to agriculture in the Levant, using a hunter-gatherer sample and a Neolithic agricultural population. The Siler hazard model was used to construct life tables, with the results indicating an improvement of one year in life expectancy at birth in the Neolithic population, however, adult females had reduced life expectancy at birth. They suggested that this could be the result of increased maternal mortality associated with increased fertility. Hershkovitz and Gopher (2008) evaluated the changes between the Natufian hunter-gatherer populations of the Levant, and the agricultural Neolithic populations. Using the ${}_{15}P_5$ method, they found significant population growth up until the Late Natufian and during two of three stages of the pre-pottery Neolithic, with slower growth in the Final Natufian period and one stage of the pre-pottery Neolithic. They concluded that the region experienced fluctuations in population dynamics, but with clear growth driven by agriculture.

Bellwood and Oxenham (2008) examined the different mechanisms of the development and dispersal of agriculture, and the impacts of these on populations. They described four concepts of agricultural origin and spread: starburst zones (high suitability for agricultural activities and evidence for radial spread); spread zones (dispersing populations of agriculturalists); friction zones (genetic and cultural mixing of agriculturalist and hunter-gatherer populations); and overshoot zones (environments unsuitable for agriculture, where farmers had to adapt their approach, sometimes returning to hunter-gatherer behaviours). They suggested that the NDT signal of high population growth would be stronger in areas where agriculture had spread, with rapid adoption, as opposed to where it developed gradually. They also noted that the traditional NDT hypothesis has implied an unsustainable and unmanageable increase in birth-rates, which at some point was controlled by increasing mortality, decreased resource availability, or some other catastrophic event.

Overall, the research associated with the NDT exemplifies rigorous and multidisciplinary approaches to palaeodemography. While work has pursued the classic NDT signal, a lack thereof and evidence that challenges the traditional hypotheses have been given due consideration and are building a picture of a more varied response to agriculture.

3.8. Epidemics and Integration with Palaeopathology

Palaeodemography is an excellent tool for evaluating morbidity and mortality in combination with palaeopathology. Signoli et al. (2002) took a multifaceted approach to past epidemics, specifically evaluating a plague cemetery in Marseilles, dating to 1722. They used a combination of historical sources, including parish registers, traditional bioarchaeological methods, and microbiology to better understand the palaeodemography of the site. Using these approaches, they determined that the plague was not age-selective, with the results being cross-validated across methods.

Gowland and Chamberlain (2005) reported on the use of Bayesian statistics to identify catastrophic mortality associated with plague. They examined the pelves of 132 individuals from the period of the Black Death and 180 adults from a normal attritional cemetery. Using catastrophic and attritional prior probabilities based on the Coale and Demeny model life tables, they applied a Bayesian approach to determining the two models of age-at-death distribution. They found the Black Death cemetery aligned very well with the catastrophic mortality model.

Extensive work by DeWitte has also centred on the risk factors and impacts of the plague (DeWitte, 2014a, 2014b, 2014c, 2016; DeWitte et al., 2017). DeWitte and Wood (2008) sought to identify the impact frailty had upon Black Death mortality, questioning the traditional view that the plague killed without discrimination. They argued that if this was true, the Black Death cemetery samples would represent the demography and epidemiology of the entire population, without bias. Using samples from England and Denmark, they found evidence to support a higher risk of death when pre-existing disease and/or poor health was indicated by skeletal lesions. DeWitte (2015) examined the conditions leading to the Black Death, including whether repeated famines during the preceding years resulted in greater susceptibility. The same methods as DeWitte (2014c) were employed and the results indicated that health was already declining before the Black Death, with survival being significantly lower in the 13th century than in the 11th-12th centuries. DeWitte et al. (2017) and DeWitte (2016) have demonstrated the relevance of such studies to current medical and epidemiological work.

Like the NDT, integrated palaeodemographic and palaeopathological approaches have showcased the insights that can be obtained from the application of bioarchaeological methods and modelling of the age-at-death distribution.

3.9. Gaps in the Application of Palaeodemography

This chapter has broadly surveyed the application of palaeodemographic techniques across the globe and throughout time. Much work has been undertaken in Europe and the Americas, while research in Asia and the Pacific has been somewhat more limited as dubious results have raised concerns about the applicability of palaeodemographic tools. In Africa and the Middle East there have been socio-political boundaries which have limited research, and in Australia there are significant sociocultural restrictions. In terms of time period, the NDT has received the most attention. As previously discussed, there are a number of reasons for this including the evaluation of demographic and ecological concepts and the opportunity to explore the potential impacts of significant subsistence changes. Additionally, Western-centric views on civilisation may also increase the appeal of NDT research. However, we are only scratching the surface of the broad and varied research questions outside of this period of time and in regions where the NDT is not known to occur.

4. The Current Status of Palaeodemography

The late 1960s and the 1970s saw palaeodemography emerge as a new field, with preliminary methods, applications and issues developed and noted by several archaeologists, physical anthropologists and demographers (Angel, 1969; Weiss and Wobst, 1973). The applications demonstrated the exciting potential of palaeodemography to provide insight into past populations and human adaptation, with studies largely focussed on the Americas, scattered studies in Europe and the Middle East, and limited applications in Southeast Asia (Angel, 1972b; Clarke, 1977; Green et al., 1974; Kennedy, 1969; Klepinger, 1979; Owsley and Bass, 1979; Pietrusewsky, 1974; Ubelaker, 1974). Many studies compared the palaeodemography of populations from different geographic and temporal origins, and it seems that there was an underlying assumption that all pre-industrial populations had similar demographic parameters. Of particular interest to researchers was the rate of maternal mortality and increased juvenile mortality seemingly associated with weaning. The combining of methodologies from physical anthropology and demography by individuals that were experts in only one or the other areas was problematic, being based on misconceptions on both sides, and resulting in methodologically flawed and impractical approaches (Angel, 1969; Petersen et al., 1975; Weiss and Wobst, 1973). Further, there was tension between the narrow scope of palaeodemographic studies, and the broad view of demographic theory. It became clear that while theory was essential to palaeodemographic interpretations, equally palaeodemography may enhance and re-evaluate theoretical concepts (Cowgill, 1975; Petersen et al., 1975; Weiss, 1975). Even in its early days, palaeodemography showed great promise.

The 1980s and 1990s saw a surge in interest in palaeodemography. While this commenced in the late 1970s with the French school, much of the work was published in French only and so did not receive much attention from the Anglophone archaeology and physical anthropology communities until the early 1980s.

Bocquet-Appel and Masset's (1982) *Farewell to Palaeodemography* was undoubtedly a pivotal point for the discipline. Whilst it was widely believed to be overly critical, and as observed later by Konigsberg and Frankenberg (2002) the voluminous response all but extinguished any talk of 'farewell', the work caused many researchers to further discuss and seek solutions to the apparent limitations of the field (Buikstra and Konigsberg, 1985; Buikstra et al., 1986; Guy et al., 1997; Hoppa and Saunders, 1998; Konigsberg and Frankenberg, 1994; Paine and Harpending, 1996, 1998; Van Gerven and Armelagos, 1983). This resulted in significant methodological advancements and a general improvement in scrutiny and error estimation. Applications of the methods further reinforced the previously hypothesised and identified trends in human population responses to subsistence changes. In particular, the human response to the adoption and/or intensification of agriculture garnered significant interest (Armelagos et al., 1991; Buikstra et al., 1986; Jackes, 1988). Concerns regarding the underpinning demographic theories received due attention and attempts were made to incorporate these into palaeodemographic interpretations (Armelagos et al., 1991; Bentley et al., 1993; Gage, 1985; Wood, 1998; Wood et al., 1992). In addition, a number of researchers began to explore less traditional means of measuring past population dynamics, including the use of demographic modelling, and alternative sources of data such as DNA, ceramics, and faunal remains (Gage, 1988, 1989; Harpending, 1994; Nelson, 1981; Stiner et al., 1999). The 1980s and 1990s represented a period of significant progress for palaeodemography, with the refinement of methods, theories, and patterns.

This culture continued in the 2000s, with the palaeodemography toolkit being further scrutinised and improved. In particular, modelling was used to address several persistent issues in palaeodemography. Application of palaeodemography was widespread and significantly advanced our understanding of the mechanisms of population change. Dates as data approaches saw greater uptake, becoming a cornerstone of palaeodemographic research on population growth. Palaeodemography was seen as the core means of evaluating population changes relating to subsistence, providing new insights into the Neolithic Demographic Transition through large-scale analyses.

The past two decades have continued to see progress and maturation in the field of palaeodemography. Underenumeration has been more thoroughly explored, but is still a challenge to quantify (Djurić et al., 2011; Gowland and Chamberlain, 2002; Pokines and De La Paz, 2016) and the impacts on current palaeodemographic measures remains contentious. There has been a significant amount of work devoted to improving estimation of the age-at-death distribution (Bocquet-Appel, 2008b; Bonneuil, 2005; Caussinus et al., 2010; Konigsberg and Frankenberg, 2002; Séguy and Buchet, 2014a), with the workshops held at the Max Planck Institute in particular representing significant input, time commitment and collaboration of a large number of researchers (Hoppa and Vaupel, 2002). It is unfortunate that such meticulously developed methods have not seen much application. There is a clear desire for simpler methods, with numerous studies defaulting back to the traditional life table method (Drusini et al., 2001; McClelland, 2015; Morongwa and Steyn, 2004; Nagaoka et al., 2006; Zarina, 2006). Additionally, the focus has largely been on reconstructing age-at-death distributions, while parameters such as fertility and population growth have received minimal attention. Pursuant to early pivotal texts in palaeodemography, including Acsádi and Nemeskéri's (1970) *History of Human Life Span and Mortality* and Weiss and Wobst's (1973) *Demographic Models for Anthropology*, the 2000s saw four methodologically-focussed books published in roughly a decade.

Hoppa and Vaupel (2002) published the outcomes of a series of palaeodemographic workshops at the Max Planck Institute for Demographic Research. The workshops brought together key palaeodemographers, bioarchaeologists and demographers to address the key issues in palaeodemography. The main goal of the workshops was to improve techniques of estimating the age-at-death distribution. Chapters in the book covered the issues relating to reference samples, the use of transition analysis, tooth cementum annulations, multi-variate latent-trait, relational model, parametric model, and hazard model approaches to age-at-death. The book provided a number of elegant solutions to age estimation issues, but unfortunately has not seen significant uptake in palaeodemographic studies. As previously noted, many of the methods seem complex and this may deter bioarchaeologists who are not familiar with such approaches. Additionally, many of the methods still rely on significant sample sizes and selection of appropriate reference populations.

Chamberlain (2006) provided a broader overview of the discipline of palaeodemography, in *Demography in Archaeology*. As a sole-authored publication, the book is far more of a textbook than any others mentioned here, following a logical structure from basic theoretical concepts in both demography and palaeodemography, to a summary of various methodologies, and the incorporation of other bioarchaeological evidence (such as pathology and trauma). It reflected on key questions about the relevance, reliability and future directions in palaeodemography. Chamberlain (2006) noted the need for better integration of evolutionary concepts, particularly life history, and the value of including greater geographic diversity of skeletal reference samples, to balance the current European focus. While relatively brief, the book summarises a large body of demographic and palaeodemographic literature.

Bocquet-Appel's (2008b) *Recent Advances in Palaeodemography* summarised new approaches to data and techniques in the discipline, and a handful of case studies. The methodological approaches included the theoretical underpinnings of using genetic data to estimate population sizes and growth, the use of land surveys to identify previously inhabited areas, Bayesian approaches to the age-at-death distribution, and model life-table methods. The book is focussed on refinements and improvements to existing methodologies, rather than the introduction of new methods. The case studies examined the palaeodemography of sites in Columbia, Portugal and North America, including a reanalysis of the Libben site.

Séguy and Buchet's (2014a) *Handbook of Palaeodemography* discusses key research questions and issues, and attempts to address these. Their focus was on identifying a pre-industrial model of population dynamics, from which they developed protocols and methods for practical application. But the book failed to make significant progress in overcoming many of the issues in palaeodemography, due to a focus on modern pre-industrial proxy populations and life table methods (refer to section 2.4.1 for further discussion of life tables) that so many researchers have concluded to be erroneous and outdated, and have ultimately abandoned. Nonetheless, the handbook comprehensively covers the problems faced by bioarchaeologists and palaeodemographers, and identifies some potential ways of overcoming these.

The publication of several methodologically-focussed books has seen palaeodemography's place as a discipline solidified. The NDT received further attention and, while there appears to be a 'NDT signal', it is not always a clear one, and there are complexities associated with the interplay of climate, subsistence, fertility, mortality and health (Bellwood and Oxenham, 2008; Cohen, 2008;

Downey et al., 2014; Eshed et al., 2004; Kohler et al., 2008; Shennan et al., 2013; Turney and Brown, 2007). In addition, there was significant application of palaeodemography to plagues and epidemics, again picking up a signal of such catastrophic events but not one strong enough to be used in isolation (DeWitte, 2014b, 2015; DeWitte and Wood, 2008; Gowland and Chamberlain, 2005; Paine, 2000).

It is clear that palaeodemography is still in a phase of maturation, and arguably the next steps are to reconcile formal demography with the reality of bioarchaeological data and the practicalities of bioarchaeological research, and integrate demographic, ecological and evolutionary theory into palaeodemographic interpretations. Such improvements would prove mutually beneficial for theory and practice, with improved analyses helping to enhance our understanding of demographic theory in action, and greater theoretical discussion informing interpretations derived from new practice.

5. Research Questions and Hypotheses

5.1. Introduction

Having evaluated the history and current status of the discipline of palaeodemography, this chapter outlines the research questions and hypotheses to be addressed by this thesis. While many authors agreed that Bocquet-Appel and Masset's (1982) *Farewell to Palaeodemography* was premature, by the early 2000s the discipline had been dismissed by many bioarchaeologists (refer section 2.4.2 for a discussion of this). Work presented at the Rostock workshop provided elegant solutions to estimating age-at-death distributions (Hoppa and Vaupel, 2002), noting some limitations (see section 2.4.4) but the tools themselves have, disappointingly, also seen limited uptake (Gage and DeWitte, 2009), although some proponents have demonstrated their exceptional value (DeWitte, 2014a, 2014b, 2014c, 2015; DeWitte and Wood, 2008). Complex methods come at the cost of practicality and accessibility for many bioarchaeologists, who have neither the resources nor skills to readily apply them. This, perhaps, has led to the retention of simpler, traditional approaches (e.g. Séguy and Buchet, 2014a). As identified in Chapter 2, numerous issues persist in the field: current methods are still undermined by the assumption of stationarity associated with life table methods and data; and infant and elderly underenumeration remain unknown quantities. Notably, while estimates of the age-at-death distribution have improved, the estimation of population dynamics such as fertility and population growth have received minimal attention.

Meanwhile, demographic temporal frequency analysis (dTFA) methods have surged in popularity. dTFA has made excellent use of the large volumes of radiocarbon data available for some regions (Collard et al., 2010; Downey et al., 2014; Dye and Komori, 1992; Peros et al., 2010; Shennan, 2009; Shennan et al., 2013; Zahid et al., 2016) in order to estimate population growth. But these methods have been subject to criticism, including taphonomic bias, erroneous modelling and questionable interpretations (Attenbrow and Hiscock, 2015; Brown, 2017; Hiscock and Attenbrow, 2016). Nonetheless, dTFA methods have continued to see significant uptake and it is pertinent to ask how they compare to skeletal-based methods with regards to estimating population increase, and whether the latter still have a significant place in palaeodemographic analyses.

There has been a plethora of applications of the existing suite of paleodemographic methods (particularly Bocquet-Appel's 2002 ${}_{15}P_5$) in Europe and America, but they have scarcely been taken up in Asia and the Pacific. Of particular concern to bioarchaeologists in these regions is the exclusion of infants from consideration in current palaeodemographic age-at-death ratios. Many sites in these regions have demonstrated excellent infant preservation and, in a discipline that is overwhelmingly limited by the quantity of data available, it seems wasteful to exclude this group from analysis. Further, some have observed that subadults aged 5-14 years of age often had good survivorship (e.g. Domett, 2001; Tayles 1999; Tayles et al., 2007), calling into question whether measures based on this age category could accurately estimate population dynamics in this part of the world.

It seems an appropriate time for renewal of the palaeodemographic toolkit for estimating population dynamics in order to address existing concerns and tailor methods to specifically suit the bioarchaeological evidence available in Asia and the Pacific Islands. Thus, a number of research questions are proposed to advance the field of palaeodemography, specifically empirical methodologies for the estimation of fertility and population growth, with a focus on the bioarchaeology of the Asia-Pacific region.

5.2. Research Questions and Hypotheses

I. Can the prevailing issues of life tables, specifically assumptions of stationarity and smoothed data, be addressed by utilising data from non-stationary, real populations when developing palaeodemographic estimates?

The assumption of population stationarity has received significant consideration, but little has been done to address it. Bocquet-Appel and Masset (1982), among others, have modelled the impacts of 0.25% population growth increments on the age-at-death distribution. In contrast, the calculation of palaeodemographic measures from, and subsequent testing of such methods on, model life tables that represent smoothed data from multiple samples has not previously been raised as a problem. Indeed, for the purpose of comparison, it is not problematic at all. It is when life table data are used to estimate population dynamics, as per the works by Bocquet-Appel, that it becomes a concern. The age-at-death distribution of model life tables is calculated based on inputs including fertility and growth rate, so the correlation between the two is hardly surprising. A circular argument is produced which may give the misleading impression of high accuracy (in the form of remarkably strong correlations).

To overcome both the issues of stationarity and smoothed data in life tables, this thesis will utilise real population data from the United Nations database to develop palaeodemographic estimates. These data are from non-stationary populations with a significant degree of variation in living conditions, climate and environment, economy, and mortality and fertility rates. This research aim is addressed in Chapters 7 McFadden and Oxenham (2018a) *The D0-14/D Ratio: A New Palaeodemographic Index and Equation for Estimating Total Fertility Rates* and 8 McFadden and Oxenham (2018b) *Rate of natural population increase as a paleodemographic measure of growth*.

II. Can pre-historic fertility rates be reasonably estimated using age-at-death data including infants?

Infants are seemingly well represented at sites throughout Southeast Asia and the Pacific Islands, due to good preservation of all age groups and numerous sites with high proportions of infants. Burial samples including Man Bac in Vietnam, Khok Phanom Di and Noen U-Loke in Thailand, Hane in the Marquesas Islands, and Honokahua in Hawaii, have subadult mortality rates of 38-56%, and at the sites in Southeast Asia subadults aged 5-14 years represent only 4-9% of total deaths (Domett and Oxenham, 2011; Pietrusewsky, 1976; Pietrusewsky et al., 1991; Tayles et al., 2007; Tayles, 1999). When traditional, infant-exclusionary methods have been applied to these samples, the results have contradicted the infant evidence. Both logically and empirically, infants are the most sensitive age category to changes in fertility and growth, and thus their inclusion will increase the accuracy of palaeodemographic estimates where they are well represented.

It is pertinent to incorporate infants into palaeodemographic measures whenever there are reasons to consider that they are not under-enumerated, since this appears to increase the accuracy of mortality and fertility estimates. Their presence in exceptionally well preserved states in Southeast Asian and Pacific samples would appear to justify this. Chapter 7 McFadden and Oxenham (2018a) *The D0-14/D Ratio: A New Palaeodemographic Index* addresses this research question by using United Nations data from 52 countries for the year 1960 to evaluate the relationship between the ratio of individuals aged 0-14 years of age to the total population and the total fertility rate.

III. Can pre-historic population growth be reasonably estimated using age-at-death data including infants?

If fertility can be estimated from the ratio of individuals aged 0-14 to the total population (D0-14/D), then we can expect that this also correlates with the birth rate and the intrinsic growth rate or rate of natural population increase (RNPI) (Angel, 1969; Bocquet-Appel, 2002): the birth rate minus the death rate (divided by 10 to calculate a percentage). If the inclusion of infants increases the accuracy of the fertility estimate, where infants are well represented, then it logically follows that they will also increase the accuracy of the RNPI estimate. Whilst RNPI fails to account for migration, it is a reasonable proxy for population growth in many circumstances, including where low or nil levels of migration or where equal migration in and out are anticipated. Nonetheless, it is important to quantify the contribution of migration and the impact this may have on the RNPI measure.

Building on Chapter 7, Chapter 8 McFadden and Oxenham (2018b) *Rate of natural population increase as a paleodemographic measure of growth* utilises the same D0-14/D ratio to estimate the RNPI. United Nations age-at-death data for 58 countries were used to calculate the RNPI and evaluate its relationship to the D0-14/D ratio. Additionally, the impact of migration on both the rate and the ratio was estimated.

IV. What is the impact of sample bias, including infant and elderly underenumeration, on the proposed palaeodemographic tools?

The palaeodemographic tools developed as part of this thesis have been, as previously noted, developed with applications in Asia and the Pacific in mind. For the tools to be more broadly useful, they must be resilient to potential biases in preservation and recovery (Djurić et al., 2011; Gordon and Buikstra, 1981; Pokines and De La Paz, 2016; Walker et al., 1988), and age-estimation (Konigsberg and Frankenberg, 1992; Lovejoy, Meindl et al., 1985) biases in the regions for which they are intended. Thus it is necessary to evaluate the impacts of infant and elderly underenumeration on the accuracy of the methods. This follows in the footsteps of earlier work by Lovejoy et al. (1985) and Paine and Harpending (1998).

Chapter 9 McFadden and Oxenham (2019a) *The Impacts of Underenumeration and Age Estimation Error on the D0-14/D ratio and Palaeodemographic Measures* addresses this research aim. The impacts of sample bias were evaluated in two ways: to test the stability of the relationship, the correlation between the D0-14/D ratio, fertility, and RNPI were calculated with data omitted (increments of 25%, 50%, 75% and 100% omission for infants, the elderly, and infants and elderly), or misclassified (based on age estimation error at the 14 years of age demarcation point of the D0-14/D ratio) to simulate a range of sample underrepresentation and age estimation error scenarios. To evaluate the practical implications, the existing equations were applied to the simulated biased samples.

V. Can these methods be validated against the archaeological narrative in Southeast Asia?

If the methods proposed in this thesis are to be confidently adopted by bioarchaeologists, it is imperative to demonstrate their ability to identify population trends. To this end, and noting the focus on the Asia-Pacific region, the rate of natural population increase method has been applied to data from mainland Southeast Asia, where an existing trend of population dynamics has been observed (Bellwood and Oxenham, 2008; Oxenham et al., 2018; Oxenham, et al., 2011) within a firm chronological framework (Higham and Higham, 2009; Higham et al., 2015) and substantial archaeological narrative. It is hypothesised that the trend detected using the RNPI method will closely reflect that of the known archaeological trend but will provide greater temporospatial specificity including short-term and highly localised growth.

This research aim is addressed in Chapter 10 McFadden, Buckley, Halcrow, and Oxenham (2018) *Detection of Temporospatially Localized Growth in Ancient Southeast Asia using Human Skeletal Remains*. The RNPI method was applied to skeletal samples from 11 sites in Southeast Asia, representing 15 chronologically distinct samples. The LOESS fitting procedure was used to evaluate the trend and comparisons were made with the archaeological narrative for the region in order to validate the results. If the RNPI method is an effective estimator, then it should detect a trend of exceptionally high population growth during the Neolithic (as agriculture intensified throughout the region) and continued growth at a lower rate during the Bronze and Iron ages, with a potentially higher rate in the Iron Age than the Bronze (indicated by evidence of increasing social complexity and heterarchy/hierarchy).

VI. Can the application of these methods provide insights into population dynamics in the Pacific?

As these new methods have been proven capable of detecting archaeologically verifiable trends in population increase, the opportunity now arises to apply them to samples where less is known of past population dynamics. The application of the tools developed in this thesis to age-at-death data derived from skeletal samples from the Pacific may inform our understanding of population growth following colonization of this region. Furthermore, it gives us the ability to evaluate trends in population dynamics following colonization of uninhabited islands (including evaluation of hypotheses such as carrying capacity and adaptation) and to assess the potential impacts of climate change and volatility associated with the Little Ice Age by contextualizing the results with other sources of information including archaeological, zooarchaeological, palaeoclimate, and palaeopathological information.

Chapter 11 McFadden, Buckley, Walter and Oxenham (in review) *Temporal trends in the colonisation of the Pacific: Palaeodemographic insights* addresses this research question.

VII. How do palaeodemographic tools for the estimation of population growth based on skeletal remains compare to recent "dates as data" approaches?

With radiocarbon dates so readily available in many parts of the world, it is imperative to the value of the methods proposed in this thesis to compare them with dTFA methods and evaluate the advantages and disadvantages of each for the purpose of estimating population increase, and how they may be used in conjunction. Such tools have facilitated the evaluation of long term, regional population growth, while identification of short-term growth has only been possible where large datasets exist, and intraregional variability has been near impossible to detect.

This research aim is addressed in Chapters 10 McFadden et al. (2018) *Detection of Temporospatially Localized Growth in Ancient Southeast Asia using Human Skeletal Remains* and 11 McFadden et al. (2018) and *Temporal trends in the colonisation of the Pacific: Palaeodemographic insights* (in review) and is further discussed in 13 *Summary and Concluding Remarks*. Applying the method provides the opportunity to reflect on its benefits and flaws, and compare these with the advantages and disadvantages of popular dTFA approaches. The potential for the methods to be used in combination to cross-validate the results of each is also considered.

6. Methodological Approach and Limitations of the Thesis

6.1. Introduction

The methodology and limitations of each individual paper is discussed in detail in Chapters 7-11. This chapter provides an overview of the methodological approach that formed the basis for the research in a broader sense. Additionally, it discusses the limitations of this approach and how those limitation impact upon Chapters 7-11. The methodologies presented in this thesis derive from earlier age-at-death ratio work by Bocquet-Appel and Masset (1982, 1996), Bocquet-Appel (2002) and Buikstra et al. (1986). Indeed, the conceptual stage of this thesis arose from a desire to include infants in the Bocquet-Appel (2002) ${}_{15}P_5$ juvenile ratio. This chapter will discuss the theoretical and practical foundations of age-at-death ratios and their limitations.

6.2. Methodological Approach

6.2.1. Data Sources

The entirety of this thesis relies on the uniformitarian hypothesis proposed by Howell (1976), specifically, that the relationship between certain features of age-at-death distributions and associated population dynamics is the same now as it has been throughout modern human history. It sounds a daunting prospect, but the concept has been widely accepted by palaeodemographers and bioarchaeologists and underpins the vast majority of work carried out within this discipline. A population, as a biological entity, must respond to internal and external factors in the same way regardless of the temporal space it exists in, for us to be able to apply standards and methods, make interpretations of the results, and contextualise through comparison. In the early days of palaeodemography when life tables were the primary method in use, many sought out tables for pre-industrial and ‘modern hunter-gatherer’ populations, as modern life tables failed to represent the dynamics of past populations. This was not to say that past populations responded in a different manner, but rather that no modern population experienced the extreme conditions of past populations, and thus the impacts of such conditions on the age-at-death distribution and population dynamics were not represented in modern life tables. High fertility and mortality model life tables from Coale and Demeny (1966) were believed by some to be the best possible approximation. However, the use of model life table variables which are not independent (Weiss and Wobst, 1973) to demonstrate the correlation between fertility estimates and the age-at-death distribution (e.g. Buikstra et al., 1986), produces circularity and is problematic. Furthermore, the uniformitarian principle is contradicted by the preference for pre-industrial data in the development of age-at-death ratios. If we take uniformitarianism to be true, the relationship between age-at-death ratios and population dynamics should be the same in modern populations as in past ones, thereby negating the requirement for pre-industrial data. Nonetheless, Bocquet-Appel and Masset (1982, 1996), Bocquet-Appel (2002), Buikstra and Konigsberg (1985), and Séguy and Buchet (2014a) have sought to utilise pre-industrial data to develop their methods, stating that industrialised populations cannot be used as a proxy for past ones, without clear evidence to support this. Even if uniformitarianism is dismissed, it seems abundantly unlikely that populations from the 1700-1800s are any better proxy for populations 10,000 years ago than industrial or post-industrial modern ones and it is likely that older data will possess more inaccuracies and greater biases. Not only does the stringent pre-industrial approach contradict the principle on which the discipline hinges, and lacks a compelling argument for doing so, but there are also a great number of advantages to utilising modern data: they are more readily accessible; they are of significantly better quality; and there are more variables available in order to evaluate interdependencies and correlations. These benefits are not realised through the use of pre-industrial data, and the practice may come at a loss of accuracy, precision, and understanding of the inherent interrelationship of population dynamics.

The papers in this thesis have utilised modern data from the United Nations statistical database (United Nations, 2017). The data are of a very high quality and are easily accessible to the public (including anyone who may wish to replicate components of the analyses carried out in this thesis). Data from the year 1960 have been used to develop the methodologies proposed in this thesis, not due to any notion of these more closely representing past populations, but because they represent a greater numerical range for the population variables of interest, particularly fertility (Chapter 7), due to predating the widespread use of the contraceptive pill. The greatest advantage of using these data is that it has provided the opportunity to evaluate interrelationships between population dynamics, including the rate of natural population increase and migration rate (Chapter 8). Modern data are confidently utilised in this thesis based on uniformitarianism and the broad acceptance of this tenet within the discipline and within most sciences. Notwithstanding, the data are skewed towards lower rates of fertility and population increase. If anything, this underestimates the strength of correlations between demographic variables and age-at-death data, as low correlations are anticipated for low fertility and population increase countries due to these populations having age-at-death distributions that are more sensitive to fluctuations in mortality than fertility.

6.2.2. The Ratio

An overlooked feature of Bocquet-Appel and Masset's (1982) paper was the somewhat vague explanation they provided for the selection of their D_{5-15}/D_{20+} ratio: "*After a few trials, we selected a proportion that we could calculate without undue risk of error*" (p.326). The subsequent iteration of $_{15}P_5$ had an improved justification, being devised to "*take into account the constraints of the skeletal data in the literature analyzed*" (Bocquet-Appel, 2002: 639). The case for the D30+/D5+ ratio is similar, as it is "*not as subject to errors in age estimation*" (Buikstra et al., 1986:533). Logically, the ratio of juveniles to adults should be able to tell us something about the fertility and growth of that population. A growing, highly fertile living population will have a large number of infants and subadults compared to adults and we would expect the deceased population to reflect this structure. As such, it is reasonable to use a ratio of juveniles to adults to predict variables such as fertility and growth. If the ratio is logically sound, we must then turn towards the practicalities. Both Bocquet-Appel and Masset (1982) and Buikstra et al. (1986) note the issues with age-estimation error, but this awareness is not reflected in their ratios to the fullest extent that it may be. Using demarcations of 20 years of age and 30 years respectively has a relatively limited impact on error reduction, due to the fact that age estimation error increases with chronological age. At the opposite end of the equations, Bocquet-Appel and Masset (1982) and Buikstra et al. (1986) excluded individuals aged 0-4 years with much greater cause: infants are notoriously underrepresented in skeletal assemblages, through a combination of preservation and recovery biases.

Despite significant improvements in age-estimation methods, the papers in this thesis have opted to utilise the ratio of juveniles aged 0-14 years to the total population (D0-14/D). This minimises the potential for error to a single point: the 14 years of age cut-off. Both the anticipated and simulated error associated with this are expounded in Chapters 7 and 9 of this thesis. Including infants in the ratio has been a deliberate move noting the good preservation and representation of infants at sites in Southeast

Asia and the Pacific (also discussed in greater details in Chapter 7). Infant deaths are logically and empirically the most sensitive to changes in fertility and growth, and as such their inclusion, where available, should increase the accuracy of estimations.

6.2.3. Regression: Linear or Polynomial?

Finally, we come to the matter of how to evaluate the relationship between the ratio and population dynamics of interest. Previous methods have opted for polynomial regression of age-at-death ratios on population variables, however, there has been little explanation as to why such modelling has been chosen. Polynomial regression can be the best model under the right circumstances. Examining the relationship between juvenile ratios and fertility and population growth, we might assume that as the ratio (the number of deceased infants and subadults relative to adults) increases, so does fertility and growth: a linear relationship provides the simplest explanation. If indeed the relationship was not linear, we may expect a second order polynomial with a slightly curved fit. There is no obvious explanation, however, that would support a genuine multi-order polynomial trend where the curve undulates up and down being reflective of the relationship between the ratio and population dynamics. Such curve fitting produces higher correlations but at the expense of a logical explanation of the relationship. Additionally, it runs the significant risk of being overfitted to the samples on which the method is developed, and has very little capacity to describe the variability in the samples it is then applied to. That is to say the method is so fitted to its reference samples that its accuracy suffers when applied elsewhere. As such, in the papers in this thesis linear regression has been utilised. Different orders of polynomial were also tested, but made no tangible improvement in any case.

6.3. Limitations

The discussion of the methodological approach in this thesis has been somewhat critical of the methods on which the discipline has been built. Such methods have provided the basis for those developed in this thesis and the primary intention of the criticisms listed here has been to highlight areas that have led to improvements and refinement. That being said, the methods proposed in this thesis possess their own limitations. One of the greatest limitations of the methods in this thesis is that they have yet to be subjected to rigorous empirical testing.

The correlations between the ratio and variables of interest have proven significant and acceptably high for the reference samples they are developed from, but require further testing against independent samples, both modern and archaic. Chapters 10 and 11 have sought to verify the accuracy and precision of the methods when applied to 'real' archaeological skeletal samples, however, further applications are needed to validate (or fine tune) the preliminary results. A common approach to this limitation is to use Monte Carlo simulations to test the resilience of the methods under a huge range of conditions. This approach has not been undertaken within this thesis. While Monte Carlo simulations are a good tool for evaluating the limits of a relationship in hypothetical scenarios, they do very little to tell us about the empirical value in real life contexts, and such the application of such methods is considered a secondary phase of testing. Notwithstanding, the methods would benefit greatly from further applications to real population and skeletal data, and the use of simulations.

The methodologies themselves cannot account for sources of uncertainty in skeletal samples: they do not accommodate underrepresentation or age-estimation bias. Instead, Chapter 9 aims to explore the impacts of such biases on the methods and quantify them rather than accommodate them. Through the iterative process of developing methodologies, future work may seek to incorporate these and other sources of uncertainty into the methods themselves. In this thesis, preference has been given to estimating and acknowledging the degree of uncertainty and error, as this provides a sound understanding of the limitations when the methods are applied to archaeologically derived samples. It is from this basis that future work can endeavour to account for uncertainty.

Reiterating earlier comments, one of the greatest challenges for the entire discipline is the inherent lack of verifiability when working with archaeological material. As there is no single source of truth, it is proposed that a multidisciplinary approach to palaeodemography where a variety of evidence and the integration of relevant theories are used to refine and improve inferences. Methods based on human skeletal remains allow validation against associated archaeological material, which arguably improves the capacity for such methods to be successfully incorporated into a multidisciplinary approach. But, the issue of verifiability persists and inferences derived from these methods must be treated with appropriate caution.

The methodological limitations presented here flow through to the results derived from the application of these methods in Chapters 10 and 11. In Chapter 10, validation against the archaeological record has been used as a means of evaluating the accuracy of the results. These limitations are perhaps more cause for concern in Chapter 11, where the archaeological narrative relating to population growth is more limited, however, this has been clearly articulated within the paper. Reviewers and critics may recognise additional limitations with the methods presented in this thesis, however, it is hoped that a greater body of work will form from these foundations and future research will aim to address these, and any other, limitations identified.

7. The D0-14/D Ratio: A New Palaeodemographic Index and Equation for Estimating Total Fertility Rates

Chapter 7 is the first publication of this thesis by compilation. Having reviewed the literature and established that status of the discipline, particularly the lack of suitable methods available for research in Asia and the Pacific, this paper aims to develop a palaeodemographic measure of fertility that includes individuals aged 0-4 years. Studies by numerous bioarchaeologists working in Southeast Asia and the Pacific have highlighted the inability of existing methods to accurately represent population dynamics in Southeast Asia, where infants are well preserved and subadults aged 5-14 years often experience good survivorship. This chapter utilises the ratio of individuals aged 0-14 year to the total population in order to estimate the total fertility rate. This chapter provides the basis for the development, evaluation, and application of new methodologies in this thesis.

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Declaration of Authorship

Contributed to overall question, formulation of arguments in manuscript, background research, statistical analysis, discussion and conclusion.

Signed Ms Clare McFadden

Composed initial question, refinement of arguments, argument formulation and editorial supervision of paper.

MF Oxenham

Signed Prof Marc Oxenham

Note on Published Papers

A PDF copy of the paper as published can be found at Appendix 1.

The D0-14/D Ratio: A New Paleodemographic Index and Equation for Estimating Total Fertility Rates

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7.1. Abstract

Objectives: The objectives of this study were to develop a new subadult-adult ratio for application to sites with good infant representation and to produce an equation to estimate the total fertility rate for a population based on the age-at-death ratio. A new approach is required as current methods exclude the 0-4 years age category due to presumed underenumeration of infants. Whilst this is true for some skeletal samples, others experience good infant representation.

Materials and Methods: Using age-at-death data and total fertility rates for 52 countries from the United Nations database for the year 1960, we examined the correlation between three age-at-death ratios and the fertility rate. We also utilised linear regression to determine an equation for calculating total fertility rate from the ratio.

Results: We achieved a correlation of 0.848 between our D0-14/D Ratio and actual fertility rates. This correlation was significantly higher ($p<0.05$) than the other ratios examined, including the d5-14/d20+ by Bocquet-Appel and Masset (1977; 1982; 1996) and the ${}_{15}P_5$ index by Bocquet-Appel (2002).

Discussion: The exclusion of infants can result in inaccurate demographic measures, particularly where subadults aged over five years of age experience robust survivorship. In addition to providing a solution for sites with good infant representation, this study indicates that the 0-4 years of age category possesses great predictive power when compared to other age categories. The regression equation provides a total fertility rate which is comparable with data regardless of their temporal origin. This method will provide more accurate demographic measures for bioarchaeological sites with good infant preservation.

7.2. Introduction

Paleodemography is the study of the demographic attributes of past populations, including population size, structure, growth, density, fertility, mortality and migration (Chamberlain, 2006). Such attributes can provide significant and valuable insight into the ability of past humans to adapt in response to environmental events, such as climate change and availability of resources, and societal change, for instance migration, warfare, and social complexity. The impact of the agricultural transition on fertility and mortality has been of great interest over recent decades, with research to date indicating major changes in health following the adoption and/or intensification of agriculture (Armelagos et al., 1991; Bocquet-Appel and Naji, 2006; Buikstra et al., 1986; Cohen and Armelagos 1984; Gage and Dewitte, 2009; Larsen, 1995; Papathanasiou, 2005; for a different trend in the Southern Levant see Eshed et al., 2004, Hershkovitz and Gopher, 2008, Kuijt, 2008, and Kuijt and Goring-Morris, 2002; and see Oxenham et al. 2006 and Bellwood and Oxenham, 2008, for a contrary pattern observed in Southeast Asia). Also of significant interest at present are the impacts of past climate change on human populations as indicated by shifts in demographic profiles (deMenocal, 2001; Tipping et al., 2008; Turney et al., 2006; Turney and Brown, 2007; Van de Noort, 2011). The age-at-death distribution is particularly sensitive to changes in fertility, far more so than mortality (Sattenspiel and Harpending, 1983). Notwithstanding, several key issues underpin paleodemography, with the predominant concerns at present being the inaccuracy of age-at-death estimation techniques, non-stationarity of populations, and underenumeration of infants (Bocquet-Appel and Masset, 1982; Buikstra and Konigsberg, 1985; Paine and Harpending, 1998).

Underenumeration of infants has been assumed to be a significant problem in paleodemography, so much so that children aged 0-4 years are generally excluded from paleodemographic analyses (Milner et al., 2008; Seguy and Buchet, 2014b). It is indeed true that in certain conditions differential preservation results in the underrepresentation of infants in the archaeological record (Gordon and Buikstra, 1981; Lewis, 2007; Walker et al., 1988; Weiss and Wobst, 1973). Further, it has been suggested that in some instances infants may be subject to different burial practices and may be interred at a separate location to the burials of individuals from other age categories (Guy et al., 1997; Milner et al., 2008). This results in missing data for a key age category which, logically, should be highly sensitive to changes in fertility. Thus, paleodemographers have tended to exclude the youngest age group from their analyses and utilise remaining age categories to estimate demographic parameters. This is one of the premises which underlies Bocquet-Appel and Masset's (1977; 1982; 1996) juvenility index.

The juvenility index was originally developed by Bocquet-Appel and Masset (1977; 1982; 1996) in response to concerns surrounding the effects of errors associated with age-at-death estimation. Bocquet-Appel and Masset (1977; 1982; 1996) proposed the use of a ratio of subadults to adults, thereby avoiding the high error rate associated with a continuous or multi-category age-at-death distribution. Further, they addressed the issue of infant underenumeration by excluding the 0-4 years age category. In its first iteration, the juvenility index examined the ratio of subadults aged 5-14 years to adults aged 20 years and over, abbreviated to d5-14/d20+ (Bocquet-Appel and Masset, 1977; 1982; 1996). Using life tables and known fertility rates for 40 populations, Bocquet-Appel and Masset (1977; 1982; 1996) used polynomial regression to derive equations to predict a number of demographic variables including mortality and fertility rates. In the second version, Bocquet-Appel (2002) adjusted the juvenility index to $_{15}P_{5}$, with the ratio being based on 45 life tables, including the original 40. For comparison with the previous index, $_{15}P_{5}$ can be articulated as d5-19/d5+ (Seguy and Buchet, 2014a). The revised ratio did not significantly increase the correlation between estimated and known fertility rates, however, it is considered to be advantageous from a practical perspective due to the age categories being more biologically distinct than those of the original d5-14/d20+ ratio (Bocquet-Appel, 2002; Seguy and Buchet, 2014c).

The $_{15}P_{5}$ juvenility index remains a widely accepted tool in paleodemography and may be suitable for those samples where either differential preservation and recovery or cultural practices have led to an apparent underrepresentation of infants (Bocquet-Appel and Naji, 2006; Hershkovitz and Gopher, 2008; Kohler et al., 2008; Kohler and Reese, 2014; Lesure et al., 2014). However, this is not always the case and in Southeast Asia, for instance, infants are often well represented in skeletal assemblages and the use of the $_{15}P_{5}$ juvenility index may fail to accurately represent the demographic parameters of such populations (Bellwood and Oxenham, 2008). This is particularly true for those sites where subadults aged 5 years and over and young adults experienced good survivorship. For example, at the Neolithic site of Man Bac, Vietnam, excellent preservation was indicated by approximately 60% of identified burials being described as complete or nearly complete, with a further ~28% being classified as incomplete due to the absence of only the skull or one or more long bones (Domett and Oxenham, 2011). Subadult age was estimated using dental mineralisation and eruption and, in the absence of dentition, long bone development, whilst adult age was estimated using combinations of the pubic symphyseal face, dental wear, and epiphyseal fusion (Domett and Oxenham, 2011). Children under 5 years of age were found to represent 47.4% of the total sample (n=78), with only 12.82% of individuals being categorised as 5 to <20 years of age (Domett and Oxenham, 2011).

The Man Bac site is not isolated in either its ideal conditions for preservation or its demographic distribution. Table 7.1 lists several sites in Southeast Asia with skeletal remains falling into the 0 to 4 years category at proportions ranging from 29.49% to 48.05%. Infant preservation and representation appears to be significant for these sites, whilst mortality between 5 and <20 years of age appears to be comparatively quite low. Applying the Bocquet-Appel and Masset (1977; 1982; 1996) juvenility index and the Bocquet-Appel (2002) $_{15}P_5$ index to these sites disregards the high infant mortality and by relying on the 5 to <20-year-old category, fails to accurately represent its younger counterparts.

Sample	**Time period**	**0-4.9 years**	**5-14.9 years**	**15-19.9 years**	**20+ years**
Khok Phanom Di[1]	Neolithic	48.05	7.79	12.99	31.17
Man Bac[2]	Neolithic	47.44	8.97	3.85	39.74
Ban Lum Khao[3]	Bronze Age	31.82	14.55	19.09	34.55
Ban Na Di[4]	Bronze Age	29.49	6.41	6.41	57.69
Noen U-Loke[5]	Iron Age	38.33	4.17	7.50	50.00

1 Tayles (1999); 2 This Study; 3 Domett (2004); 4 Domett (2001); 5 Tayles et al. (2007)

Table 7.1 Age at death distributions for sites from Southeast Asia

These Southeast Asian sites are of fundamental importance to our understanding of the Neolithic demographic transition and associated paths of inquiry, such as the causes of the transition, demographic and archaeological markers of the transition, changes in social and cultural practices, and the intrinsic and extrinsic effects of significant population increase (Bellwood and Oxenham, 2008; Bocquet-Appel, 2002; Willis and Oxenham, 2013). Just as methods have been developed to address the underrepresentation of infants at a number of sites in Europe and the Americas, it is equally important that demographic tools be developed for sites with good infant representation.

A juvenility index is required to accurately represent samples where infants are well preserved due to differences in preservation conditions, where archaeological recovery of infants has been good, and where there do not appear to be differential cultural practices impacting the representation of infants in the burial context. We propose the D0-14/D Ratio as an alternative paleodemographic tool for application to such skeletal assemblages.

7.3. Materials and Methods

The methods are largely based on those reported by Bocquet-Appel and Masset (1977; 1982; 1996), with some adjustments. It is important to note that Bocquet-Appel and Masset (1977; 1982; 1996) utilised data from life tables to develop their juvenility indices and demographic measures. The age-at-death distribution of a life table is calculated from living population data as well as mortality data, specifically, the proportion of the living that died at each age (Lacey and Speizer, 2017). This means that the resulting mortality data is a reflection of both the living age structure and the deceased age structure. We would therefore anticipate a higher correlation with living demographic parameters, including fertility rate, as they will be better reflected in the living age structure than the deceased. However, the only data available in most bioarchaeological cases of interest will be the age-at-death distribution from the skeletal population, and the living population age structure will typically be unavailable. We believe that age-at-death data are a more accurate representation of what can be derived from the skeletal sample than life tables. It is essential that the data are comparable in nature for the regression equations to be relevant and accurate. Therefore, we use real age-at-death records in place of life tables. It should also be noted that life tables assume the population is stationary: it is closed to migration; fertility and mortality are constant and equal; and the age distribution is stable (Lacey and Speizer, 2017). To address this, Bocquet-Appel (2002) used modelling to simulate varying population growth rates from -2.5 to 2.5. The populations used in our study show genuine variability in population growth. We believe our approach better represents both the data available to bioarchaeologists, and the variability in non-stationarity within and between populations.

Age-at-death data, fertility rates and population growth rates from the United Nations Database (United Nations, 2017) were utilised as the reference sample for this study. The United Nations (2017) have collected population data from national statistical offices in 230 countries since 1948.

Each year the United Nations (2017) evaluates the process and makes recommendations to statistical offices in order to continually improve accuracy and maintain relevance. We opted to utilise data from the year 1960, as this year provides a good range of fertility rates from 2.001 through to 7.363 and population growth rates from -0.281 through to 6.356. Fertility rates were available for 214 countries and regions, whilst age-at-death records were available for only 75 countries and regions. Five countries were removed as they lacked sufficient detail regarding age-at-death data. A further 16 countries and regions were excluded as they only had data for either fertility rates or age-at-death. Two regions were excluded due to not being sovereign countries and therefore having the potential for data duplication. Data were obtained for a total of 52 countries for inclusion in this study and were extracted for the following variables: Fertility rate, total (births per woman); Deaths by age, sex and urban/rural residence; and Population growth (annual %) (United Nations, 2017). Total fertility rate is the average number of children born to a woman over her lifetime, assuming she experienced the age-specific fertility rates for the population throughout her life and she survived until the end of her reproductive age span (United Nations, 2017). Total fertility rates were adjusted to three decimal places. For some countries, age-at-death data needed to be re-categorised in order to make data comparable. Most data were in five year categories (e.g. 5-9 years): these were combined to reflect the categories used in the ratios of interest (i.e. 0-4, 5-14, 15-19, 20+ years).

We calculated three ratios: the Bocquet-Appel and Masset (1977; 1982; 1996) juvenility index of d5-14/d20+; the Bocquet-Appel (2002) $_{15}P_5$ index of d5-19/d5+; and our proposed D0-14/D Ratio of d0-14/total population. Buikstra et al. (1986) proposed an alternate ratio of d30+/d5+ which they correlated with Coale and Demeny pre-industrial life tables. The Buikstra et al. (1986) ratio was not included in this study as we were only able to identify its use in one study other than the original (Schurr, 1998) and the age-at-death categories differed substantially from those used by Bocquet-Appel and Masset (1982) and Bocquet-Appel (2002). Robbins (2011) developed a subadult fertility formula using the ratio of infants to subadults (d0-1/d2-19), however, we note that the ratio was based on female-only Coale and Demeny life tables and that, similar to Buikstra et al. (1986), the ratio has seen limited application in the published literature.

We undertook simple correlation tests of the ratios to the known fertility rates, and between ratios using StatsDirect 3 (2016). We also calculated the 95% confidence interval. The test of difference between correlations is performed to determine the significance of difference and is applied where correlations are derived from the same sample and are based on the same variables. As such, this test was deemed appropriate and was undertaken using software by Lee and Preacher (2013).

Bocquet-Appel and Masset (1977; 1982; 1996) and Bocquet-Appel (2002) utilised polynomial regression of their ratios on the various paleodemographic measures to develop their equations. We set out to develop an estimate of the total fertility rate, due to priority of research interests and the complexity of other measures such as mortality and growth rate (Milner et al., 2008). We use linear regression as we believe the simplest explanation is that the relationship between age-at-death ratios and the total fertility rate is linear. Polynomial regression fits the data closer to the trendline, however, the theory behind doing this must be justified. Presently we have neither a logical nor practical justification for the relationship being anything but linear, as we would wholly expect an increasing fertility rate to produce higher numbers of deceased infants on a linear trajectory. The 40 life tables utilised by Bocquet-Appel and Masset (1977; 1982; 1996) and Bocquet-Appel (2002) showed some deviations from a linear relationship, however, we believe that both a larger sample and a demographic justification are required to warrant the use of polynomial regression in this case.

We used linear regression of Bocquet-Appel and Masset's (1977; 1982; 1996) and Bocquet-Appel's (2002) ratios on the total fertility rate to evaluate the relationship in a comparable way to our proposed method (as the results of polynomial regression and linear regression are not directly comparable), however we note that we would anticipate a reduction in the correlations previously reported for the former ratios and the total fertility rate due to the change to linear regression. Further, we would expect the inclusion of the 0-4 years age category to improve the correlation due to its hypothesised sensitivity to fertility. In order to obtain an equation to estimate the total fertility rate, we utilised simple linear regression of our subadult-adult ratio on the known total fertility rates for 52 countries. We also calculated the prediction interval, as this estimates the interval that predictions will fall into based on past observations and is therefore appropriate for our aims. Linear regression and prediction interval were undertaken using StatsDirect 3 (2016).

7.4. Results

Table 7.2 details the fertility rate, the number of individuals in each age group, total sample size, and the three calculated ratios for each country. The results of the correlation tests for the three ratios are provided in Table 7.3.

The correlation tests indicate an improvement in the accuracy of methods from the original Bocquet-Appel and Masset (1977; 1982; 1996) juvenility index, to the Bocquet-Appel (2002) ${}_{15}P_5$ index, and finally to our D0-14/D Ratio ($r=0.848$, 95% CI 0.750-0.911).

The test of difference produced a result of $p<0.05$ (one-tailed) based on the correlations for the Bocquet-Appel (2002) ${}_{15}P_5$ index (the more highly correlated of the two indices) and our D0-14/D Ratio. We undertook a one-tailed test as we anticipated that the inclusion of additional data, specifically the 0-4-year category, would result in an improved correlation.

Country	Total Fertility Rate	0-4	5-14	15 - 19	20+	Total n=	d5-14/d20+	d5-19/d5+	d0-14/total population
Albania	6.489	8597	528	140	7489	16754	0.071	0.082	0.545
Antigua and Barbuda	4.425	182	12	6	324	524	0.037	0.053	0.370
Argentina	3.109	37224	3222	2261	135776	178483	0.024	0.039	0.227
Australia	3.453	5638	898	709	81191	88436	0.011	0.019	0.074
Austria	2.690	5427	453	549	83174	89603	0.005	0.012	0.066
Barbados	4.333	563	33	19	1512	2127	0.022	0.033	0.280
Belgium	2.540	5465	628	371	107474	113938	0.006	0.009	0.053
Bulgaria	2.310	7768	909	549	54393	63619	0.017	0.026	0.136
Canada	3.811	15144	1958	1239	121337	139678	0.016	0.026	0.122
Chile	5.113	42913	2681	1338	48349	95281	0.055	0.077	0.479
Costa Rica	6.451	5371	422	115	4051	9959	0.104	0.117	0.582
Cuba	4.182	9370	917	785	31786	42858	0.029	0.051	0.240
Denmark	2.570	1913	262	218	41288	43681	0.006	0.011	0.050
Egypt	6.630	254567	14313	4467	163183	436530	0.088	0.103	0.616
El Salvador	6.674	14980	1615	582	11368	28545	0.142	0.162	0.581
Fiji	6.461	804	99	67	1207	2177	0.082	0.121	0.415
Finland	2.720	2085	445	295	36972	39797	0.012	0.020	0.064
France	2.850	22755	2827	1860	489995	517437	0.006	0.009	0.049
Greece	2.230	7508	759	448	51593	60308	0.015	0.023	0.137
Grenada	6.743	492	8	8	524	1032	0.015	0.030	0.484
Guam	6.052	78	7	8	180	273	0.039	0.077	0.311
Guatemala	6.534	33544	5509	1606	25080	65739	0.220	0.221	0.594
Guyana	5.754	1871	119	77	3088	5155	0.039	0.060	0.386
Hong Kong	5.162	6497	674	120	11845	19136	0.057	0.063	0.375
Hungary	2.020	8020	791	670	92016	101497	0.009	0.016	0.087
Iceland	4.290	87	18	7	1055	1167	0.017	0.023	0.090
Ireland	3.780	2085	244	135	30196	32660	0.008	0.012	0.071
Israel	3.866	2207	276	149	9415	12047	0.029	0.043	0.206
Italy	2.370	46863	4528	3032	426509	480932	0.011	0.017	0.107

Japan	2.001	64683	13756	9813	617983	706235	0.022	0.037	0.111
Luxembourg	2.290	194	22	13	3487	3716	0.006	0.010	0.058
Malta	3.620	356	20	13	2430	2819	0.008	0.013	0.133
Mexico	6.768	186472	20371	7691	187487	402021	0.109	0.130	0.515
Montenegro	3.603	1105	64	41	2363	3573	0.027	0.043	0.327
Netherlands	3.120	5025	909	458	81094	87486	0.011	0.017	0.068
Norway	2.850	1439	265	161	30676	32541	0.009	0.014	0.052
Poland	2.980	42304	3308	1686	176680	223978	0.019	0.027	0.204
Portugal	3.160	21502	1476	674	71272	94924	0.021	0.029	0.242
Puerto Rico	4.657	4163	478	261	10870	15772	0.044	0.064	0.294
Republic of Korea	6.155	16336	18506	6773	89041	130656	0.208	0.221	0.267
Romania	2.340	32273	2489	1288	124563	160613	0.020	0.029	0.216
Saint Lucia	6.967	708	44	19	510	1281	0.086	0.110	0.587
Saint Vincent and the Grenadines	7.224	794	23	8	378	1203	0.061	0.076	0.679
Singapore	5.454	2939	391	117	6752	10199	0.058	0.070	0.327
Spain	2.860	33575	3074	1794	52968	91411	0.058	0.084	0.401
Sri Lanka	5.541	33183	4684	1249	45802	84918	0.102	0.115	0.446
Sweden	2.170	2062	421	373	72237	75093	0.006	0.011	0.033
Switzerland	2.440	2450	356	287	49001	52094	0.007	0.013	0.054
Tonga	7.363	56	14	6	213	289	0.066	0.086	0.242
Trinidad and Tobago	5.264	1834	143	93	4538	6608	0.032	0.049	0.299
Uruguay	2.880	3230	236	189	18261	21916	0.013	0.023	0.158
Venezuela	6.616	24627	2367	926	27011	54931	0.088	0.109	0.491

Table 7.2 Fertility Rate, Age Groups, Total Population, and Ratios for 52 Countries

	d5-14/d20+ (Bocquet-Appel and Masset 1977; 1982; 1996)	d5-19/d5+ (Bocquet 2002)	d0-14/total population (D0-14/D Ratio)
n=	52	52	52
Mean	0.044	0.056	0.269
SD	0.047	0.050	0.188
Skewness	2.000	1.547	0.496
Kurtosis	7.198	5.283	2.010
r=	0.709	0.755	0.849
95% CI	0.540 to 0.823	0.607 to 0.852	0.750 to 0.911

Table 7.3 Correlations between Age-at-Death Ratios and Total Fertility Rate

The prediction interval of the D0-14/D Ratio on the total fertility rate produced the scatter plot at Figure 7.1. Simple linear regression produced the following equation to calculate total fertility rate:

$$\text{Fertility Rate} = (7.734 \times \text{D0-14/D Ratio}) + 2.224$$

With a total fertility rate of 8.2 in 1960, Rwanda has the highest rate recorded by the United Nations (2017). The biologic maximum fecundity is believed to be approximately 15 births per female for most populations, however, achieving the maximum requires all females to commence reproduction at age 15 and to not breast-feed any of their children (Leridon, 2005). This may be the case for individual females, but is not known to occur at a population level (Leridon, 2005). As such, the maximum total fertility rate for a population is likely to be significantly less than the maximum biologic fecundity. The highest total fertility rate reported by Bentley et al. (1993) in their study of populations with natural fertility (fertility in the apparent absence of birth control) was 10 for an indigenous American population in 1950. They also noted that whilst agriculturalist populations tended to have higher fertility rates than non-agriculturalist populations, there was significant overlap in the range of the two groups. Similarly, Campbell and Wood (1988) reported significant variability in the fertility rates of modern traditional societies. The definition of high, moderate and low fertility rates varies depending on the populations being evaluated, but Preston et al. (1989) provide a general guide of an average of 6.15 for high fertility, 4.59 for moderate fertility, and 1.64 for low fertility. In modern studies, anything under the replacement level (total fertility rate of 2.1) is typically considered low, and moderate and high fertility ranges are more conservative due to the reduction in fertility rates over time (United Nations, 2017).

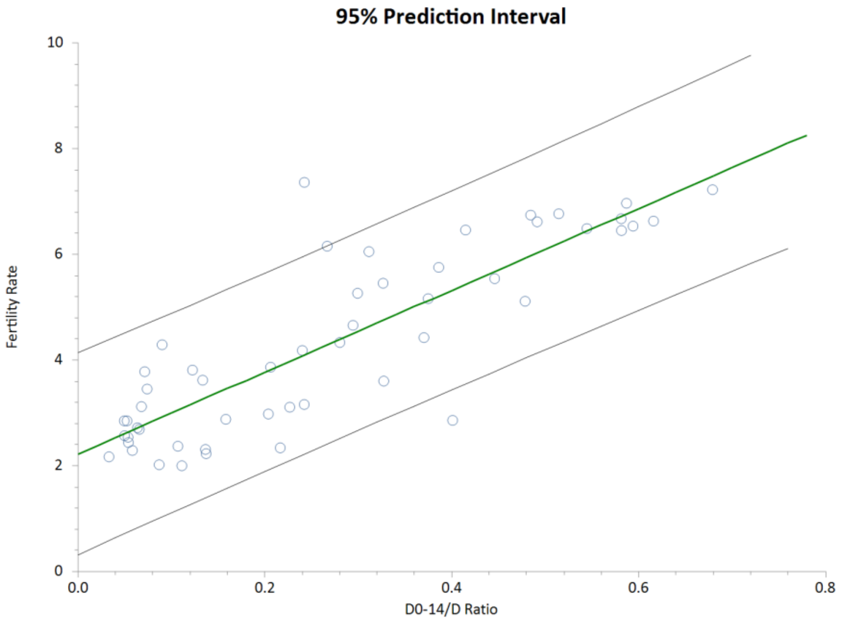

Figure 7.1 Prediction interval for the total fertility rate and D0-14/D ratio

7.5. Discussion

We have shown that the D0-14/D Ratio provides an improved correlation with actual fertility rate (r=0.848) over previous methods. It seems logical that the 0-4 year category would be the age group most sensitive to changes in fertility and our results support this. We also note that the inclusion of a greater proportion of the age-at-death data will likely increase the correlation. Our subadult-adult ratio is a significant improvement ($p<0.05$) over alternative methods. Based on these results, we suggest the D0-14/D Ratio as an appropriate alternative to existing age-at-death ratios for instances where infants are well represented in the skeletal sample.

The correlations we report here for the Bocquet-Appel and Masset (1977; 1982; 1996) juvenility index and the Bocquet-Appel (2002) $_{15}P_5$ ratio are weaker than those reported in the original papers. We believe this is due in part to Bocquet-Appel and Masset (1977; 1982; 1996) and Bocquet-Appel (2002) using a ratio derived from life tables. Utilising life tables will produce a better correlation as the fertility rate is based on the living population, and the mortality data from life tables is a proportion of the age distribution of the living population, meaning both the living and deceased age structures are represented. However, as previously noted, age-at-death data better reflect the data that bioarchaeologists obtain from skeletal samples, and the inability of bioarchaeologists to estimate the age distribution of the living population. Additionally, as earlier discussed, the shift from utilizing polynomial regression to linear regression would undoubtedly impact the correlation. We see both innovations as logical adjustments.

We believe that total fertility rate estimates produced using this equation can be compared with others, including modern data. Whilst the age distribution and ratio have been derived from age-at-death data, the fertility rate is derived from the living population, therefore the equation is based on the relationship between the age-at-death distribution and the living fertility rate. As such, estimates should be comparable with living population fertility rates. As previously noted, the age-at-death distribution is known to be more sensitive to fertility than mortality (Sattenspiel and Harpending, 1983; Paine, 1989): our results support this. The confidence interval of our method should be observed and we would suggest interpretations should be limited to estimating where a population's fertility rate fits on the global and temporal scale.

Although this method is not exempt from the key issues in paleodemography, we have made some progress in addressing these. Underenumeration of infants has remained a prominent concern in paleodemography since it was raised by early paleodemographers such as Angel (1969) and Weiss and Wobst (1973). Our D0-14/D Ratio has been developed specifically for skeletal assemblages where there are reasonable grounds to believe that infants are well represented, and therefore we do not believe infant underenumeration to be of concern when using our method if due diligence has been taken. It is imperative that researchers contextualise bioarchaeological data with respect to the site in question when considering infant representation. Where proportionately low numbers of infants are found, differential preservation and differential interment must be considered as potential causes, and where doubt exists it may be best to employ the Bocquet-Appel (2002) $_{15}P_5$ method.

The error surrounding age-at-death estimates has perhaps been the most dominant issue in paleodemography in recent years. The Rostock Manifesto endeavoured to address this issue through the application of Bayesian theorem (Hoppa and Vaupel, 2008). It has previously been observed that the use of age-at-death ratios is one mechanism that can be employed to reduce the impact of age estimation error (Bocquet-Appel, 1977; 1982; 1996; Buikstra et al., 1986), and the Bocquet-Appel (2002) $_{15}P_5$ method specifically addressed concerns around practicality of ratio demarcation points. Utilising our method restricts the error of age-at-death estimates to one component of the ratio only (specifically, the maximum age cut-off for the numerator: 14 years of age), as the denominator is the total population and is therefore impervious to age estimation error.

Nonetheless, it is noted that there will likely be a degree of error in the estimation of age for the purposes of this method and that this may have an impact on the accuracy of results. AlQahtani et al. (2014) evaluated the accuracy of three dental ageing methods: Schour and Massler; Ubelaker; and the London Atlas. For individuals with a chronological age of 13 years they reported a mean error of approximately ±1.5 years, and for a chronological age of 15 years they reported a mean error of approximately ±1 year, using the Schour and Massler and Ubelaker methods (AlQahtani et al., 2014). For the London Atlas method this was reduced to 0.79 year and 0.66 year respectively. Taking the average error for the Schour and Massler and Ubelaker methods, we might expect that some individuals with a chronological age of up to 15.9 will be erroneously placed in the 0-14 category and some individuals with a chronological age of 13.5-14 may be erroneously excluded from the 0-14 category. Rissech et al. (2013) reported average errors ranging from ±0.73 to ±2.09 years for measurements from the scapula, innominate, femur and tibia, and therefore the age range that may be incorrectly classified for the purposes of our method would likely be between 12 and 16 years of age, depending on the skeletal element. The potential for error should be considered when using the D0-14/D Ratio, along with any further potential complications due to other variables which impact age estimation such as sex and ancestry.

Finally, we have used non-stationary samples to better replicate the age-at-death distribution of real populations. There is a significant literature on the issue of non-stationarity. Some have argued that over long periods of use, burials will assume an age-at-death distribution that is stable and sometimes stationary, whilst others have criticised this theory, but note that growth rate is very difficult to estimate for archaeological sites in the absence of historical records (Bocquet-Appel and

Masset, 1982; Bocquet-Appel, 2002; Buikstra and Konigsberg, 1985; Milner et al., 2008; Moore et al., 1975; Sattenspiel and Harpending, 1983). We have achieved a significant correlation between our ratio and the known fertility rates for 52 countries with varying growth rates ranging from -0.281 to 6.356 (United Nations, 2017). As such, we believe the results of this study will hold true regardless of the stationarity or non-stationarity of the population it is applied to. The method may, however, be improved by analysing the relationship between the age-at-death distribution and other demographic measures including population growth.

7.6. Conclusion

Infant underenumeration is a known issue in paleodemography, with methods being developed to address the issue through the exclusion of the 0-4 years of age category from age-at-death distribution estimates. However, we have provided several examples of archaeological sites with good infant representation. When current methods are applied to these sites they produce inaccurate estimates of fertility due to the exclusion of the age group most sensitive to fertility. To increase the accuracy of fertility estimates for sites where representative infant data are available, we have developed the D0-14/D Ratio using United Nations (2017) age-at-death data and fertility rates. The ratio has been found to be strongly correlated with total fertility rates ($r=0.848$) and is a significant ($p<0.05$) improvement over existing methods. To transform the ratio into a comparable fertility rate, we have used linear regression to develop a total fertility rate estimation equation. This permits comparison with the total fertility rate of other populations regardless of their temporal origins. We expected that the inclusion of the 0-4 years of age category would improve the correlation with fertility due to the category's high sensitivity to changes in fertility rate and our study is supportive of this. We have considered the key concerns in paleodemography and believe that the D0-14/D Ratio addresses some of these issues, firstly by reducing the potential for age-at-death estimation error using distinct age categories and secondly by mimicking real variation in population growth through the use of non-stationary sample populations. The method would benefit from further research on the impact of other demographic variables, such as migration and mortality, but provides a valuable solution to an often-forgotten problem.

7.7. Acknowledgements

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8. Rate of Natural Population Increase as a Paleodemographic Measure of Growth

Having established the sensitivity of the D0-14/D ratio to fertility in Chapter 7, Chapter 8 proceeds to evaluate the ratio's ability to detect population growth. The rate of natural population increase (RNPI) is a good proxy for population growth, as it quantifies the contributions of births and deaths, without requiring input relating to the migration rate which is very difficult to measure from skeletal samples. Chapter 8 provides a new, equation for estimating RNPI in past populations and discusses the limitations of the method. The development of this method is key to progressing the field in Asia and the Pacific, as it provides new opportunities to utilize existing skeletal samples and gain greater insight into the population dynamics of the region, throughout periods of major change such as the intensification of agriculture, introduction of new technologies, and climate events (including the Little Ice Age).

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Signed Ms Clare McFadden

Contributed to overall question, refinement of arguments, argument formulation and editorial supervision of paper.

MF Oxenham

Signed Prof Marc Oxenham

Note on Published Papers

A PDF copy of the paper as published can be found at Appendix 2.

Rate of Natural Population Increase as a Paleodemographic Measure of Growth

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8.1. Abstract

The aim of this study was to provide a verifiable measure of population increase from age-at-death data. It was anticipated that the D0-14/D ratio would be a good predictor of the rate of natural increase (births minus deaths) due to its strong relationship with the total fertility rate. United Nations age-at-death data for 58 countries was used to calculate the rate of natural population increase and evaluate its relationship to the D0-14/D ratio. Additionally, the impact of migration on both the rate and the ratio was measured. A correlation of r=0.863 (95% CI 0.777 – 0.917) between the D0-14/D ratio and rate of natural population increase was found. Linear regression provided a simple equation for calculating the rate of population increase. The rate of natural population increase accounts for the disparity (or lack of) between births and deaths, and provides a valuable measure for evaluating ancient population variability. While the rate does not factor in migration, we believe migration should be measured independently as it is not always of interest to bioarcheological research questions and has a negligible impact on the rate of natural increase and the D0-14/D ratio. Estimating the rate of natural population increase has the potential to provide significant insights into past populations and the human response to change.

8.2. Introduction

Population growth is a demographic measure which estimates the contribution of births, deaths and migration to population size over time. In the study of ancient populations, changes in population size can tell us a great deal about the health of a population and its response to change. An example of this is the Neolithic Demographic Transition (NDT), considered to be one of the most significant events in the history of modern humans, and is variously associated with increasing social complexity, population size, and territorial pressure (Bocquet-Appel, 2008). Measuring the impacts of the NDT across the globe has been an area of significant interest to date (Armelagos et al., 1991; Bellwood and Oxenham, 2008; Bocquet-Appel and Naji, 2006; Buikstra et al., 1986; Cowgill, 1975; Eshed et al., 2004; Gage and Dewitte, 2009; Hassan and Sengel, 1973; Johansson and Horowitz, 1986; Kuijt, 2008; Papathanasiou, 2005; Shennan, 2009; Woodbridge et al., 2014), yet a reliable way in which to estimate the rate of population increase from skeletal remains has continued to elude researchers.

Previous attempts to estimate population growth are highly diverse and include demographic (Cowgill, 1975) and paleodemographic modelling (Bocquet-Appel, 2002; Schindler et al., 2012), ethnographic and paleoclimate analyses (Tallavaara et al., 2015), spatiotemporal radiocarbon date approaches (Chaput and Gajewski, 2016; Crema et al., 2016; Delgado et al., 2015; Downey et al., 2014; Rick, 1987; Zahid et al., 2016), zooarchaeological evidence of increased animal consumption (Stiner et al., 1999), and mitochondrial DNA analyses (Harpending, 1994; Excoffier and Schneider, 1999). These approaches have achieved some success, but are underpinned by several practical issues, such as unavailability of the desired data for modelling in the bioarcheological record, the requirement for two or more distinct temporal points for estimates of relative change, the difficulty of standardizing archaeological, zooarchaeological and DNA data, and lack of verifiability of such methods.

The rate of natural increase is a relatively simple demographic measure: the birth rate (births per 1,000) minus the mortality rate (deaths per 1,000) for a period or point in time, divided by 10 to convert it to a percentage (Population Reference Bureau, 2017). Its value as a paleodemographic measure has previously been noted by paleodemographers (Angel, 1969; Bocquet-Appel and Naji, 2006). The relationship between juvenile to adult ratios and total fertility rate suggests that an estimate of birth rate can be reasonably obtained (Bocquet-Appel and Masset, 1982; McFadden and

Oxenham, 2017), however, the mortality rate is somewhat more complex (Gage and Dewitte, 2009; Wood et al., 2002). The rate of natural population increase is population growth without migration though it should be noted that in demography, population growth is associated with further complexities. In contrast to fertility and birth rates, the rate of migration is very difficult to estimate and presents several theoretical and practical challenges (Clark, 1994; Burmeister, 2000). In the modern world, migration has a large impact on population growth (Zlotnik, 2004), however, its impact on the rate of natural increase is not so clear cut. Past populations may have experienced greater limits on migration due to lower population densities (Clark, 1994) and reduced mobility (Anthony, 1990), and with fewer limits on fertility, migration is anticipated to have had a relatively limited impact on the natural increase of past, in comparison to modern, populations. Further, in many cases, the aim of estimating population increase is to understand how a change in diet, economy, or lifestyle may have impacted on population health and size. In these circumstances, migration may still be of interest but as a separate research question, and therefore a somewhat different indicator may be more appropriate.

We propose that the rate of natural population increase is an optimal paleodemographic measure for questions relating to the impact of significant transitions and events with respect to the health and size of past populations. While excluding the potentially confounding factor of migration from the mix may initially appear to be an omission of valuable data, we believe that this is, in fact, of negligible impact and is indeed a practical improvement. The rate of natural increase avoids the complexities associated with measuring population growth and, when considered in the context of other archaeological evidence, may be equally valuable in cases where the extremes of little to no migration through to significant migration are indicated.

8.3. Materials and Methods

This study aimed to evaluate the relationship between the rate of natural increase and an age-at-death ratio. Due to the strong correlation achieved by McFadden and Oxenham (2017) between total fertility rate and the D0-14/D ratio (or the ratio of subadults aged 0-14 years to the entire sample), it was anticipated that the D0-14/D ratio would also correlate with the birth rate; a major component of the rate of natural increase. Additionally, the magnitude of the impact migration has on the rate of natural increase and the age-at-death distribution was also of interest. The use of modern data is based on the uniformitarian theory of paleodemography proposed by Howell (1976) and the generalized pattern of human mortality summarized by Wood et al. (2002). Data for 58 countries (SI) from the United Nations Database (2017) for the year 1960 was used, being the earliest year for which the United Nations recorded the data of interest. Other reasons for targeting this period are that this year predates the widespread use of the contraceptive pill (Liao and Dollin, 2012) and represents a greater range of natural increase rates than many of the later years. The following data were extracted: birth rate, mortality rate, age-specific deaths and net migration rate. The rate of natural increase (%) was calculated by subtracting the mortality or death rate (D_r) from the birth rate (B_r) and dividing by 10:

$$Rate\ of\ Natural\ Increase\ (\%) = (B_r - D_r) / 10$$

First-order correlation tests of the D0-14/D ratio to the calculated rate of natural increase and the net migration rate were performed, and the rate of natural increase to the net migration rate. Normal probability plots were used to identify potential outliers. It was expected that the relationship between the D0-14/D ratio and the rate of natural increase would be linear, as an increasing proportion of juvenile deaths was anticipated to predict an increased rate of natural increase. All statistics were calculated using StatsDirect 3 (2016). Rules for identifying outliers followed those of Pennsylvania State University (2017).

8.4. Results

In the first instance, a correlation of r=0.835 between the D0-14/D ratio and the rate of natural increase was observed. When residuals were plotted one outlier (Tonga) was identified from the normal distribution. In accordance with standard procedure (Pennsylvania State University, 2017), a normally distributed probability plot of residuals was observed with the removal of the outlier. This outlier was excluded from the remainder of analyses.

Descriptive results and first order correlations are provided in Table 8.1. With the outliers removed, a correlation of r=0.863 (95% CI 0.777 – 0.917) was achieved between the rate of natural increase and the D0-14/D ratio. The correlation between the rate of natural increase and migration was not significant (r=-0.158, p>0.05 two-tailed), with migration accounting for a minute amount of the variance ($r^2=0.025$). Similarly, migration was not a significant predictor of the D0-14/D ratio (r=-0.232, p>0.05 two-tailed).

	Rate of Natural Increase	**Net Migration Rate**	**D0-14/D Ratio**
n=	57	57	57
Average	2.01	-2.04	0.26
Standard deviation	1.03	7.84	0.19
	Correlation with rate of natural increase	r=-0.158	r=0.863
	95% confidence interval (CI)	-0.402 – 0.107	0.777 – 0.917
		Correlation with net migration rate	r=-0.232
		95% confidence interval (CI)	-0.465 to 0.030

Table 8.1. Descriptive statistics and first-order correlations for the rate of natural increase, net migration rate, and D0-14/D Ratio

Simple linear regression produced the following equation to calculate the rate of natural increase:

$$\text{Rate of Natural Increase (\%)} = (10.06 \times D0\text{-}14/D) - 1.61$$

8.5. Discussion

A strong relationship (r=0.863, 95% CI 0.777 – 0.917) between the D0-14/D ratio and the rate of natural increase was identified. In the absence of the mortality rate, the rate of natural population increase and the total fertility rate are inextricably linked, as they are both based on a linear relationship with juvenile mortality. This limits the interpretations that can be made based on the available data, as a high fertility rate will always be associated with high growth, and vice versa, when using this method. This should be noted when evaluating both measures. Additionally, given that a number of commentators (e.g., Konigsberg and Frankenberg, 1994; Milner et al., 1989;

Sattenspiel and Harpending, 1983) have reported that fertility has a greater impact on the age-at-death distribution than mortality, this may limit the sensitivity of the method proposed in this study to mortality. Another potential limitation of the method is that it is based on a single year of data, whilst burial samples will very rarely represent a single year. It seems logical that applying the method to a burial sample would have the effect of averaging the rate of natural increase for the period of the burial depositions. Nonetheless, archaeological context is key, and consideration should be given as to whether the sample is substantial and cohesive enough to be taken as representative of a single population.

For this method, the D0-14/D ratio was again used based on age-at-death data from real populations to estimate the rate of natural increase. A limitation of this study is that the effectiveness of the method on samples where infant underrepresentation is indicated is yet to be evaluated. Therefore, at this time the rate of natural increase estimator is recommended for sites where good infant representation is indicated. For instance, sites in Southeast Asia are known to experience good skeletal preservation overall and infant representation within the expected range (Domett, 2001; Domett, 2004; Domett and Oxenham, 2011; Tayles, 1999; Tayles et al., 2007). It is essential that researchers undertake due diligence in evaluating potential sample bias before applying this, and other paleodemographic, measures. McFadden and Oxenham (2017) provide a discussion of the potential implications of age estimation error on this measure. In summary, employing the D0-14/D ratio effectively reduces the potential impact of age estimation error to a single age group (those aged ~13-15 years of age).

McFadden and Oxenham (2017) outlined concerns regarding the use of life table data to calculate paleodemographic measures, which are based on the observation that the mortality data in life tables has been modelled, meaning they do not wholly represent the complexity and extent of natural variability in population dynamics. The use of ratios calculated from genuine age-at-death data as an alternative to data from life tables was proposed in McFadden and Oxenham (2017) and utilized again in this study. In addition to mitigating some of the challenges and concerns associated with life table derived data, our approach is easily reproducible and verifiable. As noted by Axtell et al. (2002), the lack of reproducibility has been a significant impediment in archaeology, which has previously only been overcome through the use of modelling. The method proposed in this study addresses this issue, as it can equally be applied to the same and alternative datasets to verify accuracy. Further, the interrelationship of a greater range of population dynamics and variables can be explored. In this study, the use of census-based data has permitted us to evaluate the impact of migration.

Our method does not account for population increase through migration, however, this study has determined that migration has a negligible impact on the rate of natural increase and the D0-14/D ratio. Migration has an insignificant relationship with both measures ($p>0.05$ two-tailed) and accounts for only 2.5% and 5.4% of the variation in the rate of natural population increase and D0-14/D ratio respectively. This is true for a sample where the migration rate ranges from 17.60 to -28.19 per 1000. It should be noted that this insignificant relationship does not negate the impact of migration on population growth, but solely its impact on the rate of natural increase and the proportion of juvenile deaths. As previously mentioned, migration may be expected to have occurred at a lower rate in past populations, where long-distance movement was more onerous and population densities were lower (Anthony, 1990; Clark, 1994). Where migration is evidenced, rates are difficult to estimate. The appearance of distinctive artefacts, cultural practices, and morphologically different skeletal remains have been used to indicate inward migration (Anthony, 1990). Clark (1994) raises a number of issues in the study of migration, including that migration is density-dependent and a phenomenon belonging to the protohistoric and historic periods, and that the scale and process of migration is difficult to differentiate in the archaeological record. Burmeister (2000) discussed further challenges, such as differentiating between cultural artefacts transferred through migration or through trade, but proposed that careful consideration of all available evidence, particularly functional artefacts such as pottery and residential architecture, may largely overcome the issue.

Recent studies have focused on isotopes and dates to estimate past migration, for example, Dupras and Shwarcz (2001) used oxygen and nitrogen isotopes derived from bone to identify migration in Egypt, and Collard et al. (2010) used density of radio-carbon dates for material culture in Britain spanning the Mesolithic and Neolithic to estimate population increase, which they argued was the result of migration of farmers. The availability of alternative methods of evaluating migration, the difficulty of estimating migration rates, and its negligible impact on the rate of natural increase for modern populations where migration is significant, makes a strong case for its exclusion from our measure of population increase. Based on our results, even where migration is invisible in the archaeological record, it is unlikely to skew the rate of natural population increase to any significant extent. Further, we suggest that the question of the impact of migration on a population is, in some cases, a separate one to the impact of subsistence or environmental change (though there are examples where the two are inextricable, for example, where climate change drives both), and that the rate of natural increase is more suitable for the latter.

Significant changes in subsistence are expected to have an array of impacts on fertility, mortality, disease, and nutrition. An increase in juvenile mortality, recognized as an indicator of fertility rate and population increase, is considered a signature of the NDT, for the most part associated with adoption and/or intensification of agricultural activities (Bocquet-Appel, 2002; Bocquet-Appel and Naji, 2006; Boquet-Appel, 2008). Bocquet-Appel (2002) argued that fertility increases in the early days of the NDT was shortly followed by mortality increases, causing population expansion initially, followed by nil growth due to an equilibrium in births and deaths. He suggested that this may have resulted from an increase in zoonotic diseases. Bocquet-Appel (2002) added that an equilibrium must have been rapidly achieved, as the alternative is explosive population increase. This theory was echoed by Cohen (2008), who asserted that the NDT resulted in a shift from moderate fertility and mortality populations to high fertility and mortality populations.

Evidence for increased fertility and population growth in the early stages of the NDT has been widely reported. In Neolithic Greece, Papathanasiou (2005) reported a rise in fertility, indicated by juvenile mortality, and a slight decline in health indicated by various paleopathological markers. Woodbridge et al. (2014) used pollen evidence of agricultural clearing to indicate rapid population increase in Britain. Buikstra et al. (1986) found evidence for increased fertility in Woodland period (1000BCE to European contact) American populations, which they argued was the result of high carbohydrate consumption and potentially the availability of a suitable weaning food. They suggested the population experienced stable mortality and growth driven by the high birth rate.

The evidence for the proposed increase in mortality during and following the NDT is less clear and, as noted by Cohen (2008), is largely theory based. While many paleodemographic studies estimate life expectancy, most are cautious in their interpretations with regards to mortality. This is potentially due to broad acknowledgement that the age-at-death distribution is more sensitive to fertility than mortality (Sattenspiel and Harpending, 1983) and the issues associated with estimating life expectancy and age-specific mortality rates (Gage and Dewitte, 2009; Johansson and Horowitz, 1986; Wood et al., 2002). Modelling has been proposed as an alternative means of estimating the mortality distribution, however, it has yet to see significant application, perhaps due to its seeming complexity (Gage and Dewitte, 2009; Wood et al., 2002). As such, hypotheses suggesting that increased fertility may have been counterbalanced by increasing mortality, or that low fertility estimates are resultant of low mortality, are yet to be rigorously tested on the available bioarcheological evidence. A multi-faceted approach incorporating alternative evidence of population increase and decrease, such as the use of radiocarbon dates cross-validated with juvenility indices, for example the study by Downey et al. (2014), may be more promising. Indeed, we believe that the rate of natural population increase provides a complementary approach against which spatiotemporal radiocarbon date approaches (e.g. Chaput and Gajewski, 2016; Crema et al., 2016; Delgado et al., 2015; Zahid et al., 2016) and mortality rate modelling can be cross-validated and cross-referenced.

Changes in mortality are just one explanation for fertility and growth rates that are inconsistent with broader NDT hypotheses. There is modern evidence in support of the association between increased sedentism and increased mortality (Page et al., 2016), however, in the absence of clear archaeological evidence all alternatives should be considered. Armelagos et al. (1991) noted that there may have been contraceptive practices in place before and during the Neolithic period, and that the assumed model of high fertility and high mortality causing a state of equilibrium is questionable due to the observable increase in population sizes. They argued that increased exposure to pathogens did not necessarily cause increased mortality, due to the systematic nature of exposure and, therefore, increased resistance to pathogens. Infants and the elderly would be most susceptible to disease due to underdeveloped and reduced immune responses respectively, while women would have experienced poorer health outcomes due to the reduction in interpregnancy interval (Armelagos et al., 1991). Bellwood and Oxenham (2008) reasoned that slower, or lesser, increases in population increase may be indicative of the means by which agricultural intensification has occurred, with the introduction of agriculture into new areas causing more rapid growth than in populations where agriculture has developed and intensified. While the relationship between the rate of natural increase and fertility and birth rates somewhat limits the interpretive power of the measure, estimates of natural increase that conflict with the traditional high fertility and high mortality model should not be dismissed. Alternative explanations should be considered where a different model is indicated by the bioarcheological evidence.

8.6. Conclusion

Several important questions are raised by Bocquet-Appel (2008), such as whether population increase associated with the NDT was rapid or gradual, whether it was storage or cultivation of food that determined the increase, and what impact such growth had on culture, lifestyle and health. The rate of natural population increase accounts for the disparity (or lack of) between births and deaths, and provides a valuable measure for evaluating the impacts of such changes on ancient population dynamics. A correlation of $r=0.863$ (95% CI 0.777 – 0.917) between the D0-14/D ratio and rate of natural population increase is reported. While the rate does not factor in migration, we believe migration should be measured independently as it is not always of interest to bioarcheological research questions and is very difficult, if not impossible, to measure from the age-at-death distribution. Moreover, this study has demonstrated that migration has a negligible relationship ($r=-0.158$, $p>0.05$) with the rate of natural population increase and D0-14/D ratio, even in modern populations where migration is significant. Past migration rates are likely to be lower than modern in general and, where significant migration has occurred in past populations, it may be expected that this will be otherwise indicated in the archaeological record. The sensitivity of the D0-14/D ratio to infant underrepresentation is yet to be evaluated and therefore this measure is recommended for sites where good infant representation is indicated. The rate of natural population increase should be sensitive to the impacts of the transition to agriculture and climate change on population dynamics. When appropriate skeletal data are available, estimating the rate of natural increase, along with other paleodemographic measures, has the potential to provide exciting insights into past populations and the human response to change. Indeed, at the very least, it has the potential to enlighten our understanding of one of the most significant events in the history of modern humans. We suggest that future research should further explore the demographic theory underpinning our results and that modelling should be undertaken to evaluate an even greater range of scenarios, including data from multiple years and the impacts of sample bias.

8.7. Acknowledgements

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9. The Impacts of Underenumeration and Age Estimation Error on the D0–14/D ratio and Palaeodemographic Measures

Chapters 7 and 8 provided new measures of fertility and population increase respectively, based on the ratio of infants and subadults to the total population. For these measures to be useful in various contexts in the Asia-Pacific region and throughout the world, it is essential to evaluate the potential impacts of sample bias. Infant and elderly underenumeration, and age-at-death estimation error, were simulated and the methods applied so that the actual fertility rate and RNPI, estimated rates, and biased estimates could be compared. Chapter 9 quantifies the robusticity and resilience of the methods from Chapters 7 and 8 so that they can be confidently applied.

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Signed Ms Clare McFadden

Contributed to overall question, refinement of arguments, argument formulation and editorial supervision of paper.

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Signed Prof Marc Oxenham

Note on Published Papers

A PDF copy of the paper as published can be found at Appendix 3.

The Impacts of Underenumeration and Age Estimation Error on the D0-14/D Ratio and Palaeodemographic Measures

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Rate of natural increase
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9.1. Abstract

The objectives of this study were to evaluate the impacts of infant and elderly underenumeration and age estimation error on previously reported measures derived from the D0-14/D ratio, specifically total fertility rate and the rate of natural increase. This study used data from the United Nations database for the year 1960. A two-step approach was taken: to test the stability of the relationship we examined the correlation between the D0-14/D ratio and population dynamics of interest with data omitted or misclassified to simulate a range of sample underrepresentation and age estimation error scenarios. To evaluate the practical implications, we used our existing equations to estimate total fertility and natural increase rates using the simulated differentially represented samples and calculated the standard error of the estimate. Correlations remained robust until a small number of infants and the elderly were represented. Where both infants and the elderly were underrepresented, as much as 75% of these age categories could be removed before accuracy of the equations was significantly compromised. Where either infant underenumeration or elderly underenumeration are suspected, our palaeodemographic measures maintain accuracy when up to 25% of the sample is missing. Age estimation error had a negligible impact. These measures demonstrated robusticity in a range of sample underenumeration scenarios, particularly for sources of bias that impact both infants and the elderly equally, and age estimation error. Where either infants or the elderly have been significantly underrepresented or omitted from the burial site, alternative measures may be required.

Highlights

- The applicability of the D0-14/D-based palaeodemographic methods to skeletal samples depends on the resilience of the methods to sources of bias
- This study has demonstrated the methods are robust when both infants and the elderly are underenumerated and that age estimation error has negligible impact.
- Alternative equations for fertility and the rate of natural increase are provided for samples with severe infant underenumeration.

9.2. Introduction

Underenumeration of infants and the elderly and age estimation error are known issues in bioarchaeology. For instance, differential burial practices can result in individuals and specific age groups being interred at a different location to the main burial site. In particular, children and infants have been known to be allocated to a separate cemetery (Guy, Masset, and Baud, 1997; Milner, Wood, and Boldsen, 2008). Preservation bias is also known to affect the representativeness of burial sites (Gordon and Buikstra, 1981; Djurić, Djukić, Milovanović, Janović, and Milenković, 2011; Lewis, 2007; Walker, Johnson, and Lambert, 1988; Weiss and Wobst, 1973). Age groups with lower bone density, specifically infants and the elderly, may not preserve as well as their more robust counterparts (Djurić et al., 2011; Gordon and Buikstra, 1981). Another concern with small and frail bones is recovery bias, where bones and indeed individuals may be missed or may remain unidentified in the excavation process (Pokines and De La Paz, 2016). With regards to age estimation, it has been well established that with increasing age there is also increasing error (Kemkes- Grottenthaler, 2002; Savall et al., 2016; Wittwer-Backofen et al., 2008). Some degree of error is to be expected at any age and is also highly dependent on the presence and preservation of skeletal elements and dentition, ancestry, and the method used to estimate age.

Such omission, underrepresentation or erroneous categorisation of particular age groups at burial sites may result in a skewed age-at-death distribution, which is highly problematic for palaeodemography. Paine and Harpending (1998) undertook modelling of the impacts of infant underenumeration and elderly age estimation bias on the age-at-death distribution and palaeodemographic measures such as crude birth rate and total fertility rate. They determined ageing-bias caused a 10-20% overestimation in calculations of crude birth rate, and infant underenumeration decreased birth and fertility estimates by 20-25%. As noted by Paine and Harpending (1998), while elderly age estimation bias can be predicted, underrepresentation is exceedingly difficult to quantify without the assistance of burial records, and as such the degree to which infants and the elderly are represented is often unknown. To avoid the bias introduced by infant underenumeration, palaeodemography has sought to exclude infants from the calculation of measures based on the age-at-death data (Bocquet-Appel and Masset, 1977; 1982; Buikstra, Konigsberg and Bullington, 1986; Milner et al., 2008; Seguy and Buchet, 2014a).

The implications of elderly underenumeration on palaeodemographic measures have been less thoroughly considered. Walker et al. (1988) evaluated the impacts of preservation bias on the age-at-death distribution using a 19th century cemetery sample with associated cemetery records. They found that whilst infants and elderly represented approximately 30% and 35% of the cemetery records, they each represented less than 5% of the burial sample. As noted by Cave and Oxenham (2016) the elderly have been neglected in bioarchaeological studies, largely due to the complexities associated with estimating age from skeletal degeneration and the presumption that people in the past experienced a much younger maximum age-at-death. In palaeodemography as well, the elderly have received minimal attention.

In two recent papers (McFadden and Oxenham, 2018a; 2018b), we provided new palaeodemographic tools for estimating the total fertility rate and rate of natural population increase from the ratio of deaths 0-14 years to total deaths (D0-14/D). Both tools were developed with samples with good preservation in mind, particularly those in Southeast Asia. However, as infant and elderly underenumeration are widespread issues, it is essential to evaluate the impacts of removing or underenumerating these age categories on our palaeodemographic measures if they are to be used more broadly. Further, it is beneficial to estimate the impact of age estimation error as this affects all skeletal samples to varying degrees. The applicability of the measures relies on their resilience against such biases.

9.3. Materials and Methods

We utilised the data as used in McFadden and Oxenham (2018a; 2018b) for this study, specifically: age-at-death data, fertility rates, birth rates and mortality rates from the United Nations Database (United Nations, 2017) for the year 1960. There were 48 countries with sufficient records for inclusion. Infants were defined as individuals aged 0-4 years and the elderly as those aged 45 years or over, for consistency with previous work including Bocquet-Appel and Masset (1977; 1982), Paine and Harpending (1998), and Walker et al. (1988). In order to simulate the effects of differential burial, preservation and recovery, a number of scenarios were evaluated: the omission and underrepresentation of infants only; the omission and underrepresentation of the elderly only; and the omission and underrepresentation of both infants and the elderly.

Based on average error rates from recent studies of dental and skeletal methods (AlQahtani, Hector and Liversidge, 2014; Rissech, Márquez-Grant, and Turbón, 2013), individuals aged 12-14 years may be estimated to be over 14 years of age, and individuals aged 15-17 years may be estimated to be 14 years or younger. In order to encapsulate these ages, and due to practicalities of the available data, we used age categories 10-14 years and 15-19 years. If anything, this should overestimate the impact of ageing bias. To evaluate the effects of age- estimation bias, we developed scenarios of under-ageing (where a proportion of individuals aged 15-19 years were erroneously placed in the 10-14 years category) and over-ageing (where a proportion of individuals aged 10-14 years were erroneously placed in the 15-19 years category). For the purposes of our palaeodemographic methods, under-ageing would overestimate the number of individuals categorised as 0-14 years, and over-ageing would underestimate the number of individuals in the 0-14 years category.

To test the practical value of the original equations when applied to differentially represented samples, the D0-14/D ratios for the omission, underrepresentation and incorrectly aged scenarios were calculated, and then the total fertility rate and the rate of natural increase were estimated using our standard equations (McFadden and Oxenham, 2018a; 2018b). For underrepresentation, the impacts of removing 75%, 50% and 25% of the relevant sub-samples were evaluated. For age estimation error, the impacts of misclassifying 75%, 50% and 25% of individuals for both positive age bias (over-ageing) and negative age bias (under-ageing) were evaluated. For positive age bias, the rates were applied to individuals aged 10-14 years, simulating the impact of these individuals being over-aged and excluded from the 0-14 years component of the D0-14/D ratio. For negative age bias, the rates were applied to individuals aged 15-19 to simulate the impact of these individuals being under-aged and included in the 0-14 years group.

To quantify the actual impact of differential representation and incorrect age-estimation on estimated fertility rates and rates of natural growth, the standard error of the estimate (SEE) was calculated using the estimated rates for each scenario, where the original regression equations and the differentially represented D0-14/D ratios were used to calculate an estimated rate (Y'), and the actual rates of fertility and growth (Y). The correlations between the estimates derived from underenumerated and incorrectly aged D0-14/D ratios, the wholly represented estimates, and the actual fertility and natural increase rates were also evaluated to determine whether the relationships were significant. This alone does not indicate practical value, but in combination with the evaluation of SEE indicates the robusticity of the measures in various contexts. All statistics were performed in Microsoft Excel (2016).

9.4. Results

Applying the Total Fertility Rate and Natural Population Increase Measures to Differentially Represented Samples

The SEE provides an overall measure of the accuracy of predictions. Lower error estimates indicate observations that are more closely fitted to the regression line. Table 9.1 provides the SEEs for all underenumeration and age misclassification scenarios in this study. Based on a wholly represented sample, the SEE for the D0-14/D ratio and total fertility rate is 0.742. Where infants were underrepresented by up to 25%, the SEE increased by approximately 9% to 0.810. With the elderly underrepresented by up to 25%, the SEE also increased by 9%. Beyond this, the error exceeded practical value. In contrast, where the infants and elderly were both underrepresented, the equations remained relatively accurate with up to 75% underrepresentation of infants and the elderly, with the SEE increasing by a maximum of 12%. For age estimation, the SEE was negligibly impacted.

Table 9.1 Standard Error of the Estimate (SEE) and correlations for differentially represented samples, the total fertility rate and the rate of natural increase

Representation	**Total Fertility Rate SEE**	**% difference in SEE**	**Rate of Natural Increase SEE**	**% difference in SEE**	**Correlation with Total Fertility Rate***	**Correlation with Rate of Natural Increase***
Wholly Represented						
100%	0.742	N.A.	1.491	N.A.	0.897	0.864
Infant Underrepresentation						

75%	0.810	9%	1.653	11%	0.898	0.857
50%	1.052	42%	1.944	30%	0.899	0.847
25%	1.498	102%	2.427	63%	0.897	0.834
0%	2.243	202%	3.246	118%	0.747	0.683
Elderly Underrepresentation						
75%	0.809	9%	1.382	-7%	0.895	0.871
50%	1.065	44%	1.360	-9%	0.886	0.877
25%	1.648	122%	1.636	10%	0.862	0.874
0%	3.377	355%	3.307	122%	0.731	0.750
Infant and Elderly Underrepresentation						
75%	0.744	0%	1.477	-1%	0.898	0.865
50%	0.758	2%	1.462	-2%	0.897	0.866
25%	0.829	12%	1.466	-2%	0.894	0.866
0%	1.455	96%	1.895	27%	0.733	0.707
Under-aged (15 - 19 years)						
75%	0.735	-1%	1.476	-1%	0.899	0.866
50%	0.730	-2%	1.463	-2%	0.901	0.868
25%	0.725	-2%	1.450	-3%	0.903	0.870
Over-aged (10 - 14 years)						
75%	0.748	1%	1.501	1%	0.895	0.862
50%	0.756	2%	1.512	1%	0.893	0.860
25%	0.764	3%	1.524	2%	0.891	0.857

*p<0.05 for all correlations

For the wholly represented D0-14/D ratio and the rate of natural increase, the SEE was 1.491. Where infants were underrepresented by up to 25%, the SEE increased by approximately 11% to 1.653. With the elderly underrepresented by up to 50%, SEE decreased by 9% to 1.360. Where both were underrepresented, SEE decreased insignificantly to 1.466, or an approximately 2% decrease. Again, for age estimation error, the impact on SEE was insignificant.

Correlations with Total Fertility Rate and Rate of Natural Increase

Descriptive statistics for the ratios and total fertility rate, and the rate of natural increase, are provided in Table 9.1. For this sample, the correlation between the D0-14/D ratio and the total fertility rate was r=0.897. Reducing the representativeness of the 0-4 years age category by 25%, 50% and 75% had a negligible impact on the correlation with total fertility rate. In fact, the correlation remained above r=0.800 until only 2% of the 0-4 years age category were represented. When the 0-4 years age category were excluded, the correlation was reduced to r=0.747. Similar results were obtained for elderly underenumeration, where the correlation remained strong until only 5% of the elderly sample was represented. Omission of the elderly resulted in a correlation of r=0.731. For the underenumeration of both infants and the elderly, representativeness of 75%, 50%, and 25% produced very nearly equivalent correlations.

Representation of only 1% of the infants and elderly resulted in a correlation of r=0.791, and exclusion of both infants and the elderly reduced this to r=0.733. For age estimation bias all correlations remained robust, even where 75% of individuals in the 10-14 year (over-ageing) or individuals in the 15-19 year (under-ageing) age groups were misclassified.

For the rate of natural increase, the correlation with the D0-14/D ratio was r=0.864. Infant underenumeration had a minor impact on the correlation with the rate of natural increase, with 75%, 50% and 25% underenumeration producing correlations of r=0.857, r=0.847, and r=0.834 respectively. The correlation remained above 0.800 until only 7.5% of infants were left. With infants omitted the relationship ceased to be of practical value (r=0.683). For elderly underenumeration, there was no statistically significant difference between the wholly represented sample and the 50% and 25% underenumerated samples. With the elderly omitted, the correlation was r=0.750. For both the infants and the elderly, there was no statistically significant difference between the whole sample, and the 75%, 50%, and 25% underrepresented samples. With only 2% of the elderly and infants represented, the correlation was r=0.798 and with both omitted the correlation was r=0.707. For the age estimation bias scenarios, the correlations with rate of natural increase were consistently strong.

9.5. Discussion

Preservation Bias: Robusticity of Palaeodemographic Measures

In any scenario it is difficult to quantify the representativeness of the age-at-death distribution of a skeletal sample. The results presented here demonstrate that our palaeodemographic equations for total fertility rate and rate of natural population increase can be confidently used for samples where up to 25% of infants or the elderly (that is, one or the other) are missing.

But how accurately can we ‘eyeball’ good preservation? Skeletal completeness is one means by which the degree of preservation is estimated and, whilst it falls short of a percentage, it may be used as an indication of the sample representation (Domett and Oxenham, 2011). These results provide assurance that if good preservation equates to representation somewhere between 75% and 100% for either infants or the elderly, then these methods remain accurate and applicable without adjustment.

If one were to assume that preservation bias impacts infants and the elderly to a similar extent, as indicated by work by Walker et al. (1988), then the total fertility rate and rate of natural population increase equations can be applied to samples where as many as 75% of the infants *and* elderly are missing with only a minimal impact on the accuracy of the methods. This is the result of the reduction affecting both the numerator and denominator of the ratio. As previously noted, it is nearly impossible to quantify the degree of underenumeration without cemetery records, however, the accurate applicability of these methods on samples with just 25% representation should give bioarchaeologists confidence that these equations can be used where overall poor preservation (as opposed to complete omission via, for example, differential burial) is indicated, with no adjustments to the equations or estimation of underrepresentation necessary. This produces a far more accurate result than the tradition of deliberate omission of infants from palaeodemographic methods.

For the total fertility rate, 25% underenumeration of infants or the elderly, and 75% underenumeration of infants and the elderly, increased the SEE by between 9-11%. For the rate of natural increase, the error increased by 11% with 25% underenumeration of infants, decreased by 9% with up to 50% underenumeration of the elderly, but subsequently increased by 10% with 75% underenumeration. For both infants and the elderly, SEE decreased by 2% with 75% underenumeration. These error rates suggest that not only does the relationship between palaeodemographic measures and the D0-14/D ratio remain robust, but that the ratio remains stable enough for use in our existing equations in a range of sample-bias scenarios.

The acceptable rate of error should be evaluated on a case by case basis and it is necessary with all methods to calculate standard error based on sample size. Paine and Harpending (1998) argued that error of 10-20% was unacceptable. Whilst in isolation these rates seem high, to outright reject such error contradicts the accuracy one can hope to achieve with palaeodemographic measures even in the best-case scenarios. As observed by Wood, Holman, O’Connor, and Ferrell (2002), there are limits to the detail researchers may credibly obtain from the age-at-death distribution. Further, even modern demographic predictions experience significant error rates despite being based on large volumes of data, living populations, and often complex calculations (for example, Khan and Lutz, 2007; Office for National Statistics, 2015). We suggest that the acceptability of such error should be evaluated on a case by case basis, in the context of the sample, interpretive framework, and research aims.

Missing Infants and the Invisible Elderly: Selective Burial Practices and Recovery Bias

Where representation for either age group (but not both) is below 75%, the correlations with total fertility rate and rate of natural increase remained significant, but the SEE was too high, in our opinion, for the existing equations to be used. In order to overcome this issue, we would need to be able to confidently estimate the percentage of representation we are dealing with in order to create a bespoke predictor, however, this is a highly unlikely scenario. We do not recommend our measures be applied to samples where infants appear to be significantly underrepresented, or the elderly appear to be significantly underrepresented. Scenarios where one of these age groups may be misrepresented, but not the other, include differential burial practices and recovery bias. In both cases, infants and juveniles are the more likely candidates, due to the known occurrence of child cemeteries (Milner et al., 2008) and small bones being more susceptible to recovery bias (Pokines and De La Paz, 2016). Where infants are seemingly well represented and there are low numbers of elderly individuals, it would be necessary to consider all potential explanations before pursuing a methodology. One such scenario that should be considered is lower overall life expectancy, which could mean the apparently low representation of elderly is a true reflection of the age-at-death distribution. Notwithstanding, the potential impacts of age-estimation bias against the elderly should not be ignored (see Cave and Oxenham, 2016).

Where infants, the elderly, or both are entirely omitted from the burial samples, the proposed palaeodemographic equations are not suitably accurate for use. For infant omission or significant underenumeration (a commonly seen phenomenon), we recommend the use of the following equations, noting the correlation is reduced to r=0.747 for total fertility rate and r=0.683 for the rate of natural increase:

$$Total\ Fertility\ Rate = (32.225\ X\ D5 - 14/D5 +) + 3.028$$

$$Rate\ of\ Natural\ Increase = (17.708\ X\ D5 - 14/D5 +) + 1.259$$

These equations were developed using the dataset of the present study and the same methodology as McFadden and Oxenham (2018a, 2018b), and where D5-14 is the number of individuals age 5-14 years at death and D5+ is the number of individuals aged 5 years or over at death. For elderly omission or severe underenumeration, or dual infant and elderly omission, linear regression may similarly be used to develop alternative equations which exclude these age categories, though accuracy of such equations will also be reduced.

Age-Estimation Error

In all age-estimation scenarios evaluated, the impact on accuracy was negligible. Both over-ageing and under-ageing of individuals within the range of error for the 14 years of age demarcation point does not appear to adversely impact upon the methods for estimating total fertility rate or rate of natural increase. This should provide researchers with confidence that the methods can be applied to samples of diverse origins and using a variety of age- estimation approaches.

9.6. Conclusion

Infant and elderly underrepresentation and age-estimation have historically been problematic for palaeodemography, with the traditional approach being to intentionally omit infants from palaeodemographic measures. The results reported here show that correlations between the total fertility rate, rate of natural increase and the D0-14/D ratio remain robust even with minimal representation of each age category, however, this alone does not mean our methods (McFadden and Oxenham, 2018a; 2018b) are suitable for underrepresented samples. In terms of practical application, where infant underenumeration *or* elderly underenumeration is suspected our palaeodemographic equations maintain accuracy when up to 25% of the sample is missing, based on the results of the standard error estimates. This may be applicable for samples where good, but not complete, preservation is indicated. Age estimation error for the relevant demarcation point (14 years of age) was found to have a negligible impact on palaeodemographic methods. An anomaly was observed where SEE was reduced by underenumerating the elderly by 25-50%, and it is suggested the theoretical cause of this be explored in further research. If both infants *and* the elderly are underrepresented, the D0- 14/D ratio remains relatively stable when as many as 75% of individuals are missing from the sample, and as a result our equations remain sufficiently accurate for use. A potential application of this is where preservational bias against those with low bone density is suspected. Where either infants or the elderly have been omitted from the burial site via differential burial rites, or where they have been significantly underrepresented due to factors such as recovery bias, alternative measures may be required. This study has highlighted the need for further experimental research into differential preservation of infants and, particularly, the elderly. Infant underenumeration has been a concern for palaeodemographers for some time, however, our results indicate that elderly underenumeration should be of equal concern. Ultimately, this study has shown palaeodemographic methods derived from the D0-14/D ratio to be robust and stable in a variety of sample bias scenarios.

9.7. Acknowledgements

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10. Detection of Temporospatially Localized Growth in Ancient Southeast Asia using Human Skeletal Remains

In Chapter 10 the RNPI method is applied for the first time. Skeletal samples from Southeast Asia were selected, as this is the region the tools were intended for, and the region has a well-established, chronologically robust, archaeological record which can be used to cross-validate the results.

Publication Information

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Declaration of Authorship

Composed question, formulation of arguments in manuscript, background research, statistical analysis, discussion and conclusion.

Signed Ms Clare McFadden

Contributed to overall question, refinement of arguments, argument formulation and editorial supervision of paper.

Prof Hallie Buckley

Contributed data.

Associate Prof Sian Halcrow

Contributed to overall question, background research, refinement of arguments, argument formulation, discussion, and editorial supervision of paper; contributed data.

MF Oxenham

Signed Prof Marc Oxenham (on behalf of the collaborating authors)

Note on Published Papers

A PDF copy of the paper as published can be found at Appendix 4.

Detection of Temporospatially Localized Growth in Ancient Southeast Asia Using Human Skeletal Remains

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Keywords: paleodemography; bioarchaeology; population growth; Neolithic Demographic Transition; juvenile ratio

10.1. 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 significant 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 palaeodemographic 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.

10.2. 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; DeWitte, 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, 1984; Buikstra and Konigsberg, 1985; Gage, 1988; Konigsberg and Frankenberg, 1994), and work by Hoppa and Vaupel (2002) and the attendees of the Rostock workshop 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; Bellwood et al., 2011; Oxenham et al; 2015; Oxenham et al., in press) 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 2008; 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.

10.3. 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 2008; Rispoli et al. 2013), although the exact rates and pattern of growth and 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. 10.1). 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.

10.3.1. 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).

10.3.2. Cong Co Ngua

Cong Co Ngua is located in northern Vietnam, 30km 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).

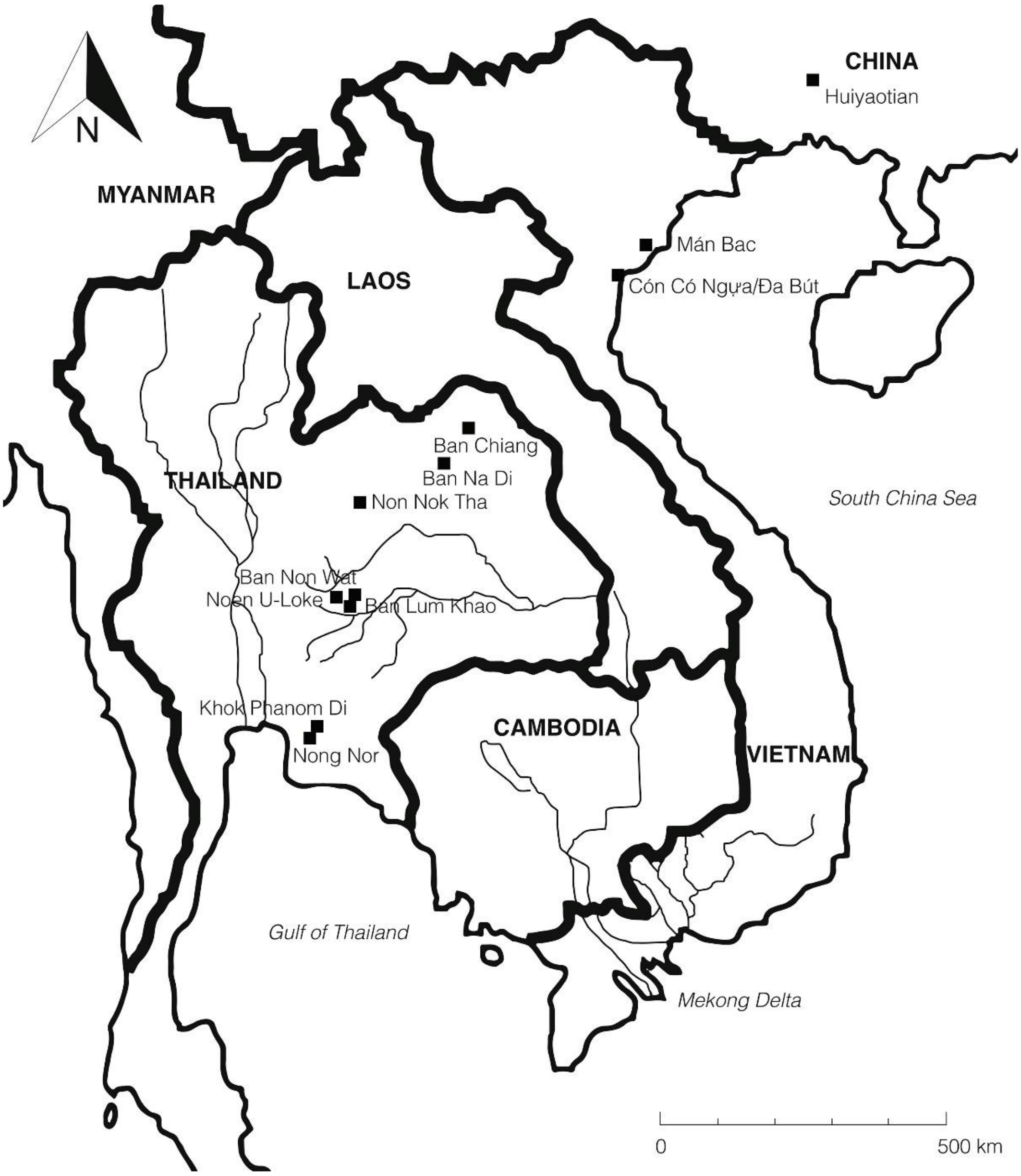

Figure 10.1 Map of Sites in Southeast Asia, adapted from Sarjeant (2017)

10.3.3. 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).

10.3.4. 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).

10.3.5. 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 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).

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

10.3.7. 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.

10.3.8. 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).

10.3.9. 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).

10.3.10. 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).

10.3.11. 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).

Sample	Site	Primary Source	Time Period	Mortuary Phase	Sample Source	Skeletal Sample n=	Radiocarbon Dates Source	Years BP	Do-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

Table 10.1 Sample information and descriptive statistics

10.4. Methods

10.4.1. 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.

10.4.2. 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.

10.4.3. 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 1,000 years. The years and rates of growth in Supplementary Table 10.S1 were used to calculate the number of individuals per original community member.

10.5. Results and Discussion

10.5.1. 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 10.1). 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. 10.2), while spatial proximity seems to be less of a predictor of likeness (Fig. 10.1). 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. 10.1), 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.

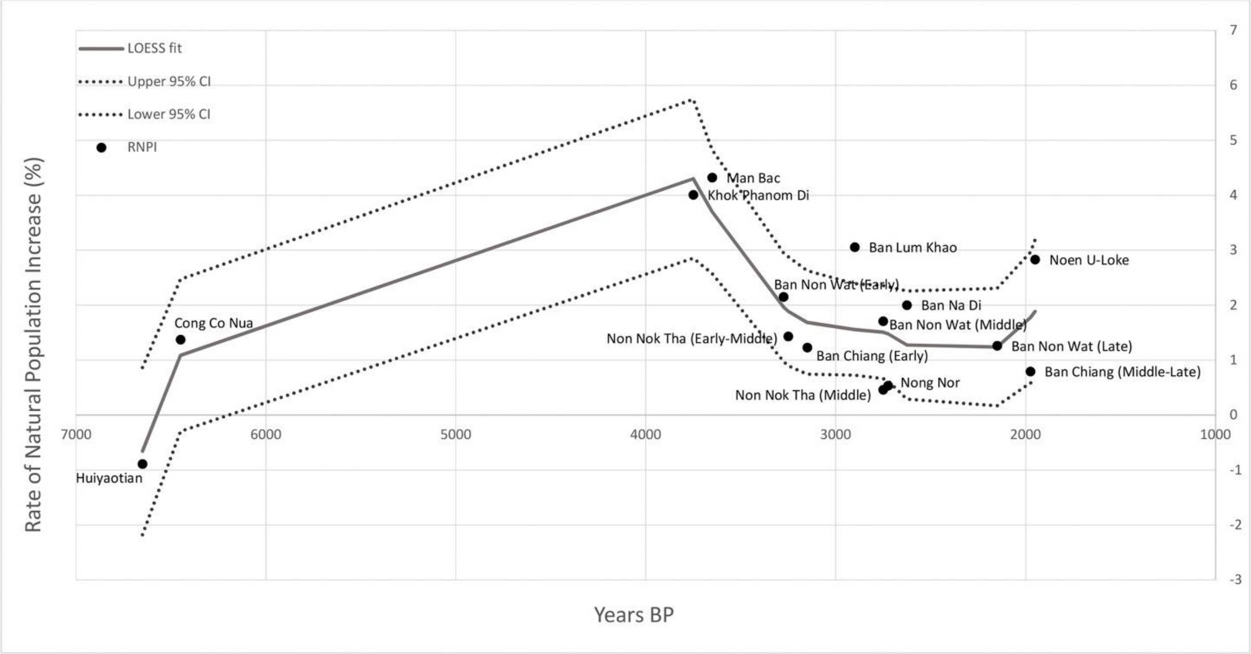

Figure 10.2 Rate of natural population increase (per annum) for 15 ancient Southeast Asian samples (LOESS fit with 95% CI)

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), 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 (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) needs to be further explored, as they each represent a range of attributes that warrant more detailed consideration. Temporal trends may result from changes in technology that occur in 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 associated and contributing factors are investigated.

10.5.2. 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; Bocquet-Appel and Naji, 2006; Bocquet-Appel, 2008; 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.

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. 10.2) 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 1,000 years. It is clear that if the rate of increase is applied as fixed for each of 1,000 years, the result is extreme: after 1,000 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 10.2).

Model	**Scenario**	**Estimated No. Individuals per Original Community Member**
Armageddon	The community is almost wiped out twice in 1,000 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 1,000 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.	1,335 individuals per 1 original community member

Table 10.2 Three models of fluctuating population growth.

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.

10.6. 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 age 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.

10.7. Acknowledgements

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10.8. Supplementary Materials for

Title: Skeletal Evidence of Temporospatially Localized Growth in Ancient Populations

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This supplementary text file includes:

Table 10.S1

Constant Growth Model	Years (n)	Rate of increase	Total increase	Number per original individual
+ve growth	1000	1.01	1010.0	20,959

Armageddon Model	Years (n)	Rate of increase	Total increase	Number per original individual
-ve growth	2	0.01	0.0	15
+ve growth	998	1.01	1010.0	

Occasional Catastrophe Model	Years (n)	Rate of increase	Total increase	Number per original individual
-ve growth	5	0.10	0.5	18
+ve growth	995	1.01	1009.5	

Regular Adverse Conditions Model	Years (n)	Rate of increase	Total increase	Number per original individual
-ve growth	100	0.80	80.0	1,335
+ve growth	900	1.03	930.0	

Table 10.S1 Rates and years for calculation of four models of population growth

11. Temporal Trends in the Colonisation of the Pacific: Palaeodemographic Insights

Following the successful application and validation of the RNPI technique in Chapter 10, the method is applied to skeletal samples from the Pacific Islands where the archaeological narrative for population growth is far more limited. It is hoped that this will provide new insights into population dynamics at the time of and following colonisation of the islands and archipelagos of the region. Specifically, it aims to compare the temporal trend against the time since colonization trend, in an effort to identify population responses to chronologically absolute and chronologically relative events.

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Signed Ms Clare McFadden

Contributed to overall question, background research, refinement of arguments, argument formulation, discussion, and editorial supervision of paper; contributed data.

Prof Hallie Buckley

Contributed to background research, refinement of arguments, argument formulation, discussion, and editorial supervision of paper.

Prof Richard Walter

Contributed to overall question, refinement of arguments, argument formulation and editorial supervision of paper.

MF Oxenham

Signed Prof Marc Oxenham (on behalf of the collaborating authors)

Temporal trends in the colonisation of the Pacific: Palaeodemographic insights

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Keywords: palaeodemography; bioarchaeology; population growth; Pacific archaeology; population dispersal

11.1. Abstract

The colonisation of eastern parts of the Pacific Islands was the last phase in the preindustrial expansion of the human species. Given the scale and challenges of the endeavour it is unsurprising that scholars have long been interested in understanding the conditions that drove and supported the exploration and colonisation of the Pacific. There has been speculation as to the influence of demographic factors, either as drivers or in some way regulating the rate and success of human expansion, but testing this has proven challenging. This study evaluates two hypotheses of population dynamics: the adaptation/resilience hypothesis proposes that populations respond to localised environmental conditions and changes in subsistence strategy, technology, differences in pathogen loads, and other events that occur at different times in different places, while the temporal hypothesis proposes that populations respond to major events such as climate change that occur in a region at an absolute point in, or over an absolute period of, time (noting that the two hypotheses are not mutually exclusive). Applying new methods for estimating the rate of natural population increase from human skeletal remains, this study utilised 23 samples to evaluate trends in population increase following the human expansion into the region. The results indicate a trend in population growth following colonisation, with initially high population growth, followed by a significant decrease and subsequently an increase growth rates. The lack of a temporal trend may represent a high degree of heterogeneity in the impacts of climate change on individual archipelagos and islands.

11.2. Introduction

The colonisation of eastern parts of the Pacific Islands was the last phase in the preindustrial expansion of the human species. Near Oceania, including the islands of New Guinea, the Bismarck archipelago and parts of the Solomon Islands, were colonised during the Upper Pleistocene some 40,000-30,000 years ago (Figure 11.1). In Near Oceania the islands are mainly of continental origin, they are geologically and ecologically complex and diverse, and include many large, inter-visible islands which could be located and settled with minimum levels of sailing knowledge and technology (Green 1991). Around 4,000 years ago speakers of Austronesian languages, including members of the Lapita cultural complex, moved through island Southeast Asia and beyond the Solomon Island chain into Remote Oceania. In Remote Oceania the islands are predominantly of volcanic origin with lower levels of geological diversity and a steep, eastward-declining gradient in biodiversity. Here much more sophisticated navigation skills and sailing technology was required to discover islands, and the establishment of successful colonies was reliant upon a range of new adaptive skills. Yet by 700 years ago over 30 million km2 of ocean had been explored and settlements established on virtually every landmass that could support a human colony. The Polynesian triangle, representing a third of the earth's surface, had been settled from Hawaii in the north, to Rapa Nui in the east and Aotearoa (New Zealand) in the south. In addition to the establishment of colonies, trade and communication networks had developed in many parts of Remote Oceania that linked distant communities into dynamic interaction networks (Weisler 1998, Weisler and Walter 2017).

Given the scale and challenges of the endeavour it is unsurprising that scholars since the time of Captain James Cook, have been interested in understanding the technological and sociological conditions that drove and supported the exploration and colonisation of the Pacific. It has long been assumed that demographic factors played a major role; either as drivers or in some way regulating the rate and success of human expansion. In his 1984 volume, Kirch set out a theoretical model of post-colonisation demographic change based on a logistic model of growth. He argued that a high rate of population increase was essential to the success of colonising populations. Population levels would grow quickly but would stabilise as the carrying capacity of the environment was approached. The underlying assumption of the model is that many Pacific Islands represent pristine and plentiful environments which could easily sustain enormous population growth in the period immediately following colonisation. Kirch (1984) suggested that an initial rate of natural population increase

(RNPI) of 4% was plausible, based on comparisons with historic data from Pitcairn Island. Testing this model against life tables generated from skeletal data from the Marquesas, Tonga and Hawaii proved problematic, however, due to the quality of the dating record.

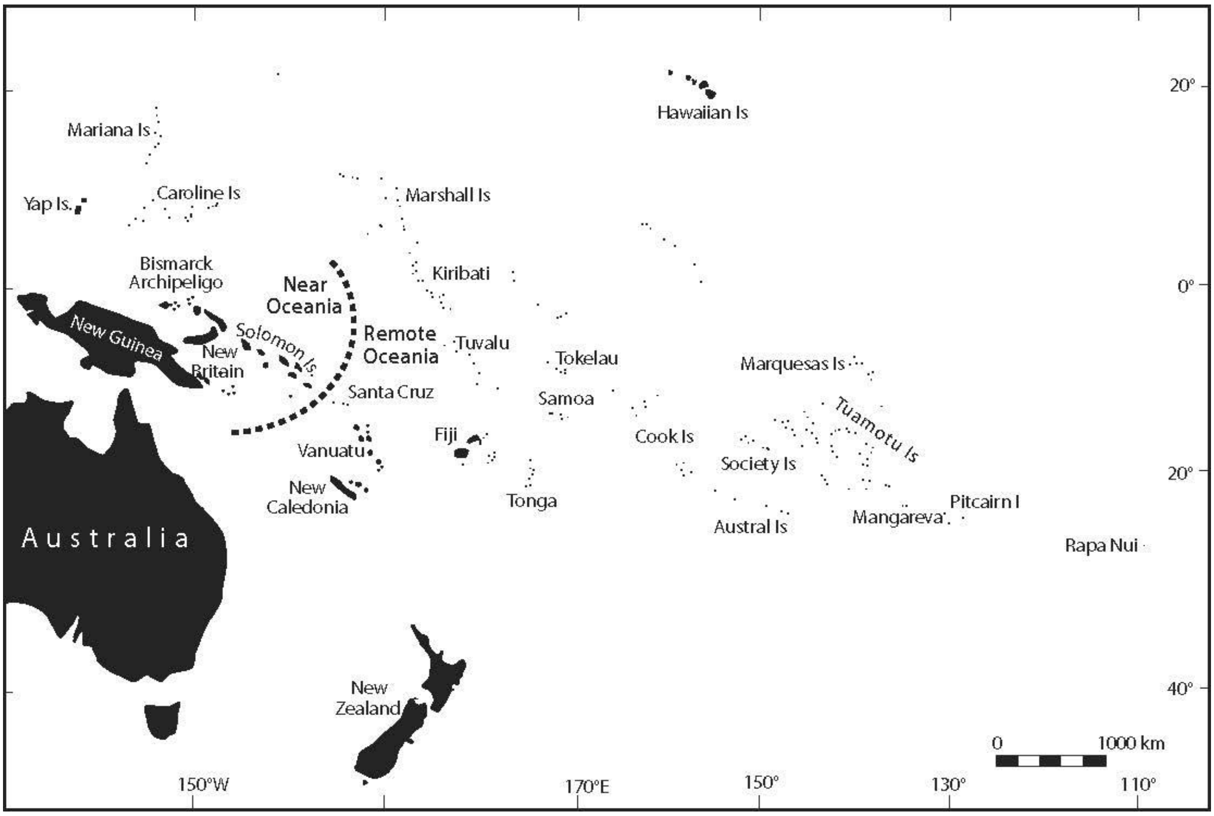

Figure 11.1 Pacific map showing Near and Remote Oceania

Clark (1988) agreed fundamentally with Kirch's (1984) model for Pacific population growth, but disputed the extrapolation of data from sites, to islands and archipelagos. Further, he cited evidence for significant population density in the region at the time of European contact, which contrasted with Kirch's (1984) model of a stable or declining growth rate in late prehistory. Clark (1988) noted that the rate of growth may have slowed but absolute population numbers continued to increase. Sutton and Molloy (1989) critiqued previous studies, particularly Kirch (1984), suggesting that Pacific palaeodemography was underpinned by erroneous assumptions regarding the growth curve, density dependency and mortality. They argued against Kirch's (1984) view that carrying capacity limited population growth across islands and archipelagos. Observing that the age at death distribution is more sensitive to fertility than mortality, Sutton and Molloy (1989) re-analysed the data from Kirch (1984) as well as some additional datasets and concluded that late prehistoric fertility rates were varied, rather than generally low as island carrying capacity was reached. However, such differences do not necessarily negate the limiting effect of carrying-capacity and could indicate variability in the rate at which populations reached the limits of their local environment. Brewis (1995) argued that the demography of each island and archipelago was unique due to differing social and ecological contexts, but that island living also brings about consistent challenges that may even transcend time and major events, including European contact. She agreed that prehistoric populations were probably on a path towards equilibrium, before suffering a near-catastrophic collapse at the time of European contact. Nonetheless, she also suggested that Pacific populations were likely often in a state of flux with seasonal or irregular environmental pressures impacting on population dynamics. Catastrophic events such as cyclones, droughts, tsunamis, volcanic eruptions and flooding would have impacted upon populations at the local level. This is well documented, for example, in the case of the failure of the breadfruit crop in the Marquesas that devastated local populations between about 1800 and 1803 (Thomas 1990).

In addition to environmental stressors, human action also influenced demographic processes. As Kirch (1984:123) observed, “Polynesians actively manipulated, modified, and, at times, degraded their island habitats, producing ecological changes which were fraught with major consequences”. Environmental manipulation (Anderson, 2002; Burley, 1998; Kirch et al., 2004; McCoy and Graves, 2010), changes in subsistence (Commendador et al., 2013; Field et al., 2009; Kinaston et al., 2014; Richards et al., 2009), regional differences in pathogen loads, and evidence of ill-health (Kirch, 2000; Buckley, 2006; Buckley and Oxenham, 2016; Buckley, 2016) are indicated throughout the history of the Pacific Islands. However, it is highly likely that a complex and multidirectional relationship existed between these variables and population dynamics. A possible indirect archaeological indicator of population pressure is the record of fortification construction. Kirch (1984) framed palaeodemography in the context of ecological and cultural stressors, but believed that conflict and fortification was a response to increasing populations and subsequent territoriality. This, he argued, was particularly evident on islands and archipelagos where colonisation occurred relatively late, including Hawaii and New Zealand. Field and Lape (2010) reported that peaks in fortification construction in some of the Pacific Islands may have coincided with periods of severe climate conditions associated with the Little Ice Age and El Nino Southern Oscillation. Although they argued against population pressure as a prime driver in fortification construction, there is clearly a complex relationship with environment, ecology, and sociocultural change, with populations both influencing and being influenced by such factors.

Beyond the theoretical modelling of population dynamics, several researchers have developed demographic models from skeletal sources. This includes analyses by Kirch (1984), Sutton and Molloy (1989), and Pietrusewsky and colleagues (Pietrusewsky et al., 1991; 1994; 1997; Pietrusewsky and Douglas, 1994) which have utilised traditional methods (Bocquet-Appel and Masset, 1982; Buikstra et al., 1986) that excluded children under five years of age. Others have drawn population inferences from house size and relative frequency (Kirch 1984; Kirch and Rallu, 2007), and, most recently, from demographic temporal frequency analyses (dTFA) (Fitzhugh et al., 2017). Utilising newly available skeletal data and tools that incorporate infants and children under five years of age to increase accuracy (McFadden and Oxenham, 2018; 2019), this study aims to provide new insights into palaeodemography and human adaptation and resilience in the Pacific Islands using human skeletal remains to reconstruct ancient population dynamics. Two hypotheses are evaluated: the adaptation/resilience hypothesis, and the temporal hypothesis.

The adaptation/resilience hypothesis proposes that populations respond (by way of adaptation or in terms of variable levels of resilience) to localised environmental conditions, including resource availability and constraints, and changes in subsistence strategy, technology, differences in pathogen loads, and other events that occur at different times in different places. The most prominent example of this is the transition to, and intensification of, agriculture, which occurred at different points in time around the world but produced a strikingly similar pattern in population dynamics during and after the event. Bocquet-Appel (2002; 2009), Bocquet-Appel and Naji (2006), and Kohler et al. (2008) used time since intensification of agriculture in Europe, north Africa and north America to evaluate trends in population response. In the Pacific, populations entered new, uninhabited lands and had to adapt and respond to the new ecological conditions they were faced with. This is expected to produce a similar trend in population growth over time during and since colonisation of each island and archipelago.

The temporal hypothesis proposes that populations respond to major events such as climate change that occur in a region at an absolute point in, or over an absolute period of, time. If climate change effects within the region had a significant impact on population dynamics, we would expect to observe a temporal trend starting at that point. The effects of climate change on populations has been evaluated in other parts of the world. Using dTFA methods, Tallavaara and Seppa (2012) identified an abrupt decline in population growth in association with late-Holocene cooling in eastern Fennoscandia. Similarly, Tallavaara et al. (2015) observed the effects of climate change on population dynamics between 30,000-13,000 years ago in Europe. This was corroborated by Burke et al. (2018) who found suitable human habitats were reduced in western Europe during the Last Glacial Maximum.

The two hypotheses are not mutually exclusive, and both may have influenced population dynamics in the Pacific. The results of both analyses are discussed in the context of the existing data and literature on climate, ecology, infectious disease, subsistence, technology, and social hierarchy and conflict in the region.

11.3. Materials

This study utilised published data for twenty samples and the authors' own data for three samples (Table 11.1). Whilst every effort has been made to ensure the reliability and accuracy of the data included in this study, it is pertinent to note the limitations and caveats that apply to both individual samples and all skeletal samples more broadly.

11.3.1. Age estimation

Where possible, unit records were reviewed to determine the number of subadults aged 0-14 years and the total number of individuals. In some cases, unit records were not published, and the reported numbers were utilised. If the reported age categories overlapped the 15 years of age demarcation, and unit records were not provided, the number of individuals aged under 15 years was estimated as a proportion of the age category (for example, if the age category was 12-16 years, 66% of individuals in that age group were estimated to be under 15 years of age). As per McFadden and Oxenham (2019), the error involved in this is very unlikely to have any meaningful impact on the estimated RNPI.

11.3.2. Sample representativeness

The earliest large cemetery assemblage from New Zealand is from Wairau Bar which dates to the early fourteenth century (Jacomb et al. 2014). Unfortunately, the sample was excluded due to the absence of any subadults, indicating significant bias as observed by Buckley et al. (2010). Teouma has been included in the study due to the presence of a significant number of infants (including many pre-term infants), however, these data are still likely skewed by the almost complete absence of children. This is suspected to be the result of this cohort being interred elsewhere.

It is possible that sample bias has occurred at other sites included in this study. Traditionally, skeletal samples with low infant and subadult representation have broadly been considered to be misrepresentative of the population they derive from due to differential deposition, poor preservation, or recovery bias. In this study, only samples where infants are not at all represented have been excluded. It is also important to note that the existence of some samples with low proportions of infants and subadults is necessary if we accept that there were periods of population decline in prehistory.

Uripiv and Vao are notably small samples and may not be representative of the populations from which they are derived. The sample for Mangaia represents two pre-contact sites, Tautua and Te Rua Rere, as census data is reported by period only (Anton and Steadman, 2003) and therefore it was not possible to extract data by individual site. These are the only two sites that are reported to cover the pre-contact period, and it is notable that Tautua only contains four individuals (Anton and Steadman, 2003). As such, the mixing of the samples is unlikely to significantly impact the RNPI, which is more representative of Te Rua Rere than Tautua.

Table 11.1 Skeletal sample set with estimate of colonisation date for island based

Site	Island/Island Group	Colonisation Date Estimate*	Age-at-death Source	n=	Do-14	Date Source	Date Range
Tautua and Te Rua Rere	Mangaia, Cook Islands	810 - 720 BP (Kirch 2017)	Antón and Steadman (2003)	63	26	Antón and Steadman (2003)	675-270 BP
Bourewa	Viti Levu, Fiji	3001 – 2790 BP (Irwin et al. 2011)	Author's own	27	2	Stantis et al. (2015)	750-150 BP
Sigatoka	Viti Levu, Fiji		Pietrusewsky et al. (1994)	52	8	Pietrusewsky et al. (2017)	1700-1300 BP
Hane	Ua Huka, Marquesas	784 – 692 BP (Allen 2014)	Pietrusewsky (1976)	39	15[1]	Anderson and Sinoto (2002)	850-750 BP
Apuruguan	Guam, Marianas	3200 – 3080 BP (Petchey et al. 2016)	Douglas et al. (1997)	152	44	Douglas et al. (1997)	950-429 BP
Naton Beach	Guam, Marianas		Pietrusewsky et al. (1997)	26	7	Pietrusewsky et al. (1997)	950-550 BP
Pu'u Ali'I	Guam, Marianas	950 – 740 BP (Athens et al. 2014)	Kirch (1984)	92	40	Dye (1992)	550 BP

Site	Island/Island Group	Colonisation Date Estimate*	Age-at-death Source	n=	D0-14	Date Source	Date Range
Mokapu	Hawaii, Hawaiian Is.		Snow (1974)	1171	333	Bowen (1974)	845-172 BP
Kualoa	Oahu, Hawaiian Is.		Pietrusewsky and Douglas (1994)	41	10	Pietrusewsky and Douglas (1994)	550-350 BP
Keopu	Oahu, Hawaiian Is.		Collins (1986)	340	77[1]	Collins (1986)	620-172 BP
Honokahua	Hawaii, Hawaiian Is.		Pietrusewsky et al. (1991)	712	278	Pietrusewsky et al. (1991)	1340-150 BP
Oleai Saipan	Saipan, Marianas	3200 – 3080 BP (Petchey et al. 2016)	Pietrusewsky et al. (1997)	35	5	Graves (1991); Pietrusewsky et al. (1997)	950-429 BP
Chelechol ra Orrak	Palau	3100 – 2900 BP (Clark et al., 2006)	Fitzpatrick (2003)	26	9	Fitzpatrick and Jew (2018)	3000 BP
Atele	Tongatapu, Tonga	2846 – 2830 BP (Burley et al., 2015)	Author's own	96	34	Stantis et al. (2015)	500-150 BP

Site	Island/Island Group	Colonisation Date Estimate*	Age-at-death Source	n=	Do-14	Date Source	Date Range
Talasiu	Tongatapu, Tonga		Herrscher et al. (2018)	21	4	Herrscher et al. (2018)	2600-2400 BP
Teouma	Efate, Vanuatu	3000 – 2870 BP (Petchey et al. 2015)	Author's own	78	15[1]	Petchey et al. (2014)	2940-2710 BP
Vao	Malekula, Vanuatu		Bedford et al. (2011)	7	1	Bedford et al. (2011)	2300-1900 BP
Uripiv	Malekula, Vanuatu		Bedford et al. (2011)	8	5	Bedford et al. (2011)	3090-2600 BP
Manukau	North Island, New Zealand	656 – 620 BP (Holdaway et al. 2014)	Campbell (2011) and Hudson (2011)	88	29[1]	Campbell (2011) and Hudson (2011)	320-260 BP
Nau Nau	Rapa Nui	721 - 550 BP (Hunt and Lipo 2006)	Gill (2000)	138	49	Commendador et al. (2014)	450-300 BP
Pain Haka	Flores	Pleistocene	Galipaud et al. (2016)	33	12	Galipaud et al. (2016)	3000-2500 BP
Nebira	Papua	Pleistocene	Pietrusewsky (1976)	38	4	Bulmer (1975)	720-280 BP

Site	Island/Island Group	Colonisation Date Estimate*	Age-at-death Source	n=	D0-14	Date Source	Date Range
Namu	Taumako, Solomon Islands	2783-2380 BP (Walter and Sheppard 2017)	Buckley (2016)	226	83	Whitehead et al. (1986)	420-250 BP

1. The number of sub adults aged 0-14 years was estimated due to age categories which overlapped the demarcation point.

*The colonisation date estimate is based on the earliest secure dates as discussed in the Materials section.

11.3.3. Dates for island settlement

The estimate for date of settlement of each island or island group is conservative. We have based these estimates on the earliest radiocarbon dates reported in the literature that appear to be from a secure stratigraphic context and on identified short-lived species. These dates will always post-date the actual colonisation date by some unknown time.

11.3.4. Sample dates

Similarly, the dates for each sample suffer from the typical uncertainties associated with archaeological dating. The sample with the lowest confidence date estimation is Mokapu. The site is known to be pre-European contact due to the absence of any European material (Bowen, 1974), however, even several decades after the original excavation, little more is known about its chronology. This places the age of Mokapu at any point between the settlement of Hawaii in 950-740 BP (Athens et al., 2014) and European contact in 1778 (or 172 BP). In this study, the midpoint for settlement (845 BP) and the known date of European contact (172 BP) have been used to determine the sample date midpoint (508.5 BP).

11.3.5. Island diversity

To account for variations in geographic and ecological diversity we have adopted the simple classification of island type used by Kirch (2017). In this system, islands are divided into four groups. 1) Island arcs or continental islands are the oldest island forms with complex geological histories and typically, large areas of arable land. They are concentrated in Near Oceania. 2) Volcanic high islands vary considerably in size but are sufficiently elevated to induce windward precipitation. They are typically basaltic but with a highly simplified geological history compared to continental islands. Tropical volcanic high islands have coral reefs and may subside through time to form atolls or submerged reefs. 3) Makatea islands are uplifted coral platforms that may, or may not, have a central volcanic core. Freshwater and arable soils are in shorter supply than volcanic high islands. 4) Atolls are low platforms of sand built on coral foundations which are frequently arranged in a ring around a central lagoon. Atolls have no standing water sources, no stone other than coral and only thin, patchy topsoils. Table 11.2 shows island form and size for each island that provided a sample set. Island size is included here as a rough proxy for relative carrying capacity.

Table 11.2 Island size and form (following Kirch (2017)) for each island that provided a skeletal sample set

Site, Island	**Island Form**	**Island land area (km2)**	**Estimate of arable land (km2)**
Tautua and Te Rua Rere **Mangaia**	Makatea	52	20[1]
Bourewa, Sigatoka **Viti Levu**	Island arc	10,388	935[2]
Hane, **Ua Huka**	Volcanic High Island	83	42[3]
Apuruguan, Naton Beach **Guam**	Makatea	544	10[2]
Pu'u Ali'I, Keopu **Hawaii**	Volcanic High Island	10,430	1,048[3]
Mokapu, Kualoa **Oahu**	Volcanic High Island	1,545	150[3]
Honokahua, **Maui**	Volcanic High Island	1,883	183[3]
Oleai **Saipan**	Makatea	115	3[2]
Chalechol ra Orrak, **Palau**	Makatea	459	10[2]
Atele, **Tongatapu**	Makatea	260	182[3]
Teouma, **Efate**	Volcanic High Island	900	15[2]

Site, Island	**Island Form**	**Island land area (km2)**	**Estimate of arable land (km2)**
Vao and Uripriv **Malekula**	Volcanic High Island	2,041	33[2]
Manukau, **North Island, New Zealand**	Island arc	113,729	4,549[3]
Nau Nau, **Rapa Nui**	Volcanic High Island	164	106[3]
Pain Haka **Flores**	Volcanic High Island	13,540	1,760[2]
Nebira **PNG**	Island arc	462,860	3,240[2]
Namu, **Taumako**	Volcanic High Island	10	0.1[2]

Basis of estimates:

1Kirch et al. 1995. Prehistory and Human Ecology in Eastern Polynesia: Excavations at Tangatatau Rockshelter, Mangaia, Cook Islands. Archaeology in Oceania 30: 47-65. (p. 49)

[2]CIA World Factbook (https://www.cia.gov/library/publications/the-world-factbook/fields/2097.html?countryName=&countryCode=&regionCode=n) - % of arable land for country used to calculate figure (this source used when figures weren't available in Kirch 1984).

[3]Kirch 1984. The Evolution of the Polynesian Chiefdoms. Cambridge University Press. (Table 10, p. 98.) Note: The total land area given for Mangaia in this table was anomalous, so Kirch et al. 1995 used instead.

11.4. Methods

The methods of McFadden and Oxenham (2018) were used to estimate the rate of natural population increase (RNPI). The method is based on the linear relationship between the ratio of juveniles to the total population (individuals who died aged 0-14 year divided by the total sample size, or D0-14/D ratio) and the RNPI in modern human populations. The D0-14/D ratios for each sample and equation produced by McFadden and Oxenham (2018) were used to calculate the RNPI estimates. In order to evaluate the trend in population growth following colonisation and the potential impacts of carrying capacity, adaptation, and technological and social change, the rates of increase for each sample were plotted based on the mid-point of the time elapsed since colonisation (see Table 11.1 and Table 11.3) of each island or island group (Figure 11.2). This follows previous studies where the time since agricultural introduction or intensification has been analysed (Bocquet-Appel, 2002; 2009; Bocquet-Appel and Naji, 2006; Kohler et al., 2008). Additionally, the RNPI estimates were plotted by years before present (BP) to evaluate the impacts of climate change which occurs on an absolute, rather than relative, temporal scale (Figure 11.3). The data from Nebira and Pain Haka were included in the temporal (years BP) analysis but were excluded from the years since colonisation analysis, due to being associated with islands or archipelagos that had very early colonisation, in some cases predating modern humans. This meant these samples could not be compared based on time since colonisation.

In order to evaluate trends in the time since colonisation and based on absolute chronology, the mid-point of the date range for colonisation and the mid-point of the years BP for the burial site were calculated .To plot the RNPI by years since colonisation, the mid-point of the years BP for the burial site was subtracted from the mid-point of the date range for colonisation, to give an estimate of years since colonisation. To plot the absolute chronological trend, the raw mid-point of years BP for each burial site was used. Linear and polynomial models were applied to determine the best fit based on significance and correlation.

The D0-14/D ratio has been shown to be unaffected by migration rates of between -2.82% and 1.76%, however, its resilience to migration rates greater than this are unknown (McFadden and Oxenham, 2018). In the study area, it is unlikely that migration events following the first wave of colonisation had a significant effect on population dynamics over the long term. Some islands (such as Rapa Nui) and some archipelagos (such as Hawaii and New Zealand) were probably settled once, or in a series of landfalls over a very short period and received no subsequent migrant populations. In all the islands and island groups apart from Rapa Nui, communication networks linked communities within and beyond the local archipelagos. There would have been regular movements of people, ideas and items of exchange within communication networks, but for the most part, there is little archaeological evidence for large-scale, post-colonisation migration, or population movement or replacement. The possible exceptions to this would be coastal Papua where both oral tradition (Neumann 1992) and archaeology suggest some large-scale movements of different culture groups over recent centuries. But again, this is unlikely to have impacted on population dynamics within the time frames and scale of resolution of the current study.

11.5. Results

The D0-14/D ratio, calculated RNPI (including 95% confidence interval (CI)), the mid-point of the estimated years BP, and the mid-point of estimated years since colonisation for each site are provided in Table 11.3. The estimated RNPI ranged from -0.86% for Bourewa to 4.68% for Uripiv. Plotting the data from Table 11.3 using a second order polynomial, the years since colonisation trend produced a moderate trend of $r^2=0.344$ ($p<0.05$, Durbin-Watson test within normal range), while the temporal trend showed greater variability ($r^2=0.122$, $p>0.05$, Durbin-Watson test within normal range).

Table 11.3 D0-14/D ratio, 95% CI, rate of natural population increase, mid-point of years since colonisation, and mid-point of years BP for each site

Site	**Island/Archipelago**	**n=**	**D0-14/D Ratio**	**95% CI**	**RNPI %**	**Mid-point Years Since Colonisation**	**Mid-point Years BP for Burial Site**
Mangaia	Cook Islands	63	0.41	0.29-0.53	2.54	292.5	472.5
Bourewa	Fiji	27	0.07	-0.03-0.17	-0.86	2445.5	450
Sigatoka	Fiji	52	0.15	0.05-0.25	-0.06	1395.5	1500
Hane	Marquesas	39	0.38	0.23-0.53	2.26	0	800
Apuruguan	Guam	152	0.29	0.22-0.36	1.30	2560.5	689.5
Naton Beach	Guam	26	0.27	0.10-0.44	1.10	2415	725
Pu'u Ali'I	Hawaii	92	0.43	0.33-0.53	2.76	295	550
Mokapu	Hawaii	1171	0.28	0.25-0.31	1.25	336.5	508.5
Kualoa	Hawaii	41	0.24	0.11-0.37	0.84	395	450
Keopu	Hawaii	340	0.23	0.19-0.27	0.67	621	224
Honokahua	Hawaii	712	0.39	0.35-0.43	2.31	100	745
Oleai Saipan	Marianas	35	0.14	0.03-0.26	-0.17	2450.5	689.5
Chelechol ra Orrak	Palau	26	0.35	0.17-0.53	1.87	0	3000
Tongatapu / Atele	Tonga	96	0.35	0.26-0.45	1.95	2513	325
Talasiu	Tonga	21	0.19	0.02-0.36	0.31	435	2500
Teouma	Vanuatu	78	0.19	0.10-0.28	0.32	110	2825
Vao	Vanuatu	7	0.14	-0.12-0.40	-0.17	835	2100
Uripiv	Vanuatu	8	0.63	0.30-0.97	4.68	90	2845
Manukau	New Zealand	88	0.33	0.23-0.43	1.71	348	290
Nau	Rapa Nui	138	0.36	0.28-0.44	1.96	375	375
Taumako	Solomon	226	0.37	0.31-0.43	2.09	2246.5	335
Pain Haka	Flores	33	0.36	0.20-0.52	2.05	n.a.	2750
Nebira	Papua	38	0.11	0.01-0.21	-0.55	n.a.	500

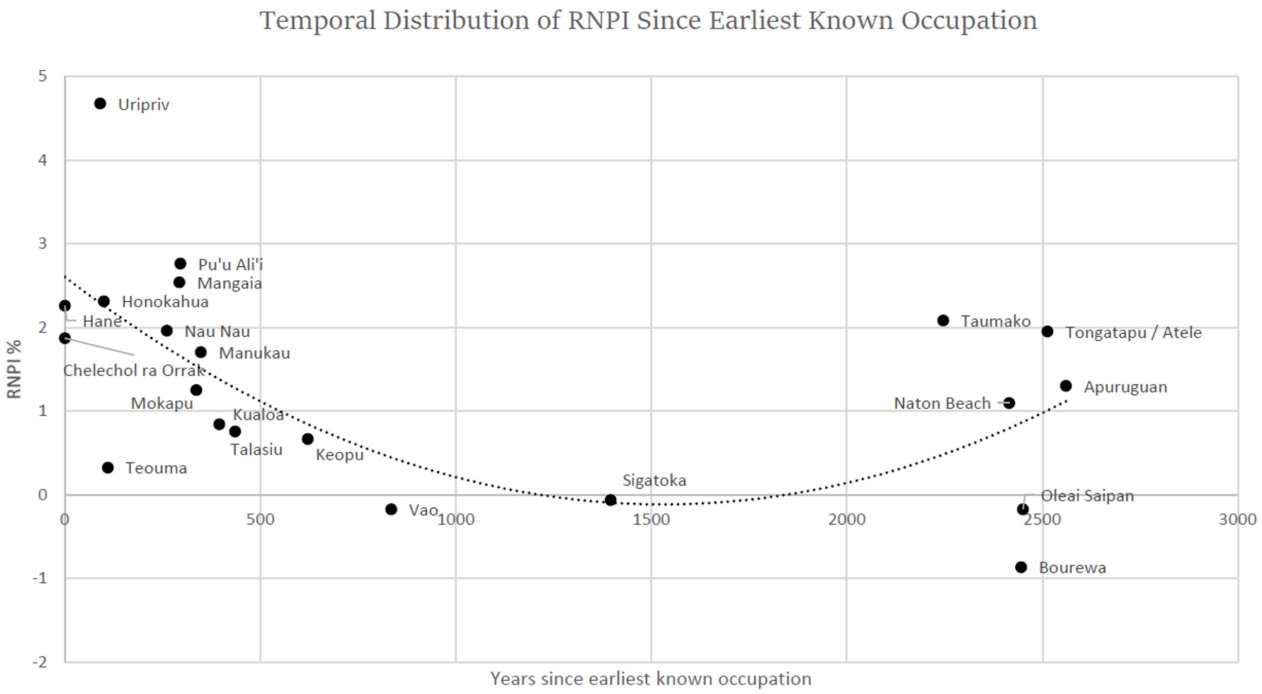

Figure 11.2 Distribution of sites by years since earliest known occupation date

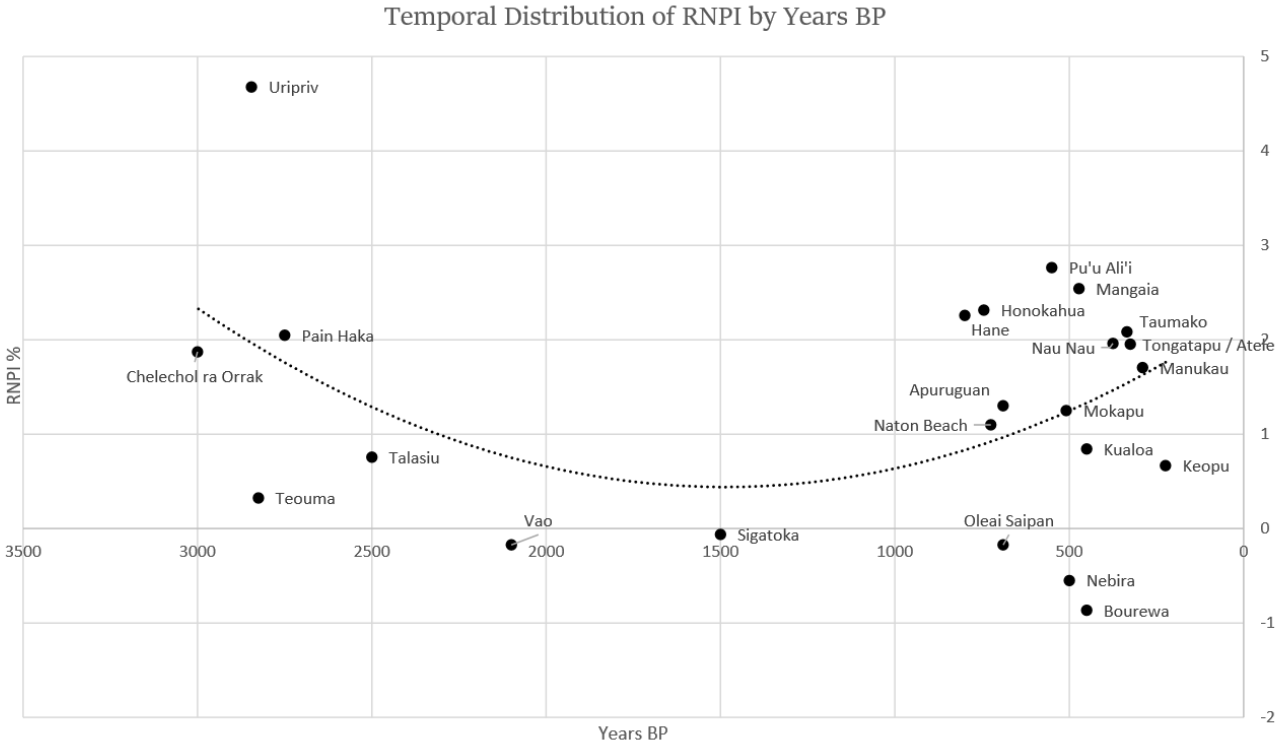

Figure 11.3 Distribution of sites by years before present (BP)

11.6. Discussion

11.6.1. Paleodemographic Findings

Our analyses produced a stronger and clearer trend for the adaptation/resilience hypothesis. High population growth at the time of, and immediately following, colonisation was observed for the majority of the islands and archipelagos included in this study. This was followed by a decline in growth and even, in some cases, a possible decline in populations (negative growth rates). Subsequently, it appears that Pacific populations generally began to increase again up until European contact, although this is not the case for all islands and archipelagos. For Hawaii, the five samples in this study are suggestive of population stabilisation over time with relatively slower growth in the late pre-contact period, consistent with early estimates by Kirch (1984). A similar trend was observed for Vanuatu although there were no late pre-contact samples available for this study. The Fijian samples indicated population decline but interpretations are limited by the small number of samples (n=2). The overall trend by years since colonisation closely mirrors that reported for Southeast Asian sites from the Neolithic to the Iron Age (McFadden et al., 2018), however, it is notable that the Pacific samples of similar antiquity show greater spatial homogeneity (where there are sufficient data to evaluate this) in contrast to observations from the Southeast Asian study. The temporal trend of years before present produced a far weaker trend and demonstrated significant variability from approximately 800 BP until European contact.

It is notable that a number of previous authors have speculated that there may have been very low growth rates (0.005 proposed by Kirch (1984) and 0.00875 by Brewis et al. (1990)) for early populations in the Pacific. As per McFadden et al. (2018), we argue that such low growth rates over long periods of time are to be expected and reflect the oscillating nature of population dynamics. We believe our method identifies some of these oscillations, allowing us to examine the conditions associated with the various peaks and troughs in population growth. It is also important to note that such low growth rates would involve an extraordinary level of self-regulation. Equally, we do not propose that these growth rates held steady over hundreds or thousands of years, but that these rates are representative of the samples from which they derive, for the period over which the sample was amassed (see McFadden et al. (2018) for further explanation of various oscillating models of growth).

11.6.2. Years Since Colonisation Trend

The trend in years since colonisation (Figure 11.2) allows us to evaluate the adaptation/resilience hypothesis, specifically the localised conditions that may have impacted populations as they colonised previously uninhabited islands. Some of the factors that may have impacted upon populations include dietary and subsistence adaptation, pathogen loads, resource availability (including faunal extinctions), and carrying capacity. As previously noted, if we assume that populations may have a similar response to the pressures of moving into a new environment, then we may anticipate a similar population response in the period following colonisation of an island. As this event takes place at different times in different locations, a trend in relative time since colonisation is supportive of this theory. Observations from the Neolithic Demographic Transition, which was also a multifactorial event with a range of impacts on populations, set a precedent for such a response.

Diet, Subsistence, and Adaptation

There is a multitude of evidence for dietary change following colonisation in the Pacific Islands. Swift et al. (2018) reported on changes in diet composition as evidenced by isotope analyses from commensal rats. While Richards et al. (2009) found the diet of the Hanamiai population in the Marquesas Islands to be largely terrestrial, Swift et al. (2018) identified a decreasingly terrestrial and increasingly marine diet at sites in the Marquesas, with the most significant changes occurring between 1200-1400AD respectively. A similar pattern was observed in Fiji between 1000-1200AD, while Mangareva, in French Polynesia, showed a consistent marine focus (Swift et al., 2018). At Teouma, the diet was found to include a mixture of marine and terrestrial animals (Kinaston et al., 2014), and Valentin et al. (2014) reported a decline in consumption of high tropic level foods approximately 500 years after colonisation, potentially indicative of a reduction in native animal resources through extinctions, other adaptations to environmental and climatic changes, or possibly social stratification. Commendador et al. (2013) found that the Rapa Nui diet was predominantly terrestrial, with a possible slight increase in marine consumption over time. Morrison and Hunt (2007) analysed shellfish assemblages from three stratigraphic and chronological zones from Nu'alolo Kai, Kaua'I, and found a shift over time from large shellfish, to smaller, more abundant shellfish and more diverse taxa. This, they argued, could indicate foraging intensification and resource depletion forcing a change in foraging strategy. There is also substantial diet variability between coastal and inland sites. Field et al. (2009) identified an increase in terrestrial sources between 2700 to 760 BP, but the retention of a predominantly marine diet. At Sigatoka, diet reportedly remained stable over 900 years, with a terrestrial focus. Field et al. (2009) concluded that larger islands likely had a greater terrestrial resource base, permitting faster incorporation into the diet. The research to date implicates a number of causes for dietary changes, including exhaustion of resources, climate change, and intentional shift in strategy.

Horticulture and agriculture can be seen as both an adaptation to ecological and environmental conditions, and a driver of ecological and environmental change. Kirch et al. (2004) reported on apparent dryland agriculture at Haleakala Volcano, Maui. Evidence of terracing, cultivation layers and digging-stick impressions were found at the site and the presence of sweet potato and ki root in residential sites suggest these were the main crops (Kirch et al., 2004). Kirch et al. (2004) suggested that the persistence of agricultural activities under less than ideal ecological conditions could be indicative of demographic and economic pressures. McCoy and Graves (2010) also discussed evidence for early agriculture in Hawaii, dating to between 1400 and 1650 AD. Land clearing, terracing, and other forms of landscape manipulation have been found (McCoy and Graves, 2010). Kirch (1982) discussed the impacts of agriculture on the Hawaiian ecosystem, suggesting that intensive land use and manipulation resulted in degradation of lowland areas, changes to vegetation, and extinctions. On the island of Mangaia, Cook Islands, evidence of deforestation through burning and the introduction of foreign plants following colonisation are indicative of horticultural practices (Kirch, 1996). These activities had a range of consequences including increased soil erosion. Burley (1998) noted that much debate exists around evidence for early agriculture and horticulture in Tonga, but that there is evidence of significant ecological impacts of human activities. Broadly, deforestation and erosion have been observed throughout Oceania in two patterns: late starting (in terms of time since colonisation) and slow changes in the larger western islands, and quicker, more substantial changes in the eastern islands (Anderson, 2002).

A major consequence of subsistence strategies, agriculture, and introduction of new species is the extinction of native wildlife. Using wetland coring data and bones of extinct birds from the ‘Ewa Plain, Athens et al. (2002) reported that avian extinctions occurred within the period immediately following colonisation of Hawai'i but were likely due to the destruction of native lowland forests by the introduced *Rattus exulans*. Using a systematic review of extinction data for Hawai'i, Boyer (2008) found that large and ground-nesting birds were the most susceptible to extinction in the period following colonisation, and suggested competition with and destruction by the common rat, coupled with land clearing for agricultural purposes, caused the extinctions. Kirch (1996) reported the extinction of at least 13 native birds on the island of Mangaia, Cook Islands following colonisation, and similarly argued for combined causes. Steadman (1995; 1997) has demonstrated that extinctions following colonisation have been far-reaching, occurring throughout Polynesia, Micronesia and Melanesia. He estimated a total loss in the order of 8000 species across Oceania's major islands, with human and introduced faunal predation, and habitat loss through land use and manipulation, being the major culprits. Terrestrial wildlife were also impacted, particularly frogs, crocodiles, lizards and tortoises (Anderson, 2002).

As observed during the transition to and intensification of agriculture, changes in diet and subsistence strategies can have major impacts on population growth. Depletion, and extinction, of certain species through consumption and possible behavioural shifts may represent a period of adaptation to the local environment. As the new inhabitants exhausted some resources, but equally became more familiar with those in abundance, changes in species selection may have occurred. The subsequent implementation of horticultural and agricultural practices represents a shift in economy and the ability to sustain larger populations. These factors may have contributed to the trend observed in Figure 11.2.

Local Ecology and Carrying Capacity

While adaptation to local conditions would have been essential to survival, there are conditions outside of human control that may have exerted influence over population growth. Availability of potable water and suitability of conditions for horticulture would have had major implications for subsistence strategy (e.g. Kirch, 2007). So too would have the extent of available arable land.

The carrying capacity growth model, or logistic growth model, states that populations grow exponentially until reaching an upper limit, known as carrying capacity or K, at which point growth plateaus. The model has been used to explain growth in a range of biological scenarios, but for human population growth it has been hypothesised that populations living in regions with restricted natural resources (including islands and migration into uninhabited areas) will grow exponentially to the point that the resource limits are reached (i.e. population consumption and resources are at equilibrium), then growth will cease and the population size will stabilise before resources are irreparably diminished (Diamond, 1977). Tuljapurkar et al. (2007) noted that there are challenges in applying a carrying capacity model, as it is highly dependent on contextual factors (including ecology, technology, and behaviour) when are often difficult to assess or determine from the archaeological record. There are further complexities, including Kirch and Rallu's (2007) observation that human populations rarely achieve maximum growth, and if so, do not sustain it for any significant period of time. Whilst elusive, many researchers believe that carrying capacity played a significant role in the palaeodemography of the Pacific (Kirch, 1984; Kirch and Rallu, 2007; Athens et al., 2007; Leppard, 2016). In contrast, Sutton and Molloy (1989) were highly critical of what they considered the misuse of an outdated demographic model. Importantly, they note that increase in warfare, agriculture and social complexity do not necessarily reflect population stress, citing Boserupian theory in support (Sutton and Molloy, 1989).

Disease Ecology

The potential influence of pathogens such as malaria impacting human settlement and population growth in the Pacific islands was first argued by Groube in 1993. The intense endemicity of malaria in Near Oceania and archipelagos west of and including Vanuatu has long been recognised as having a negative impacting on human health in this region (Lambert, 1941; Sayers, 1943) and its complete absence in Polynesia is posited as one factor allowing for the population sizes noted at European contact (Groube, 1993; Kirch, 2000). A possible association between the presence of malaria in the west and its absence in Polynesia has also been noted in the skeletal record as indicators of non-specific stress (Buckley, 2006). Malaria and other pathogens follow a similar decrease in intensity and number as the biodiversity of plant and animal resources available to colonising groups and may have influenced population growth in the past but is difficult to test directly as many do not leave diagnostic changes in the skeleton. However, the presence of nutritional deficiency diseases such as scurvy at Teouma (Buckley et al., 2014) and probably 'Atele, Tongatapu (Buckley, 2000), in young infants attest to the influence of disease on maternal and infant health in these populations. Indeed, skeletal pathology diagnostic of scurvy in foetal individuals at Teouma demonstrate the fragility of island environments and transitioning subsistence strategies for colonising populations.

11.6.3. Temporal Trend - Climate Change and the Little Ice Age

The trend in years BP permits us to evaluate the temporal hypothesis, specifically the potential effects of events that occur at absolute points in time. The Little Ice Age (LIA) is believed to have impacted upon climate in the Pacific from approximately 850 to 200 BP. Evaluating the temporal trend (Figure 11.3) in light of this, the LIA may be implicated during this period of greater palaeodemographic variability and even population volatility. If the LIA impacted upon islands and archipelagos in different ways, this may explain the variability in growth rates. Nunn (2007) argued that the LIA, or 'AD 1300 Event', caused widespread disruption to populations in the Pacific islands. Around 1350AD, sea levels fell 50-80cm and the temperature fell by approximately 1.4C in New Zealand (Nunn, 2007), and 0.56 in the New Zealand alps (Lorrey et al., 2014), and possibly more through the northern parts of the Pacific. Prior to this climatic event, humans are thought to have been dependent on coastal plain foods such as coconuts, taro and yams, but the falling sea level could cause a fall in water tables of coastal lowlands, thereby impacting upon key crops (McCall, 1994; Nunn, 2007). Marine dietary sources may also have been impacted by increased turbidity and exposure of coral reefs (McCall, 1994; Nunn, 2007). Increased precipitation is believed to have caused highland erosion and lowland sedimentation (Nunn, 2000). Nunn (2007) speculated that some islands may have had a reduction in food availability in the order of 80% over approximately 100 years, and that increased fortifications around this time may indicate increased conflict over resources. Bridgman (1983) argued that increased climate volatility, including variability in trade winds, increased storminess and increased volcanic dust, may all have prevented voyaging in the Pacific during the LIA. McCall (1994) suggested that marginal areas and small islands of the Pacific would have been abandoned as they were more subject to the pressures of resource reduction and climate volatility, forcing populations back on to larger and better resourced islands, whilst Nunn (2000) argued that large coastal settlements would have been abandoned, with populations moving to fortifiable habitats such as caves and hilltops.

The effects of the LIA have been challenged by a number of researchers, including Allen (2006) and Spriggs (2010). Allen (2006) cited evidence for cooling in the Pacific during the Medieval Warm

Period (named as such due to warming in the Northern Hemisphere) and found that the Palmyra coral record indicated a warm interval at 1300AD, but with nonetheless stormy and turbulent conditions. Allen (2006) also argued for intraregional variability, suggesting that the four climatic response regions identified by Salinger et al. (1995; 2001) may extend into antiquity and could be relevant to interpretations of climate volatility and change in the prehistoric Pacific. Spriggs (2010) suggested that human populations may have been prepared for and/or able to adapt to climatic conditions, due to ongoing instability including ENSO cycles. Regardless of its exact nature, climate volatility would have the potential to cause many of the diet and subsistence changes previously described. If we accept that there was intraregional variability in climate response (Allen, 2006), this could provide an alternative explanation as to why dietary shifts occurred at different times in different places. These changes, in turn, may have impacted population growth through the region. However, this model only offers an explanation for the lack of a trend from 800 BP (Figure 11.3). As previously noted, the models are not mutually exclusive and factors relating to both adaptation and climate change may be at play.

Limitations

Small sample sizes and infant underrepresentation were identified as two prominent factors that had the potential to influence model outcomes. With the negative growth sites (with potential infant/subadult underrepresentation), Teouma (where very few non-infant subadults were found), and Uripiv and Vao (small samples) removed, the temporal trend became significantly weaker ($r^2=0.0005$). The adaptation trend also weakened somewhat ($r^2=0.236$), but notably the shape of the trend was unchanged. The reduced correlation is not caused by any one site, providing some assurance that they may indeed be representative. There are only two points (Sigatoka and Vao) between 500 and 2500 years since colonisation, and this study would benefit greatly from the addition of more data points during this period. Furthermore, additional data for islands and archipelagos with only a small number, or narrow chronological range, of sites would improve the interpretive power of this study.

The mid-points for the estimated years BP and period of colonisation for each site have been used to establish the chronological and years since colonisation trends. However, there is potential that the mid-point of either date range does not accurately reflect the mid-point of the burial usage or occupation period, as the site may have experienced more or less usage at various points in time or the skeletal sample may have been deposited varying periods. Furthermore, the ranges for colonisation indicate a lack of certainty about the exact time of the event. As such, it is important to note that the estimates of RNPI are an average for the period over which the skeletal sample was deposited, and the colonisation mid-point indicates an estimate of the timing of the actual colonisation event. This may reduce the temporal precision of the results reported in this study.

11.7. Conclusion

There are two main interpretations to be made from the data presented in this study. Firstly, the trend in population growth following colonisation indicates initially high population growth, followed by slowing and even declining growth, and finally a shift back to higher growth rates. These results are in favour of the adaptation/resilience hypothesis. This trend is remarkably similar to that associated with the Neolithic Demographic Transition in mainland Southeast Asia (McFadden et al., 2018), however, it is only observed if the populations throughout the region are analysed as whole. It is possible that the similarity in trends reflects consistency in population response (adaptation and resilience) to major changes, over time. This model supports the view that populations with good capacity for growth colonised the Pacific islands and archipelagos, but growth slowed and declined as they underwent a process of adaptation to their new environment, which involved changes in diet, subsistence strategy and landscape manipulation. Subsequent to successful adaptation, populations were able to achieve higher growth again, with improved understanding and management of resources. This is a simplified model and we would certainly anticipate adverse conditions, such as disease and natural disasters, and favourable ones, to cause peaks and troughs on a smaller scale. Secondly, the lack of a temporal trend, particularly from 800 BP onwards, may represent a high degree of heterogeneity in the impacts of the LIA on individual archipelagos, islands, and even localised populations. As such, there is also evidence for the validity of the temporal hypothesis. Arguably, both trends support Golson's (1972) assertion that at the time of European contact the island populations were in different stages of demographic oscillation.

11.8. Acknowledgements

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12. Addressing the Research Questions and Hypotheses

This thesis set out to provide, and validate, a new palaeodemographic toolkit that addresses some of the persistent issues in palaeodemography and accommodates the bioarchaeological evidence available in Asia and the Pacific Islands. This chapter summarises the conclusions of the manuscripts that form the body of this thesis, and contextualises them in the research questions that the thesis aimed to address.

I. Can the prevailing issues of life tables, specifically assumptions of stationarity and smoothed data, be addressed by utilising data from non-stationary, real populations when developing palaeodemographic estimates?

As previously noted, the stationarity and stability of a population can have impacts upon its age-at-death distribution. As stationarity is rare, and some populations are unstable, developing methods from populations that are both may produce estimates that are not applicable to target samples. Additionally, model life table variables (fertility rate, age-specific mortality rates, etc.) are not independent and so they are not appropriate for the development of estimators. The methods developed in Chapters 7 McFadden and Oxenham (2018a) *The D0-14/D Ratio: A New Palaeodemographic Index and Equation for Estimating Total Fertility Rates* and 8 McFadden and Oxenham (2018b) *Rate of natural population increase as a paleodemographic measure of growth* utilised United Nations data from real, non-stationary populations in order to overcome the issues associated with life tables, specifically, non-stationarity of populations (Gage, 1988; Horowitz et al., 1988; Johansson and Horowitz, 1986; Milner et al., 2007; Sattenspiel and Harpending, 1983; Wood et al., 1992) and smoothed, circular data (McFadden and Oxenham, 2018a) (refer sections 2.4.3 and 2.4.1 respectively for further discussion). In doing so, the requirement to run simulations with slight variations in growth rates (Bocquet-Appel, 2002) has been eliminated. The data are not smoothed and represent raw census data (although some countries have had demographic modelling applied to fill in gaps in data or make minor corrections). Applying linear regression to these data has produced acceptably strong correlations of r=0.848 and r=0.863 (p<0.05) between the D0-14/D ratio and fertility and rate of natural population increase (RNPI) respectively, and thus non-stationarity does not appear to have compromised accuracy.

II. Can pre-historic fertility rates be reasonably estimated using age-at-death data including infants?

Chapter 7 sought to evaluate whether a new age-at-death ratio including infant deaths, D0-14/D, could be used to estimate the total fertility rate of populations. The ability to do this would significantly benefit work in Asia and the Pacific where good infant representation is often found (Domett and Oxenham, 2011; Pietrusewsky, 1976; Pietrusewsky et al., 1991; Tayles et al., 2007; Tayles, 1999). United Nations data from 52 countries for the year 1960 were used to evaluate the relationship between the ratio of individuals aged 0-14 years of age to the total population and the Total Fertility Rate. Based on linear regression, a correlation of r=0.848 between the D0-14/D Ratio and Total Fertility Rates was calculated. This correlation was significantly higher (p<0.05) than previous ratios, including the d5-14/d20+ by Bocquet-Appel and Masset (1977, 1982, 1996) and the ${}_{15}P_5$ index by Bocquet-Appel (2002).

It was anticipated that the inclusion of the 0-4 year age category would improve the correlation with fertility, due to the high sensitivity of infant mortality to changes in fertility rate: this study indicates this to be true. The regression equation provides an accessible means of estimating total fertility rates for past populations and provides a more accurate demographic measure for archaeological assemblages with good infant preservation. In this thesis, a new and highly tailored solution has been provided for the estimation of fertility rates in Asia and the Pacific, by making use of infant skeletal remains which are often well represented in the region. It is hoped that the method will provide new insights into fertility in ancient communities throughout Asia, the Pacific, and across the globe.

III. Can pre-historic population growth be reasonably estimated using age-at-death data including infants?

Chapter 8 aimed to identify whether the D0-14/D ratio (McFadden and Oxenham, 2018a) could be used to estimate a population growth proxy. The rate of natural population increase (RNPI) was selected as it provides a simpler measure of population growth, accommodating births and deaths and excluding the complexities of measuring migration (Burmeister, 2000; Clark, 1994). Using United Nations age-at-death data for 58 countries to calculate the RNPI and evaluate its relationship to the D0-14/D ratio, a correlation of $r=0.863$ (95% CI 0.777 – 0.917) was found between the D0-14/D ratio and RNPI. Again, linear regression provided an equation for calculating the RNPI with ease in past populations.

Migration was observed to have a negligible association with the RNPI and the D0-14/D ratio ($r=-0.158$, $p>0.05$), even in modern populations where migration is significant (Zlotnik, 2004). It is likely that past migration rates were lower than modern in general and, where significant migration has occurred, we would expect to find other indicators in the archaeological record (Anthony, 1990; Clark, 1994). As observed by Angel (1969) and Bocquet-Appel (2002), the RNPI provides a robust proxy for population growth. The method has been developed with good infant representation in mind and has provided new potential for insights into past populations and their responses to change, both in the Asia-Pacific region and more broadly.

IV. What is the impact of sample bias, including infant and elderly underenumeration, on the proposed palaeodemographic tools?

Chapter 9 McFadden and Oxenham (2019a) *The Impacts of Underenumeration and Age Estimation Error on the D0–14/D ratio and Palaeodemographic Measures* aimed to evaluate the impacts of sample bias on the aforementioned palaeodemographic measures of fertility (Chapter 7) and RNPI (Chapter 8) expanding on earlier work by Lovejoy et al. (1985) and Paine and Harpending (1998). The effects were evaluated in two ways: stability was tested by calculating the correlation between the D0-14/D ratio, fertility, and RNPI with data omitted or misclassified to simulate a range of sample underrepresentation and age estimation error scenarios. To quantify the practical implications, the equations were applied to simulated biased samples and the standard error of the estimate was calculated in a range of scenarios.

Correlations remained robust where both infants and the elderly were underrepresented, with up to 75% of both of these age categories removed before accuracy of the equations was significantly compromised (greater than 12% increase in standard error of the estimate). Where either infants or the elderly (not both) were underenumerated, the palaeodemographic measures maintained accuracy when up to 25% of the sample was missing but not beyond this. Interestingly, age estimation error had a negligible impact on accuracy of the estimates, likely due to the minimization by using a single demarcation point (14 years of age).

These measures demonstrated robustness in a range of sample bias scenarios, when both infants and the elderly were equally underrepresented (a very possible scenario based on Walker et al., 1988) and age estimation error. In the case of significant infant or elderly underrepresentation or omission, alternative methods may be needed. This evaluation of the impacts of sample bias on these methods should provide greater assurance regarding the accuracy and robusticity of the methods, when applied to samples throughout the world. It is hoped that this will assist bioarchaeologists in confidently adopting the methods outlined in this thesis and further reinforce the validity of the case studies presented in Chapters 10 and 11.

V. Can these methods be validated against the archaeological narrative in Southeast Asia?

Chapter 10 McFadden, Buckley, Halcrow, and Oxenham (2018) *Detection of Temporospatially Localized Growth in Ancient Southeast Asia using Human Skeletal Remains* detailed the application of the RNPI method to 11 sites and 15 chronologically distinct samples in Southeast Asia. Through use of the LOESS fitting procedure, a trend of temporal homogeneity and spatial heterogeneity was identified, whereby populations appear to have experienced a similar trajectory over time, although some temporospatially proximal populations demonstrated significant variation. The temporal trend was validated against the existing archaeological narrative for the region (Bellwood and Oxenham, 2008; Higham and Higham, 2009; Higham et al., 2015; Oxenham et al., 2013; 2018) and found to provide a strikingly similar pattern. The inclusion of infants produced estimates of RNPI that align far more closely with the archaeologically-indicated population trends of in the region.

Intraregional variability may be indicative of differing population responses to major technological, economic and sociocultural events. This would be consistent with the variable population response observed at the regional level in the global analysis of the Neolithic Demographic Transition, with Southeast Asia deviating from the traditional trend of decreasing health (Bellwood and Oxenham, 2008). Alternatively, such variability may reflect the absorption of smaller communities into larger neighbouring ones. Hopefully future studies will reveal the cause of this spatial heterogeneity. The validation of the RNPI method against the existing archaeological narrative is indicative of the accuracy and precision of the estimator when applied to bioarchaeological samples.

VI. Can the application of these methods provide insights into population dynamics in the Pacific?

Chapter 11 McFadden, Buckley, Walter and Oxenham (in review) *Temporal trends in the colonisation of the Pacific: Palaeodemographic insights* addresses this research question by applying the RNPI method to samples from the Pacific Islands and evaluating trends over absolute time, and relative time since colonization. When one examines the region as a whole, the analyses identify a moderate polynomial trend in RNPI when plotted by time since colonization, specifically, Pacific populations experienced high population growth at the time of colonization, which then decreased, and subsequently recovered prior to European contact. In contrast, the absolute chronological trend indicated a high degree of variability, particularly after 1300CE which coincides with the Little Ice Age. Existing literature on the climate, ecology, culture, technology, and social dynamics of the Pacific Islands in the past are used to contextualise the trends. These new results provide a number of possible interpretations regarding resilience and adaptation, both to climate events and volatility, and to the impacts of new ecological conditions.

This study demonstrates the potential for the methods proposed in this thesis to provide new insights into population dynamics in regions where there was previously limited, or low confidence, palaeodemographic research.

VII. How do palaeodemographic tools for the estimation of population growth based on skeletal remains compare to recent "dates as data" approaches?

In addition to their primary aims, Chapters 10 and 11 provided the opportunity to identify advantages and disadvantages of the RNPI method and compare these with dTFA techniques. The application of the RNPI method to samples in Southeast Asia and the Pacific has demonstrated its ability to detect high resolution temporospatial growth. The method can utilise small sample sizes and is not dependent on relative changes over time in a single region: it can be used for isolated sites and single case studies. dTFA methods require larger volumes of data and multiple temporal points to estimate changes in frequencies of radiocarbon dates (Downey et al., 2014; Peros et al., 2010; Shennan et al., 2013; Zahid et al., 2016). To support the requirement for large datasets, such methods are typically applied to geographically extensive and archaeologically well-studied regions rather than individual sites or communities.

The RNPI method has been demonstrated to be a useful tool for small datasets or where intraregional variability is suspected, by making excellent use of the data available and producing high precision estimates. Notwithstanding, the RNPI measure can be used in combination with existing methods, included dTFA (as per Downey et al., 2014) to develop a more holistic, and cross-validated view of population trends. In isolation, the RNPI method can provide a deeper and more localised understanding of the conditions that may impact upon population dynamics and, conversely, the way in which communities respond to change and events.

Limitations

There are several limitations of this thesis in addressing its aims. We cannot be certain that the data used to develop these methods accurately reflect the range of variation for past populations. The utilised data are skewed towards non-stationary but largely stable populations, and those with low rates of fertility and growth. Furthermore, as the populations included are large in size (country level) they are unlikely to reflect the degree of instability that may be observed in population sizes that we would expect to be dealing with in the palaeodemographic context. Future work should seek to apply the methods to small populations with accurate demographic records to evaluate their effectiveness in the face of greater instability.

The methods have not been tested on other modern samples to further evaluate their accuracy, nor have they been subjected to Monte Carlo simulations or formal bootstrapping. While the correlations reported are promising, the robustness of the methods needs further evaluation through a variety of scenario tests. At present, the potential for error is only reported and no attempts have been made to accommodate error or uncertainty into the methods. This limitation should be noted when applying the methods.

Preliminary validation has been performed by plotting estimates derived from the proposed methods and comparing the patterns to those derived from the archaeological record, however, this is a single case study. Further archaeological case studies, where a robust archaeological narrative exists, are needed in order to build confidence in the accuracy and precision of these methods. Such studies may highlight issues with the broad applicability of the methods, or may find them resilient to variability.

13. Summary and Concluding Remarks

In 1982, Jean-Pierre Bocquet-Appel and Claude Masset farewelled palaeodemography due to what they considered to be a range of theoretical and practical problems with the discipline (Bocquet-Appel and Masset, 1982). Their adieu was clearly premature and was met by a chorus of optimism regarding the state of the discipline (Buikstra and Konigsberg, 1985; Konigsberg and Frankenberg, 1994; Van Gerven and Armelagos, 1983). Nonetheless, several serious issues were raised and their publication can be credited with stimulating greater scrutiny and a flurry of new research in palaeodemography. Both the methods developed by Bocquet-Appel and Masset (1982, 1996) and Bocquet-Appel (2002) and the critical discussion they stimulated have provided the foundations for this thesis.

Wood (1998) argued that palaeodemography was hindered by its empirical focus and advocated for a theory-based approach to the study of past population dynamics. A lack of practical awareness, however, can undermine methodological work if it is perceived to be too complex to apply. Methods of age-at-death profiling proposed by Wood et al. (2002), Konigsberg and Frankenberg (1992), and Gage (1988, 1989) provided sophisticated solutions to deal with error and bias in palaeodemography but have, unfortunately, seen very little practical application. This thesis has aimed to be particularly pragmatic and to provide accessible, yet reliable tools for estimating population dynamics. It has focused on identifying the most parsimonious solutions to existing issues and gaps in palaeodemography. It has relied on empiricism rather than theory to produce and test reliable tools for evaluating past population dynamics, and has contextualised the results using archaeological evidence, as well as demographic theory where needed, to ensure interpretations are meaningful and informed.

Chapters 7 and 8 have provided new palaeodemographic tools, with increased accuracy over previous methods and suitability for use on well preserved skeletal samples that have been reported for a number of sites in Asia and the Pacific, and Chapter 9 has evaluated the robustness and resilience of these tools relative to various sources of sample bias, including infant and elderly underenumeration and age estimation bias. Chapters 10 and 11 detail applications of these tools to archaeological skeletal samples, demonstrating the utility and capability of the methods, particularly their temporospatial precision and accuracy as informed by the archaeological narrative, and the interpretive framework into which they can be integrated. Additionally, Chapters 10 and 11 provided exciting new insights into population dynamics in Southeast Asia and the Pacific Islands, where previously palaeodemographic work had been limited and relied on infant-exclusionary tools. The methods and case studies showcased in this thesis indicate a bright future for palaeodemography in the Asia-Pacific region, and indeed the world. The accessibility and accuracy indicated thus far of these methods will hopefully re-establish palaeodemography, particularly studies of fertility and growth, as a cornerstone of bioarchaeological studies.

This thesis has highlighted a range of opportunities for future research. From a methodological perspective, there is capacity for fine-tuning of the fertility and RNPI estimators, particularly through simulated models, and further validation tests on alternative samples. Additionally, there are undoubtedly further palaeodemographic measures that can be developed using a similar methodology to that used in this thesis, for example, McFadden and Oxenham (2019b) provide one such example where the ratio of females to males aged 20-24 years has been used to estimate the maternal mortality rate. Ways to meaningfully derive measures of mean age-at-death and migration would be of particular benefit to the discipline, though will surely be challenging to realise.

In terms of practical application, Chapter 10 highlighted apparent spatial heterogeneity in ancient Southeast Asia and identified several possible causes for this. Does the spatial variability in population dynamics indicate a differential response to technological, economic and social change? Or are we seeing the process of communities being absorbed by neighbouring populations, with the gradual abandonment of the original sites? These questions, and more, warrant further exploration. Chapter 11 provided insights regarding population dynamics in the Pacific Islands, illustrating the value of the methodological tool kit where there is a somewhat limited and patchy archaeological record. Greater incorporation of other sources of evidence, or more skeletal samples, may serve to further validate the tentative conclusions of that study. Of course, the opportunities to apply these methods in these regions and elsewhere in Asia, the Pacific, and indeed the world, are many.

The palaeodemographic case studies presented in this thesis provide a great opportunity for comparison and amalgamation with the palaeopathological evidence for the respective regions (Buckley, 2006; Buckley et al., 2014; Clark et al., 2014; Domett and Tayles, 2007; Domett, 2001; Oxenham and Tayles, 2006; Oxenham and Domett, 2011; Willis and Oxenham, 2013) in order to gain a greater understanding of the complex relationship between population dynamics, ecology, economy, and health. Hazards and survival analyses (Blondiaux et al., 2015; 2016; DeWitte, 2014a; 2014b; Gamble et al., 2017), in combination with the methods proposed and results reported in this thesis, may significantly contribute to the evaluation of the relationship between morbidity and mortality, and further contextualise the ecological conditions and residual impacts of disease.

Ultimately it is hoped that this thesis will stimulate further palaeodemographic research in Asia and the Pacific, bringing this region of the world to centre stage. The seeming precision of the methods included in this thesis provides opportunities to investigate hypotheses outside of major events, specifically the Neolithic Demographic Transition. Shifting away from this focus allows us to appreciate the complexity and impacts of other subsistence strategies and technological innovations, which have influenced much of human history and prehistory, as well as shorter term events such as disease. It is time for a palaeodemographic revival which steers away from Western-centricism, both in geographic region and outdated attitudes towards human advancement.

Out of the darkness of '*…Expectancy and False Hope'* (Bocquet-Appel and Masset, 1996:571), this thesis has provided a new hope for empirical palaeodemography in Asia and the Pacific.

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Appendices

Appendix 1 – Published copy of ‘The D0-14/D ratio: A new paleodemographic index and equation for estimating total fertility rates’

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RESEARCH ARTICLE

The D0-14/D ratio: A new paleodemographic index and equation for estimating total fertility rates

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Abstract

Objectives: The objectives of this study were to develop a new subadult–adult ratio for application to sites with good infant representation and to produce an equation to estimate the total fertility rate for a population based on the age-at-death ratio. A new approach is required as current methods exclude the 0–4 years age category due to presumed underenumeration of infants. While this is true for some skeletal samples, others experience good infant representation.

Materials and Methods: Using age-at-death data and total fertility rates for 52 countries from the United Nations database for the year 1960, we examined the correlation between three age-at-death ratios and the fertility rate. We also utilized linear regression to determine an equation for calculating total fertility rate from the ratio.

Results: We achieved a correlation of 0.848 between our D0-14/D Ratio and actual fertility rates. This correlation was significantly higher ($p < .05$) than the other ratios examined, including the d5-14/d20+ by Bocquet-Appel and Masset (1977, 1982, 1996) and the ${}_{15}P_5$ index by Bocquet-Appel (2002).

Discussion: The exclusion of infants can result in inaccurate demographic measures, particularly where subadults aged over 5 years of age experience robust survivorship. In addition to providing a solution for sites with good infant representation, this study indicates that the 0–4 years of age category possesses great predictive power when compared to other age categories. The regression equation provides a total fertility rate which is comparable with data regardless of their temporal origin. This method will provide more accurate demographic measures for bioarcheological sites with good infant preservation.

KEYWORDS
${}_{15}P_5$ index, age-at-death, d5-14/d20+ index, fertility rate, paleodemography

1 | INTRODUCTION

Paleodemography is the study of the demographic attributes of past populations, including population size, structure, growth, density, fertility, mortality, and migration (Chamberlain, 2006). Such attributes can provide significant and valuable insight into the ability of past humans to adapt in response to environmental events, such as climate change and availability of resources, and societal change, for instance migration, warfare, and social complexity. The impact of the agricultural transition on fertility and mortality has been of great interest over recent decades, with research to date indicating major changes in health (both positive and negative) following the adoption and/or intensification of agriculture globally (Armelagos, Goodman, Jacobs, & Kenneth, 1991; Bellwood & Oxenham, 2008; Bocquet-Appel & Naji, 2006; Buikstra, Konigsberg, & Bullington, 1986; Cohen & Armelagos 1984; Eshed, Gopher, Gage, & Hershkovitz, 2004; Gage & Dewitte, 2009; Hershkovitz & Gopher, 2008; Kuijt, 2008; Kuijt & Goring-Morris, 2002; Larsen 1995; Oxenham, Nguyen, & Nguyen, 2006; Papathanasiou, 2005). Also of significant interest at present are the impacts of past climate change on human populations as indicated by shifts in demographic profiles (deMenocal, 2001; Tipping, Davies, McCulloch, & Tisdall, 2008; Turney, Baillie, Palmer, & Brown, 2006; Turney & Brown, 2007; Van de Noort, 2011). Notwithstanding, several key issues underpin paleodemography, with the predominant concerns at present being the inaccuracy of age-at-death estimation techniques, nonstationarity of populations, and underenumeration of infants (Bocquet-Appel & Masset, 1982; Buikstra & Konigsberg, 1985; Paine & Harpending, 1998).

Underenumeration of infants has been assumed to be a significant problem in paleodemography, so much so that children aged 0–4 years are generally excluded from paleodemographic analyses (Milner, Wood, & Boldsen, 2008; Seguy & Buchet, 2013a). It is indeed true that in certain conditions differential preservation results in the underrepresentation of infants in the archaeological record (Gordon & Buikstra, 1981; Lewis, 2007; Walker, Johnson, & Lambert, 1988; Weiss & Wobst, 1973). Further, it has been suggested that in some instances infants may be subject to different burial practices and may be interred at a separate location to the burials of individuals from other age categories (Guy, Masset, & Baud, 1997; Milner et al., 2008). This results in missing data for a key age category which, logically, should be highly sensitive to changes in fertility. Thus, paleodemographers have tended to exclude the youngest age group from their analyses and utilize remaining age categories to estimate demographic parameters. This is one of the premises which underlies Bocquet-Appel and Masset's (1977, 1982, 1996) juvenility index.

The juvenility index was originally developed by Bocquet-Appel and Masset (1977, 1982, 1996) in response to concerns surrounding the effects of errors associated with age-at-death estimation. Bocquet-Appel and Masset (1977, 1982, 1996) proposed the use of a ratio of subadults to adults, thereby avoiding the high error rate associated with a continuous or multicategory age-at-death distribution. Furthermore, they addressed the issue of infant underenumeration by excluding the 0–4 years age category. In its first iteration, the juvenility index examined the ratio of subadults aged 5–14 years to adults aged 20 years and over, abbreviated to d5–14/d20+ (Bocquet-Appel & Masset, 1977, 1982, 1996). Using life tables and known fertility rates for 40 populations, Bocquet-Appel and Masset (1977, 1982, 1996) used polynomial regression to derive equations to predict a number of demographic variables including mortality and fertility rates. In the second version, Bocquet-Appel (2002) adjusted the juvenility index to ${}_{15}P_5$, with the ratio being based on 45 life tables, including the original 40. For comparison with the previous index, ${}_{15}P_5$ can be articulated as d5–19/d5+ (Seguy & Buchet, 2013b). The revised ratio did not significantly increase the correlation between estimated and known fertility rates; however, it is considered to be advantageous from a practical perspective due to the age categories being more biologically distinct than those of the original d5–14/d20+ ratio (Bocquet-Appel, 2002; Seguy & Buchet, 2013b).

The ${}_{15}P_5$ juvenility index remains a widely accepted tool in paleodemography and may be suitable for those samples where either differential preservation and recovery or cultural practices have led to an apparent underrepresentation of infants (Bocquet-Appel & Naji, 2006; Hershkovitz & Gopher, 2008; Kohler, Glaude, Bocquet-Appel, & Kemp, 2008; Kohler & Reese, 2014; Lesure, Martin, Bishop, Jackson, & Chykerda, 2014). However, this is not always the case and in Southeast Asia, for instance, infants are often well represented in skeletal assemblages and the use of the ${}_{15}P_5$ juvenility index may fail to accurately represent the demographic parameters of such populations (Bellwood & Oxenham, 2008). This is particularly true for those sites where subadults aged 5 years and over and young adults experienced good survivorship. For example, at the Neolithic site of Man Bac, Vietnam, excellent preservation was indicated by ∼60% of identified burials being described as complete or nearly complete, with a further ∼28% being classified as incomplete due to the absence of only the skull or one or more long bones (Domett & Oxenham, 2011). Subadult age was estimated using dental mineralization and eruption and, in the absence of dentition, long bone development, while adult age was estimated using combinations of the pubic symphyseal face, dental wear, and epiphyseal fusion (Domett & Oxenham, 2011). Children under 5 years of age were found to represent 47.4% of the total sample ($n = 78$), with only 12.82% of individuals being categorized as 5 to <20 years of age (Domett & Oxenham, 2011).

The Man Bac site is not isolated in either its ideal conditions for preservation or its demographic distribution. Table 1 lists several sites in Southeast Asia with skeletal remains falling into the 0–4 years category at proportions ranging from 29.49% to 48.05%. Infant preservation and representation appears to be significant for these sites, while mortality between 5 and <20 years of age appears to be comparatively quite low. Applying the Bocquet-Appel and Masset (1977, 1982, 1996) juvenility index and the Bocquet-Appel (2002) ${}_{15}P_5$ index to these

TABLE 1 Age-at-death distributions for sites from Southeast Asia

Sample	Time period	0–4.9 years	5–14.9 years	15–19.9 years	20+ years
Khok Phanom Di[a]	Neolithic	48.05	7.79	12.99	31.17
Man Bac[b]	Neolithic	47.44	8.97	3.85	39.74
Ban Lum Khao[c]	Bronze Age	31.82	14.55	19.09	34.55
Ban Na Di[d]	Bronze Age	29.49	6.41	6.41	57.69
Noen U-Loke[e]	Iron Age	38.33	4.17	7.50	50.00

[a] Tayles (1999).
[b] This Study.
[c] Domett (2004).
[d] Domett (2001).
[e] Tayles, Halcrow, and Domett (2007).

sites disregards the high infant mortality and by relying on the 5 to <20-year-old category, fails to accurately represent its younger counterparts.

These Southeast Asian sites are of fundamental importance to our understanding of the Neolithic demographic transition and associated paths of inquiry, such as the causes of the transition, demographic, and archaeological markers of the transition, changes in social and cultural practices, and the intrinsic and extrinsic effects of significant population increase (Bellwood & Oxenham, 2008; Bocquet-Appel, 2002; Willis & Oxenham 2013). Just as methods have been developed to address the underrepresentation of infants at a number of sites in Europe and the Americas, it is equally important that demographic tools be developed for sites with good infant representation.

A juvenility index is required to accurately represent samples where infants are well preserved due to differences in preservation conditions, where archaeological recovery of infants has been good, and where there do not appear to be differential cultural practices impacting the representation of infants in the burial context. We propose the D0–14/D ratio as an alternative paleodemographic tool for application to such skeletal assemblages.

2 | MATERIALS AND METHODS

The methods are largely based on those reported by Bocquet-Appel and Masset (1977, 1982, 1996), with some adjustments. It is important to note that Bocquet-Appel and Masset (1977, 1982, 1996) utilized data from model life tables to develop their juvenility indices and demographic measures. The age-at-death distribution of a model life table is calculated from living population data as well as mortality data, specifically, the proportion of the living that died at each age in a theoretical cohort (Lacey & Speizer, 2017). The process of modelling smooths out natural variation in the age-at-death distribution, normalizes age-specific mortality rates, and can be used to fill in gaps in mortality data where they exist (Moultrie, 2013). We would therefore anticipate a higher correlation with demographic parameters, including fertility rate, and the age-at-death structure of life tables due to the reduced variability. We believe that raw age-at-death data are a more accurate representation of what can be derived from a skeletal sample. The use of a ratio calculated from genuine age-at-death data avoids the requirement for modelling age-specific mortality rates, thus simplifying the process. A further concern with the use of life tables is that they assume the population is stationary: it is closed to migration; fertility and mortality are constant and equal; and the age distribution is stable (Lacey & Speizer, 2017). To address this, Bocquet-Appel (2002) used modelling to simulate varying population growth rates from −2.5 to 2.5. The populations used in our study show natural variability in population growth and, while there is an expectation that this will reduce the correlation with fertility rates, we see this as an improved reflection of the complex nature of population dynamics. We believe our approach better represents both the data available to bioarchaeologists and the variability in nonstationarity within and between populations.

Age-at-death data, fertility rates, and population growth rates from the United Nations Database (United Nations, 2017) were utilized as the reference sample for this study. The United Nations (2017) have collected population data from national statistical offices in 230 countries since 1948. Each year the United Nations (2017) evaluates the process and makes recommendations to statistical offices in order to continually improve accuracy and maintain relevance. We opted to utilize data from the year 1960, as this year provides a good range of fertility rates from 2.001 through to 7.363 and population growth rates from −0.281 through to 6.356. Fertility rates were available for 214 countries and regions, whilst age-at-death records were available for only 75 countries and regions. Five countries were removed as they lacked sufficient detail regarding age-at-death data. A further 16 countries and regions were excluded as they only had data for either fertility rates or age-at-death. Two regions were excluded due to not being sovereign countries and therefore having the potential for data duplication. Data were obtained for a total of 52 countries for inclusion in this study and were extracted for the following variables: fertility rate, total (births per woman); deaths by age, sex, and urban/rural residence; and population growth (annual %) (United Nations, 2017). Total fertility rate is the average number of children born to a woman over her lifetime, assuming she experienced the age-specific fertility rates for the population throughout her life and she survived until the end of her reproductive age span (United Nations, 2017). Total fertility rates were adjusted to three decimal places. For some countries, age-at-death data needed to be recategorized to make data comparable. Most data were in five-year categories (e.g., 5–9 years): these were combined to reflect the categories used in the ratios of interest (i.e., 0–4, 5–14, 15–19, 20+ years).

We calculated three ratios: the Bocquet-Appel and Masset (1977, 1982, 1996) juvenility index of d5–14/d20+; the Bocquet-Appel (2002) $_{15}P_5$ index of d5–19/d5+; and our proposed D0–14/D ratio of d0–14/total population. Buikstra et al. (1986) proposed an alternate ratio of d30+/d5+, which they correlated with Coale and Demeny preindustrial life tables. The Buikstra et al. (1986) ratio was not included in this study as we were only able to identify its use in one study other than the original (Schurr, 1998) and the age-at-death categories differed substantially from those used by Bocquet-Appel and Masset (1982) and Bocquet-Appel (2002). Robbins (2011) developed a subadult fertility formula using the ratio of infants to subadults (d0–1/d2–19), however, we note that the ratio was based on female-only Coale and Demeny life tables and that, similar to Buikstra et al. (1986), the ratio has seen limited application in the published literature.

We undertook simple correlation tests of the ratios to the known fertility rates, and between ratios using StatsDirect 3 (2016). We also calculated the 95% confidence interval. The test of difference between correlations is performed to determine the significance of difference and is applied where correlations are derived from the same sample and are based on the same variables. As such, this test was deemed appropriate and was undertaken using software by Lee and Preacher (2013).

Bocquet-Appel and Masset (1977, 1982, 1996) and Bocquet-Appel (2002) utilized polynomial regression of their ratios on the various paleodemographic measures to develop their equations. We set out to develop an estimate of the total fertility rate, due to priority of research interests and the complexity of other measures such as mortality and growth rate (Milner et al., 2008). We use linear regression as we believe the simplest explanation is that the relationship between age-at-death ratios and the total fertility rate is linear. Polynomial regression fits the data closer to the trend line; however, the theory behind doing this must be justified. At present, we have neither a logical nor practical justification for the relationship being anything but linear, as we would wholly expect an increasing fertility rate to produce higher numbers of deceased infants on a linear trajectory. The 40 life tables utilized by Bocquet-Appel and Masset (1977, 1982, 1996) and Bocquet-Appel (2002) showed some deviations from a linear relationship; however, we believe that both a larger sample and a demographic justification are required to warrant the use of polynomial regression in this case.

We used linear regression of Bocquet-Appel and Masset's (1977, 1982, 1996) and Bocquet-Appel's (2002) ratios on the total fertility rate to evaluate the relationship in a comparable way to our proposed method (as the results of polynomial regression and linear regression are not directly comparable); however, we note that we would anticipate a reduction in the correlations previously reported for the former ratios and the total fertility rate due to the change to linear regression. Furthermore, we would expect the inclusion of the 0–4 years age category in our ratio to improve the correlation due to its hypothesized sensitivity to fertility. To obtain an equation to estimate the total fertility rate, we utilized simple linear regression of our subadult–adult ratio on the known total fertility rates for 52 countries. We also calculated the prediction interval, as this estimates the interval that predictions will fall into based on past observations and is therefore appropriate for our aims. Linear regression and prediction interval were undertaken using StatsDirect 3 (2016).

3 | RESULTS

Table 2 details the fertility rate, the number of individuals in each age group, total sample size, and the three calculated ratios for each country. The results of the correlation tests for the three ratios are provided in Table 3. The age-at-death distribution is known to be more sensitive to fertility than mortality (Sattenspiel & Harpending, 1983; Paine, 1989): our results support a strong relationship between the age-at-death structure and total fertility rate.

The correlation tests indicate an improvement in the accuracy of methods from the original Bocquet-Appel and Masset (1977, 1982, 1996) juvenility index, to the Bocquet-Appel (2002) ${}_{15}P_5$ index, and finally to our D0–14/D ratio ($r = 0.848$, 95% CI 0.750–0.911).

The test of difference produced a result of $p < 0.05$ (one-tailed) based on the correlations for the Bocquet-Appel (2002) ${}_{15}P_5$ index (the more highly correlated of the two indices) and our D0–14/D ratio. We undertook a one-tailed test as we anticipated that the inclusion of additional data, specifically the 0- to 4-year category, would result in an improved correlation.

The prediction interval of the D0–14/D ratio on the total fertility rate produced the scatter plot at Figure 1. Simple linear regression produced the following equation to calculate total fertility rate:

$$\text{Fertility Rate} = (7.734 \times \text{D0–14/D ratio}) + 2.224$$

With a total fertility rate of 8.2 in 1960, Rwanda has the highest rate recorded by the United Nations (2017). The biologic maximum fecundity is believed to be approximately 15 births per female for most populations, however, achieving the maximum requires all females to commence reproduction at age 15 and to not breast-feed any of their children (Leridon, 2005). This may be the case for individual females, but is not known to occur at a population level (Leridon, 2005). As such, the maximum total fertility rate for a population is likely to be significantly less than the maximum biologic fecundity. The highest total fertility rate reported by Bentley, Goldberg, and Jasieńska (1993) in their study of populations with natural fertility (fertility in the apparent absence of birth control) was 10 for an indigenous American population in 1950. They also noted that whilst agriculturalist populations tended to have higher fertility rates than nonagriculturalist populations, there was significant overlap in the range of the two groups. Similarly, Campbell and Wood (1988) reported significant variability in the fertility rates of modern traditional societies. The definition of high, moderate, and low fertility rates varies depending on the populations being evaluated, but Preston, Himes, and Eggers (1989) provide a general guide of an average of 6.15 for high fertility, 4.59 for moderate fertility, and 1.64 for low fertility. In modern studies, anything under the replacement level (total fertility rate of 2.1) is typically considered low, and moderate and high fertility ranges are more conservative due to the reduction in fertility rates over time (United Nations, 2017).

4 | DISCUSSION

We have shown that the D0–14/D Ratio provides an improved correlation with actual fertility rate ($r = 0.848$) over previous methods. It seems logical that the 0- to 4-years category would be the age group most sensitive to changes in fertility and our results support this. We also note that the inclusion of a greater proportion of the age-at-death data will likely increase the correlation. Our subadult–adult ratio is a significant improvement ($p < 0.05$) over alternative methods. Based on these results, we suggest the D0–14/D ratio as an appropriate alternative to existing age-at-death ratios for instances where infants are well represented in the skeletal sample.

The correlations we report here for the Bocquet-Appel and Masset (1977, 1982, 1996) juvenility index and the Bocquet-Appel (2002) ${}_{15}P_5$ ratio are weaker than those reported in the original papers. We believe this is due in part to Bocquet-Appel and Masset (1977, 1982, 1996) and Bocquet-Appel (2002) using a ratio derived from life tables. However, as previously noted, age-at-death data better reflect the data that bioarcheologists obtain from skeletal samples and the natural variability of past populations. Additionally, as earlier discussed, the shift from utilizing polynomial regression to linear regression would undoubtedly impact the correlation. We see both innovations as logical adjustments.

TABLE 2 Fertility rate, age groups, total population, and ratios for 52 countries

Country	Total fertility rate	0–4	5–14	15–19	20+	Total *n*	d5–14/d20+	d5–19/d5+	d0–14/total population
Albania	6.489	8,597	528	140	7,489	16,754	0.071	0.082	0.545
Antigua and Barbuda	4.425	182	12	6	324	524	0.037	0.053	0.370
Argentina	3.109	37,224	3,222	2,261	135,776	178,483	0.024	0.039	0.227
Australia	3.453	5,638	898	709	81,191	88,436	0.011	0.019	0.074
Austria	2.690	5,427	453	549	83,174	89,603	0.005	0.012	0.066
Barbados	4.333	563	33	19	1,512	2,127	0.022	0.033	0.280
Belgium	2.540	5,465	628	371	107,474	113,938	0.006	0.009	0.053
Bulgaria	2.310	7,768	909	549	54,393	63,619	0.017	0.026	0.136
Canada	3.811	15,144	1,958	1,239	121,337	139,678	0.016	0.026	0.122
Chile	5.113	42,913	2,681	1,338	48,349	95,281	0.055	0.077	0.479
Costa Rica	6.451	5,371	422	115	4,051	9,959	0.104	0.117	0.582
Cuba	4.182	9,370	917	785	31,786	42,858	0.029	0.051	0.240
Denmark	2.570	1,913	262	218	41,288	43,681	0.006	0.011	0.050
Egypt	6.630	254,567	14,313	4,467	163,183	436,530	0.088	0.103	0.616
El Salvador	6.674	14,980	1,615	582	11,368	28,545	0.142	0.162	0.581
Fiji	6.461	804	99	67	1,207	2,177	0.082	0.121	0.415
Finland	2.720	2,085	445	295	36,972	39,797	0.012	0.020	0.064
France	2.850	22,755	2,827	1,860	489,995	517,437	0.006	0.009	0.049
Greece	2.230	7,508	759	448	51,593	60,308	0.015	0.023	0.137
Grenada	6.743	492	8	8	524	1,032	0.015	0.030	0.484
Guam	6.052	78	7	8	180	273	0.039	0.077	0.311
Guatemala	6.534	33,544	5,509	1,606	25,080	65,739	0.220	0.221	0.594
Guyana	5.754	1,871	119	77	3,088	5,155	0.039	0.060	0.386
Hong Kong	5.162	6,497	674	120	11,845	19,136	0.057	0.063	0.375
Hungary	2.020	8,020	791	670	92,016	101,497	0.009	0.016	0.087
Iceland	4.290	87	18	7	1,055	1,167	0.017	0.023	0.090
Ireland	3.780	2,085	244	135	30,196	32,660	0.008	0.012	0.071
Israel	3.866	2,207	276	149	9,415	12,047	0.029	0.043	0.206
Italy	2.370	46,863	4,528	3,032	426,509	480,932	0.011	0.017	0.107
Japan	2.001	64,683	13,756	9,813	617,983	706,235	0.022	0.037	0.111
Luxembourg	2.290	194	22	13	3,487	3,716	0.006	0.010	0.058
Malta	3.620	356	20	13	2,430	2,819	0.008	0.013	0.133
Mexico	6.768	186,472	20,371	7,691	187,487	402,021	0.109	0.130	0.515
Montenegro	3.603	1,105	64	41	2,363	3,573	0.027	0.043	0.327
Netherlands	3.120	5,025	909	458	81,094	87,486	0.011	0.017	0.068
Norway	2.850	1,439	265	161	30,676	32,541	0.009	0.014	0.052
Poland	2.980	42,304	3,308	1,686	176,680	223,978	0.019	0.027	0.204
Portugal	3.160	21,502	1,476	674	71,272	94,924	0.021	0.029	0.242

(Continues)

TABLE 2 (Continued)

Country	Total fertility rate	0–4	5–14	15–19	20+	Total *n*	d5–14/d20+	d5–19/d5+	d0–14/total population
Puerto Rico	4.657	4,163	478	261	10,870	15,772	0.044	0.064	0.294
Republic of Korea	6.155	16,336	18,506	6,773	89,041	130,656	0.208	0.221	0.267
Romania	2.340	32,273	2,489	1,288	124,563	160,613	0.020	0.029	0.216
Saint Lucia	6.967	708	44	19	510	1,281	0.086	0.110	0.587
Saint Vincent and the Grenadines	7.224	794	23	8	378	1,203	0.061	0.076	0.679
Singapore	5.454	2,939	391	117	6,752	10,199	0.058	0.070	0.327
Spain	2.860	33,575	3,074	1,794	52,968	91,411	0.058	0.084	0.401
Sri Lanka	5.541	33,183	4,684	1,249	45,802	84,918	0.102	0.115	0.446
Sweden	2.170	2,062	421	373	72,237	75,093	0.006	0.011	0.033
Switzerland	2.440	2,450	356	287	49,001	52,094	0.007	0.013	0.054
Tonga	7.363	56	14	6	213	289	0.066	0.086	0.242
Trinidad and Tobago	5.264	1,834	143	93	4,538	6,608	0.032	0.049	0.299
Uruguay	2.880	3,230	236	189	18,261	21,916	0.013	0.023	0.158
Venezuela	6.616	24,627	2,367	926	27,011	54,931	0.088	0.109	0.491

We believe that total fertility rate estimates produced using this equation can be compared with others, including modern data. While the age distribution and ratio have been derived from age-at-death data, the fertility rate is derived from the living population; therefore, the equation is based on the relationship between the age-at-death distribution and the living fertility rate. As such, estimates should be comparable with living population fertility rates. The confidence interval of our method should be observed and we would suggest interpretations should be limited to estimating where a population's fertility rate fits on the global and temporal scale.

Although this method is not exempt from the key issues in paleodemography, we have made some progress in addressing these. Underenumeration of infants has remained a prominent concern in paleodemography since it was raised by early paleodemographers such as Angel (1969) and Weiss and Wobst (1973). Our D0–14/D ratio has been developed specifically for skeletal assemblages where there are reasonable grounds to believe that infants are well represented, and therefore, we do not believe infant underenumeration to be of concern when using our method if due diligence has been taken. It is imperative that researchers contextualize bioarcheological data with respect to the site in question when considering infant representation. Where proportionately low numbers of infants are found, differential preservation and differential interment must be considered as potential causes, and where doubt exists, it may be best to employ the Bocquet-Appel (2002) $_{15}P_5$ method.

The error surrounding age-at-death estimates has perhaps been the most dominant issue in paleodemography in recent years. The Rostock Manifesto endeavored to address this issue through the application of Bayesian theorem (Hoppa & Vaupel, 2008). It has previously been observed that the use of age-at-death ratios is one mechanism

TABLE 3 Correlations between age-at-death ratios and total fertility rate

	d5–14/d20+(Bocquet-Appel & Masset, 1977, 1982, 1996)	d5–19/d5+ (Bocquet-Appel, 2002)	d0–14/total population (D0–14/D ratio)
n	52	52	52
Mean	0.044	0.056	0.269
SD	0.047	0.050	0.188
Skewness	2.000	1.547	0.496
Kurtosis	7.198	5.283	2.010
r	0.709	0.755	0.849
95% CI	0.540–0.823	0.607–0.852	0.750–0.911

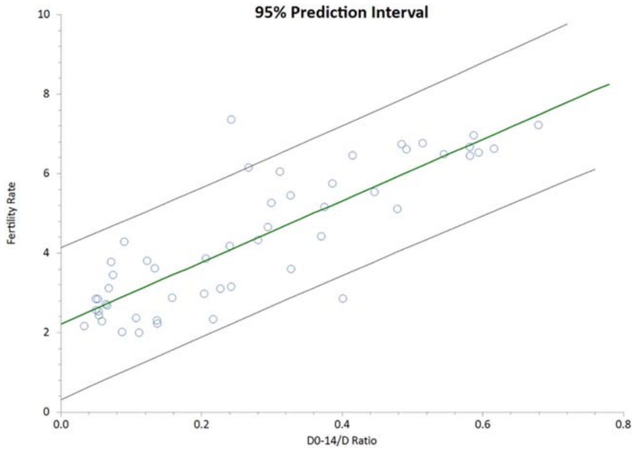

FIGURE 1 Prediction interval for the total fertility rate and D0–14/D ratio

that can be employed to reduce the impact of age estimation error (Bocquet-Appel & Masset, 1977, 1982, 1996; Buikstra et al., 1986), and the Bocquet-Appel (2002) $_{15}P_5$ method specifically addressed concerns around the practicality of ratio demarcation points. Utilizing our method restricts the error of age-at-death estimates to one component of the ratio only (specifically, the maximum age cutoff for the numerator: 14 years of age), as the denominator is the total population and is therefore impervious to age estimation error.

Nonetheless, it is noted that there will likely be a degree of error in the estimation of age for the purposes of this method and that this may have an impact on the accuracy of results. AlQahtani, Hector, and Liversidge (2014) evaluated the accuracy of three dental ageing methods: Schour and Massler, Ubelaker, and the London Atlas. For individuals with a chronological age of 13 years they reported a mean error of ∼±1.5 years, and for a chronological age of 15 years they reported a mean error of ∼±1 year, using the Schour and Massler and Ubelaker methods (AlQahtani et al., 2014). For the London Atlas method this was reduced to 0.79 and 0.66 years, respectively. Taking the average error for the Schour and Massler and Ubelaker methods, we might expect that some individuals with a chronological age of up to 15.9 will be erroneously placed in the 0–14 category and some individuals with a chronological age of 13.5–14 may be erroneously excluded from the 0–14 category. Rissech, Marquez-Grant, and Turbon (2012) reported average errors ranging from ±0.73 to ±2.09 years for measurements from the scapula, innominate, femur, and tibia, and therefore, the age range that may be incorrectly classified for the purposes of our method would likely be between 12 and 16 years of age, depending on the skeletal element. The potential for error should be considered when using the D0–14/D ratio, along with any further potential complications due to other variables which impact age estimation such as sex and ancestry.

Finally, we have used nonstationary samples to better replicate the age-at-death distribution of real populations. There is a significant literature on the issue of nonstationarity. Some have argued that over long periods of use, burials will assume an age-at-death distribution that is stable and sometimes stationary, while others have criticized this theory, but note that growth rates are very difficult to estimate for archaeological sites in the absence of historical records (Bocquet-Appel & Masset, 1982; Bocquet-Appel, 2002; Buikstra & Konigsberg, 1985; Milner et al., 2008; Moore, Swedlund, & Armelagos, 1975; Sattenspiel & Harpending, 1983). We have achieved a significant correlation between our ratio and the known fertility rates for 52 countries with varying growth rates ranging from −0.281 to 6.356 (United Nations, 2017). As such, we believe the results of this study will hold true regardless of the stationarity or nonstationarity of the population it is applied to. The method may, however, be improved by analyzing the relationship between the age-at-death distribution and other demographic measures including population growth.

5 | CONCLUSION

Infant underenumeration is a known issue in paleodemography, with methods being developed to address the issue through the exclusion of the 0–4 years of age category from age-at-death distribution estimates. However, we have provided several examples of archaeological sites with good infant representation. When current methods are applied to these sites they produce inaccurate estimates of fertility due to the exclusion of the age group most sensitive to fertility. To increase the accuracy of fertility estimates for sites where representative infant data are available, we have developed the D0–14/D ratio using United Nations (2017) age-at-death data and fertility rates. The ratio has been found to be strongly correlated with total fertility rates ($r = 0.848$) and is a significant ($p < 0.05$) improvement over existing methods. To transform the ratio into a comparable fertility rate, we have used linear regression to develop a total fertility rate estimation equation. This permits comparison with the total fertility rate of other populations regardless of their temporal origins. We expected that the inclusion of the 0–4 years of age category would improve the correlation with fertility due to the category's high sensitivity to changes in fertility rate and our study is supportive of this. We have considered the key concerns in paleodemography and believe that the D0–14/D ratio addresses some of these issues, first by reducing the potential for age-at-death estimation error using distinct age categories and second by mimicking real variation in population growth through the use of nonstationary sample populations. The method would benefit from further research on the impact of other demographic variables, such as migration and mortality, but provides a valuable solution to an often-forgotten problem.

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Appendix 2 – Published copy of 'Rate of natural population increase as a paleodemographic measure of growth'

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Rate of natural population increase as a paleodemographic measure of growth☆

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A R T I C L E I N F O

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A B S T R A C T

The aim of this study was to provide a verifiable measure of population increase from age-at-death data. It was anticipated that the D0-14/D ratio would be a good predictor of the rate of natural increase (births minus deaths) due to its strong relationship with the total fertility rate. United Nations age-at-death data for 58 countries was used to calculate the rate of natural population increase and evaluate its relationship to the D0-14/D ratio. Additionally, the impact of migration on both the rate and the ratio was measured. A correlation of $r = 0.863$ (95% CI 0.777–0.917) between the D0-14/D ratio and rate of natural population increase was found. Linear regression provided a simple equation for calculating the rate of population increase. The rate of natural population increase accounts for the disparity (or lack of) between births and deaths, and provides a valuable measure for evaluating ancient population variability. While the rate does not factor in migration, we believe migration should be measured independently as it is not always of interest to bioarcheological research questions and has a negligible impact on the rate of natural increase and the D0-14/D ratio. Estimating the rate of natural population increase has the potential to provide significant insights into past populations and the human response to change.

Population growth is a demographic measure which estimates the contribution of births, deaths and migration to population size over time. In the study of ancient populations, changes in population size can tell us a great deal about the health of a population and its response to change. An example of this is the Neolithic Demographic Transition (NDT), considered to be one of the most significant events in the history of modern humans, and is variously associated with increasing social complexity, population size, and territorial pressure (Bocquet-Appel, 2008). Measuring the impacts of the NDT across the globe has been an area of significant interest to date (Armelagos et al., 1991; Bellwood and Oxenham, 2008; Bocquet-Appel and Naji, 2006; Buikstra et al., 1986; Cowgill, 1975; Eshed et al., 2004; Gage and Dewitte, 2009; Hassan and Sengel, 1973; Johansson and Horowitz, 1986; Kohler and Reese, 2014; Kuijt, 2008; Papathanasiou, 2005; Shennan, 2009; Woodbridge et al., 2014), yet a reliable way in which to estimate the rate of population increase from skeletal remains has continued to elude researchers.

Previous attempts to estimate population growth are highly diverse and include demographic (Cowgill, 1975) and paleodemographic modelling (Bocquet-Appel, 2002; Schindler et al., 2012), ethnographic and paleoclimate analyses (Tallavaara et al., 2015), spatiotemporal radiocarbon date approaches (Chaput and Gajewski, 2016; Crema et al., 2016; Delgado et al., 2015; Downey et al., 2014; Rick, 1987; Zahid et al., 2016), zooarchaeological evidence of increased animal consumption (Stiner et al., 1999), and mitochondrial DNA analyses (Harpending, 1994; Excoffier and Schneider, 1999). These approaches have achieved some success, but are underpinned by several practical issues, such as unavailability of the desired data for modelling in the bioarcheological record, the requirement for two or more distinct temporal points for estimates of relative change, the difficulty of standardizing archaeological, zooarchaeological and DNA data, and lack of verifiability of such methods.

The rate of natural increase is a relatively simple demographic measure: the birth rate (births per 1000) minus the mortality rate (deaths per 1000) for a period or point in time, divided by 10 to convert it to a percentage (Population Reference Bureau, 2017). Its value as a paleodemographic measure has previously been noted by paleodemographers (Angel, 1969; Bocquet-Appel and Naji, 2006). The relationship between juvenile to adult ratios and total fertility rate suggests that an estimate of birth rate can be reasonably obtained (Bocquet-Appel and Masset, 1982; McFadden and Oxenham, 2017), however, the mortality rate is somewhat more complex (Gage and Dewitte, 2009; Wood et al.,

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☆ The authors declare that they have no competing interests.

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2002). The rate of natural population increase is population growth without migration though it should be noted that in demography, population growth is associated with further complexities. In contrast to fertility and birth rates, the rate of migration is very difficult to estimate and presents several theoretical and practical challenges (Clark, 1994; Burmeister, 2000). In the modern world, migration has a large impact on population growth (Zlotnik, 2004), however, its impact on the rate of natural increase is not so clear cut. Past populations may have experienced greater limits on migration due to lower population densities (Clark, 1994) and reduced mobility (Anthony, 1990), and with fewer limits on fertility, migration is anticipated to have had a relatively limited impact on the natural increase of past, in comparison to modern, populations. Further, in many cases, the aim of estimating population increase is to understand how a change in diet, economy, or lifestyle may have impacted on population health and size. In these circumstances, migration may still be of interest but as a separate research question, and therefore a somewhat different indicator may be more appropriate.

We propose that the rate of natural population increase is an optimal paleodemographic measure for questions relating to the impact of significant transitions and events with respect to the health and size of past populations. While excluding the potentially confounding factor of migration from the mix may initially appear to be an omission of valuable data, we believe that this is, in fact, of negligible impact and is indeed a practical improvement. The rate of natural increase avoids the complexities associated with measuring population growth and, when considered in the context of other archaeological evidence, may be equally valuable in cases where the extremes of little to no migration through to significant migration are indicated.

1. Materials and methods

This study aimed to evaluate the relationship between the rate of natural increase and an age-at-death ratio. Due to the strong correlation achieved by McFadden and Oxenham (2017) between total fertility rate and the D0-14/D ratio (or the ratio of subadults aged 0–14 years to the entire sample), it was anticipated that the D0-14/D ratio would also correlate with the birth rate; a major component of the rate of natural increase. Additionally, the magnitude of the impact migration has on the rate of natural increase and the age-at-death distribution was also of interest. The use of modern data is based on the uniformitarian theory of paleodemography proposed by Howell (1976) and the generalized pattern of human mortality summarized by Wood et al. (2002). Data for 58 countries (SI) from the United Nations Database (2017) for the year 1960 were used, being the earliest year for which the United Nations recorded the data of interest. Other reasons for targeting this period are that this year predates the widespread use of the contraceptive pill (Liao and Dollin, 2012) and represents a greater range of natural increase rates than many of the later years. The following data were extracted: birth rate, mortality rate, age-specific deaths and net migration rate. The rate of natural increase (%) was calculated by subtracting the mortality or death rate (D_r) from the birth rate (B_r) and dividing by 10:

$$\text{Rate of Natural Increase (\%)} = (\mathrm{B_r} - \mathrm{D_r})/10$$

First-order correlation tests of the D0-14/D ratio to the calculated rate of natural increase and the net migration rate were performed, and the rate of natural increase to the net migration rate. Normal probability plots were used to identify potential outliers. It was expected that the relationship between the D0-14/D ratio and the rate of natural increase would be linear, as an increasing proportion of juvenile deaths was anticipated to predict an increased rate of natural increase. All statistics were calculated using StatsDirect 3 (2016). Rules for identifying outliers followed those of Pennsylvania State University (2017).

Table 1
Descriptive statistics and first-order correlations for the rate of natural increase, net migration rate, and D0-14/D ratio.

	Rate of natural increase	Net migration rate	D0-14/D Ratio
n=	57	57	57
Average	2.01	−2.04	0.26
Standard deviation	1.03	7.84	0.19
	Correlation with rate of natural increase	r = −0.158	r = 0.863
	95% confidence interval (CI)	−0.402–0.107	0.777–0.917
		Correlation with net migration rate	r = −0.232
		95% confidence interval (CI)	−0.465 to 0.030

2. Results

In the first instance, a correlation of $r = 0.835$ between the D0-14/D ratio and the rate of natural increase was observed. When residuals were plotted one outlier (Tonga) was identified from the normal distribution. In accordance with standard procedure (Pennsylvania State University, 2017), a normally distributed probability plot of residuals was observed with the removal of the outlier. This outlier was excluded from the remainder of analyses.

Descriptive results and first order correlations are provided in Table 1. With the outliers removed, a correlation of $r = 0.863$ (95% CI 0.777–0.917) was achieved between the rate of natural increase and the D0–14/D ratio. The correlation between the rate of natural increase and migration was not significant ($r = -0.158$, $p > 0.05$ two-tailed), with migration accounting for a minute amount of the variance ($r^2 = 0.025$). Similarly, migration was not a significant predictor of the D0-14/D ratio ($r = -0.232$, $p > 0.05$ two-tailed).

Simple linear regression produced the following equation to calculate the rate of natural increase:

$$\text{Rate of Natural Increase (\%)} = (10.06 \times \mathrm{D0} - 14/\mathrm{D}) - 1.61$$

3. Discussion

A strong relationship ($r = 0.863$, 95% CI 0.777–0.917) between the D0–14/D ratio and the rate of natural increase was identified. In the absence of the mortality rate, the rate of natural population increase and the total fertility rate are inextricably linked, as they are both based on a linear relationship with juvenile mortality. This limits the interpretations that can be made based on the available data, as a high fertility rate will always be associated with high growth, and vice versa, when using this method. This should be noted when evaluating both measures. Additionally, given that a number of commentators (e.g., Konigsberg and Frankenberg, 1994; Milner et al., 1989; Sattenspiel and Harpending, 1983) have reported that fertility has a greater impact on the age-at-death distribution than mortality, this may limit the sensitivity of the method proposed in this study to mortality. Another potential limitation of the method is that it is based on a single year of data, whilst burial samples will very rarely represent a single year. It seems logical that applying the method to a burial sample would have the effect of averaging the rate of natural increase for the period of the burial depositions. Nonetheless, archaeological context is key, and consideration should be given as to whether the sample is substantial and cohesive enough to be taken as representative of a single population.

For this method, the D0-14/D ratio was used based on age-at-death data from real populations to estimate the rate of natural increase. A limitation of this study is that the effectiveness of the method on samples where infant underrepresentation is indicated is yet to be evaluated. Therefore, at this time the rate of natural increase estimator is recommended for sites where good infant representation is indicated. For instance, sites in Southeast Asia are known to experience good skeletal preservation overall and infant representation within the expected range (Domett, 2001; Domett, 2004; Domett and Oxenham, 2011; Tayles, 1999; Tayles et al., 2007). It is essential that researchers undertake due diligence in evaluating potential sample bias before applying this, and other paleodemographic, measures. McFadden and Oxenham (2017) provide a discussion of the potential implications of age estimation error on this measure. In summary, employing the D0-14/D ratio effectively reduces the potential impact of age estimation error to a single age group (those aged ~13–15 years of age).

McFadden and Oxenham (2017) outlined concerns regarding the use of life table data to calculate paleodemographic measures, which are based on the observation that the mortality data in life tables has been modelled, meaning they do not wholly represent the complexity and extent of natural variability in population dynamics. The use of ratios calculated from genuine age-at-death data as an alternative to data from life tables was proposed in McFadden and Oxenham (2017) and utilized again in this study. In addition to mitigating some of the challenges and concerns associated with life table derived data, our approach is easily reproducible and verifiable. As noted by Axtell et al. (2002), the lack of reproducibility has been a significant impediment in archaeology, which has previously only been overcome through the use of modelling. The method proposed in this study addresses this issue, as it can equally be applied to the same and alternative datasets to verify accuracy. Further, the interrelationship of a greater range of population dynamics and variables can be explored. In this study, the use of census-based data has permitted us to evaluate the impact of migration.

Our method does not account for population increase through migration, however, this study has determined that migration has a negligible impact on the rate of natural increase and the D0-14/D ratio. Migration has an insignificant relationship with both measures ($p > 0.05$ two-tailed) and accounts for only 2.5% and 5.4% of the variation in the rate of natural population increase and D0-14/D ratio respectively. This is true for a sample where the migration rate ranges from 17.60 to −28.19 per 1000. It should be noted that this insignificant relationship does not negate the impact of migration on population growth, but solely its impact on the rate of natural increase and the proportion of juvenile deaths. As previously mentioned, migration may be expected to have occurred at a lower rate in past populations, where long-distance movement was more onerous and population densities were lower (Anthony, 1990; Clark, 1994). Where migration is evidenced, rates are difficult to estimate. The appearance of distinctive artefacts, cultural practices, and morphologically different skeletal remains has been used to indicate inward migration (Anthony, 1990). Clark (1994) raises a number of issues in the study of migration, including that migration is density-dependent and a phenomenon belonging to the protohistoric and historic periods, and that the scale and process of migration is difficult to differentiate in the archaeological record. Burmeister (2000) discussed further challenges, such as differentiating between cultural artefacts transferred through migration or through trade, but proposed that careful consideration of all available evidence, particularly functional artefacts such as pottery and residential architecture, may largely overcome the issue.

Recent studies have focused on isotopes and dates to estimate past migration, for example, Dupras and Schwarz (2001) used oxygen and nitrogen isotopes derived from bone to identify migration in Egypt, and Collard et al. (2010) used density of radio-carbon dates for material culture in Britain spanning the Mesolithic and Neolithic to estimate population increase, which they argued was the result of migration of farmers. The availability of alternative methods of evaluating migration, the difficulty of estimating migration rates, and its negligible impact on the rate of natural increase for modern populations where migration is significant, makes a strong case for its exclusion from our measure of population increase. Based on our results, even where migration is invisible in the archaeological record, it is unlikely to skew the rate of natural population increase to any significant extent. Further, we suggest that the question of the impact of migration on a population is, in some cases, a separate one to the impact of subsistence or environmental change (though there are examples where the two are inextricable, for example, where climate change drives both), and that the rate of natural increase is more suitable for the latter.

Significant changes in subsistence are expected to have an array of impacts on fertility, mortality, disease, and nutrition. An increase in juvenile mortality, recognized as an indicator of fertility rate and population increase, is considered a signature of the NDT, for the most part associated with adoption and/or intensification of agricultural activities (Bocquet-Appel, 2002; Bocquet-Appel and Naji, 2006; Bocquet-Appel, 2008). Bocquet-Appel (2002) argued that fertility increases in the early days of the NDT was shortly followed by mortality increases, causing population expansion initially, followed by nil growth due to an equilibrium in births and deaths. He suggested that this may have resulted from an increase in zoonotic diseases. Bocquet-Appel (2002) added that an equilibrium must have been rapidly achieved, as the alternative is explosive population increase. This theory was echoed by Cohen (2008), who asserted that the NDT resulted in a shift from moderate fertility and mortality populations to high fertility and mortality populations.

Evidence for increased fertility and population growth in the early stages of the NDT has been widely reported. In Neolithic Greece, Papathanasiou (2005) reported a rise in fertility, indicated by juvenile mortality, and a slight decline in health indicated by various paleopathological markers. Woodbridge et al. (2014) used pollen evidence of agricultural clearing to indicate rapid population increase in Britain. Buikstra et al. (1986) found evidence for increased fertility in Woodland period (1000 BCE to European contact) American populations, which they argued was the result of high carbohydrate consumption and potentially the availability of a suitable weaning food. They suggested the population experienced stable mortality and growth driven by the high birth rate.

The evidence for the proposed increase in mortality during and following the NDT is less clear and, as noted by Cohen (2008), is largely theory based. While many paleodemographic studies estimate life expectancy, most are cautious in their interpretations with regards to mortality. This is potentially due to broad acknowledgement that the age-at-death distribution is more sensitive to fertility than mortality (Sattenspiel and Harpending, 1983) and the issues associated with estimating life expectancy and age-specific mortality rates (Gage and Dewitte, 2009; Johansson and Horowitz, 1986; Wood et al., 2002). Modelling has been proposed as an alternative means of estimating the mortality distribution, however, it has yet to see significant application, perhaps due to its seeming complexity (Gage and Dewitte, 2009; Wood et al., 2002). As such, hypotheses suggesting that increased fertility may have been counterbalanced by increasing mortality, or that low fertility estimates are resultant of low mortality, are yet to be rigorously tested on the available bioarcheological evidence. A multi-faceted approach incorporating alternative evidence of population increase and decrease, such as the use of radiocarbon dates cross-validated with juvenility indices, for example the study by Downey et al. (2014), may be more promising. Indeed, we believe that the rate of natural population increase provides a complementary approach against which spatio-temporal radiocarbon date approaches (e.g. Chaput and Gajewski, 2016; Crema et al., 2016; Delgado et al., 2015; Zahid et al., 2016) and mortality rate modelling can be cross-validated and cross-referenced.

Changes in mortality are just one explanation for fertility and growth rates that are inconsistent with broader NDT hypotheses. There is modern evidence in support of the association between increased sedentism and increased mortality (Page et al., 2016), however, in the absence of clear archaeological evidence all alternatives should be considered. Armelagos et al. (1991) noted that there may have been contraceptive practices in place before and during the Neolithic period, and that the assumed model of high fertility and high mortality causing a state of equilibrium is questionable due to the observable increase in population sizes. They argued that increased exposure to pathogens did not necessarily cause increased mortality, due to the systematic nature of exposure and, therefore, increased resistance to pathogens. Infants and the elderly would be most susceptible to disease due to underdeveloped and reduced immune responses respectively, while women would have experienced poorer health outcomes due to the reduction in interpregnancy interval (Armelagos et al., 1991). Bellwood and Oxenham (2008) reasoned that slower, or lesser, increases in population increase may be indicative of the means by which agricultural intensification has occurred, with the introduction of agriculture into new areas causing more rapid growth than in populations where agriculture has developed and intensified. While the relationship between the rate of natural increase and fertility and birth rates somewhat limits the interpretive power of the measure, estimates of natural increase that conflict with the traditional high fertility and high mortality model should not be dismissed. Alternative explanations should be considered where a different model is indicated by the bioarcheological evidence.

4. Conclusion

Several important questions are raised by Bocquet-Appel (2008), such as whether population increase associated with the NDT was rapid or gradual, whether it was storage or cultivation of food that determined the increase, and what impact such growth had on culture, lifestyle and health. The rate of natural population increase accounts for the disparity (or lack of) between births and deaths, and provides a valuable measure for evaluating the impacts of such changes on ancient population dynamics. A correlation of $r = 0.863$ (95% CI 0.777–0.917) between the D0-14/D ratio and rate of natural population increase is reported. While the rate does not factor in migration, we believe migration should be measured independently as it is not always of interest to bioarcheological research questions and is very difficult, if not impossible, to measure from the age-at-death distribution. Moreover, this study has demonstrated that migration has a negligible relationship ($r = -0.158$, $p > 0.05$) with the rate of natural population increase and D0–14/D ratio, even in modern populations where migration is significant. Past migration rates are likely to be lower than modern in general and, where significant migration has occurred in past populations, it may be expected that this will be otherwise indicated in the archaeological record. The sensitivity of the D0–14/D ratio to infant underrepresentation is yet to be evaluated and therefore this measure is recommended for sites where good infant representation is indicated. The rate of natural population increase should be sensitive to the impacts of the transition to agriculture and climate change on population dynamics. When appropriate skeletal data are available, estimating the rate of natural increase, along with other paleodemographic measures, has the potential to provide exciting insights into past populations and the human response to change. Indeed, at the very least, it has the potential to enlighten our understanding of one of the most significant events in the history of modern humans. We suggest that future research should further explore the demographic theory underpinning our results and that modelling should be undertaken to evaluate an even greater range of scenarios, including data from multiple years and the impacts of sample bias.

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Appendix 3 - Published copy of 'The impacts of underenumeration and age estimation error on the D0–14/D ratio and palaeodemographic measures'

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The impacts of underenumeration and age estimation error on the D0–14/D ratio and palaeodemographic measures

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ABSTRACT

The objectives of this study were to evaluate the impacts of infant and elderly underenumeration and age estimation error on previously reported measures derived from the D0–14/D ratio, specifically total fertility rate and the rate of natural increase. This study used data from the United Nations database for the year 1960. A two-step approach was taken: to test the stability of the relationship we examined the correlation between the D0–14/D ratio and population dynamics of interest with data omitted or misclassified to simulate a range of sample underrepresentation and age estimation error scenarios. To evaluate the practical implications, we used our existing equations to estimate total fertility and natural increase rates using the simulated differentially represented samples and calculated the standard error of the estimate. Correlations remained robust until a small number of infants and the elderly were represented. Where both infants and the elderly were underrepresented, as much as 75% of these age categories could be removed before accuracy of the equations was significantly compromised. Where either infant underenumeration or elderly underenumeration is suspected, our palaeodemographic measures maintain accuracy when up to 25% of the sample is missing. Age estimation error had a negligible impact. These measures demonstrated robusticity in a range of sample underenumeration scenarios, particularly for sources of bias that impact both infants and the elderly equally, and age estimation error. Where either infants or the elderly have been significantly underrepresented or omitted from the burial site, alternative measures may be required.

1. Introduction

Underenumeration of infants and the elderly and age estimation error are known issues in bioarchaeology. For instance, differential burial practices can result in individuals and specific age groups being interred at a different location to the main burial site. In particular, children and infants have been known to be allocated to a separate cemetery (Guy et al., 1997; Milner et al., 2008). Preservation bias is also known to affect the representativeness of burial sites (Gordon and Buikstra, 1981; Djurić et al., 2011; Lewis, 2007; Walker et al., 1988; Weiss and Wobst, 1973). Age groups with lower bone density, specifically infants and the elderly, may not preserve as well as their more robust counterparts (Djurić et al., 2011; Gordon and Buikstra, 1981). Another concern with small and frail bones is recovery bias, where bones and indeed individuals may be missed or may remain unidentified in the excavation process (Pokines and Paz, 2016). With regards to age estimation, it has been well established that with increasing age there is also increasing error (Kemkes-Grottenthaler, 2002; Savall et al., 2016; Wittwer-Backofen et al., 2008). Some degree of error is to be expected at any age and is also highly dependent on the presence and preservation of skeletal elements and dentition, ancestry, and the method used to estimate age.

Such omission, underrepresentation or erroneous categorisation of particular age groups at burial sites may result in a skewed age-at-death distribution, which is highly problematic for palaeodemography. Paine and Harpending (1998) undertook modelling of the impacts of infant underenumeration and elderly age estimation bias on the age-at-death distribution and palaeodemographic measures such as crude birth rate and total fertility rate. They determined ageing-bias caused a 10–20% overestimation in calculations of crude birth rate, and infant underenumeration decreased birth and fertility estimates by 20–25%. As noted by Paine and Harpending (1998), while elderly age estimation bias can be predicted, underrepresentation is exceedingly difficult to quantify without the assistance of burial records, and as such the degree to which infants and the elderly are represented is often unknown. To avoid the bias introduced by infant underenumeration, palaeodemography has sought to exclude infants from the calculation of measures based on age-at-death data (Bocquet-Appel and Masset, 1977, 1982;

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Buikstra et al., 1986; Milner et al., 2008; Seguy and Buchet, 2013).

The implications of elderly underenumeration on palaeodemographic measures have been less thoroughly considered. Walker et al. (1988) evaluated the impacts of preservation bias on the age-at-death distribution using a 19th century cemetery sample with associated cemetery records. They found that whilst infants and elderly represented approximately 30% and 35% of the cemetery records, they each represented less than 5% of the burial sample. As noted by Cave and Oxenham (2014) the elderly have been neglected in bioarchaeological studies, largely due to the complexities associated with estimating age from skeletal degeneration and the presumption that people in the past experienced a much younger maximum age-at-death. In palaeodemography as well, the elderly have received minimal attention.

In two recent papers (McFadden and Oxenham, 2018a, 2018b), we provided new palaeodemographic tools for estimating the total fertility rate and rate of natural population increase from the ratio of deaths 0–14 years to total deaths (D0–14/D). Both tools were developed with samples with good preservation in mind, particularly those in Southeast Asia. However, as infant and elderly underenumeration are widespread issues, it is essential to evaluate the impacts of removing or underenumerating these age categories on our palaeodemographic measures if they are to be used more broadly. Further, it is beneficial to estimate the impact of age estimation error as this affects all skeletal samples to varying degrees. The applicability of the measures relies on their resilience in the face of such biases.

2. Materials and methods

We utilised the data as used in McFadden and Oxenham (2018a, 2018b) for this study, specifically: age-at-death data, fertility rates, birth rates and mortality rates from the United Nations Database (United Nations, 2017) for the year 1960. There were 48 countries with sufficient records for inclusion. Infants were defined as individuals aged 0–4 years and the elderly as those aged 45 years or over, for consistency with previous work including Bocquet-Appel and Masset (1977, 1982), Paine and Harpending (1998), and Walker et al. (1988). In order to simulate the effects of differential burial, preservation and recovery, a number of scenarios were evaluated: the omission and underrepresentation of infants only; the omission and underrepresentation of the elderly only; and the omission and underrepresentation of both infants and the elderly.

Based on average error rates from recent studies of dental and skeletal methods (AlQahtani et al., 2014; Rissech et al., 2013), individuals aged 12–14 years may be estimated to be over 14 years of age, and individuals aged 15–17 years may be estimated to be 14 years or younger. In order to encapsulate these ages, and due to practicalities of the available data, we used age categories 10–14 years and 15–19 years. If anything, this should overestimate the impact of ageing bias. To evaluate the effects of age- estimation bias, we developed scenarios of under-ageing (where a proportion of individuals aged 15–19 years were erroneously placed in the 10–14 years category) and over-ageing (where a proportion of individuals aged 10–14 years were erroneously placed in the 15–19 years category). For the purposes of our palaeodemographic methods, under-ageing would overestimate the number of individuals categorised as 0–14 years, and over-ageing would underestimate the number of individuals in the 0–14 years category.

To test the practical value of the original equations when applied to differentially represented samples, the D0–14/D ratios for the omission, underrepresentation and incorrectly aged scenarios were calculated, and then the total fertility rate and the rate of natural increase were estimated using our standard equations (McFadden and Oxenham, 2018a, 2018b). For underrepresentation, the impacts of removing 75%, 50% and 25% of the relevant sub-samples were evaluated. For age estimation error, the impacts of misclassifying 75%, 50% and 25% of individuals for both positive age bias (over-ageing) and negative age bias (under-ageing) were evaluated. For positive age bias, the rates were applied to individuals aged 10–14 years, simulating the impact of these individuals being over-aged and excluded from the 0–14 years component of the D0–14/D ratio. For negative age bias, the rates were applied to individuals aged 15–19 to simulate the impact of these individuals being under-aged and included in the 0–14 years group.

To quantify the actual impact of differential representation and incorrect age-estimation on estimated fertility rates and rates of natural growth, the standard error of the estimate (SEE) was calculated using the estimated rates for each scenario, where the original regression equations and the differentially represented D0–14/D ratios were used to calculate an estimated rate (Y'), and the actual rates of fertility and growth (Y). The correlations between the estimates derived from underenumerated and incorrectly aged D0–14/D ratios, the wholly represented estimates, and the actual fertility and natural increase rates were also evaluated to determine whether the relationships were significant. This alone does not indicate practical value, but in combination with the evaluation of SEE indicates the robusticity of the measures in various contexts. All statistics were performed in Microsoft Excel (2016).

3. Results

3.1. Applying the total fertility rate and natural population increase measures to differentially represented samples

The SEE provides an overall measure of the accuracy of predictions. Lower error estimates indicate observations that are more closely fitted to the regression line. Table 1 provides the SEEs for all underenumeration and age misclassification scenarios in this study. Based on a wholly represented sample, the SEE for the D0–14/D ratio and total fertility rate is 0.742. Where infants were underrepresented by up to 25%, the SEE increased by approximately 9% to 0.810. With the elderly underrepresented by up to 25%, the SEE also increased by 9%. Beyond this, the error exceeded practical value. In contrast, where the infants and elderly were both underrepresented, the equations remained relatively accurate with up to 75% underrepresentation of infants and the elderly, with the SEE increasing by a maximum of 12%. For age estimation, the SEE was negligibly impacted.

For the wholly represented D0–14/D ratio and the rate of natural increase, the SEE was 1.491. Where infants were underrepresented by up to 25%, the SEE increased by approximately 11% to 1.653. With the elderly underrepresented by up to 50%, SEE decreased by 9% to 1.360. Where both were underrepresented, SEE decreased insignificantly to 1.466, or an approximately 2% decrease. Again, for age estimation error, the impact on SEE was insignificant.

3.2. Correlations with total fertility rate and rate of natural increase

Descriptive statistics for the ratios and total fertility rate, and the rate of natural increase, are provided in Table 1. For this sample, the correlation between the D0–14/D ratio and the total fertility rate was r = 0.897. Reducing the representativeness of the 0–4 years age category by 25%, 50% and 75% had a negligible impact on the correlation with total fertility rate. In fact, the correlation remained above r = 0.800 until only 2% of the 0–4 years age category were represented. When the 0–4 years age category were excluded, the correlation was reduced to r = 0.747. Similar results were obtained for elderly underenumeration, where the correlation remained strong until only 5% of the elderly sample was represented. Omission of the elderly resulted in a correlation of r = 0.731. For the underenumeration of both infants and the elderly, representativeness of 75%, 50%, and 25% produced very nearly equivalent correlations.

Representation of only 1% of the infants and elderly resulted in a correlation of r = 0.791, and exclusion of both infants and the elderly reduced this to r = 0.733. For age estimation bias all correlations

Table 1
Standard Error of the Estimate (SEE) and correlations for differentially represented samples, the total fertility rate and the rate of natural increase.

Representation	Total fertility rate SEE	% difference in SEE	Rate of natural increase SEE	% difference in SEE	Correlation with total fertility rate*	Correlation with rate of natural increase*
Wholly represented						
100%	0.742	N.A.	1.491	N.A.	0.897	0.864
Infant underrepresentation						
75%	0.810	9%	1.653	11%	0.898	0.857
50%	1.052	42%	1.944	30%	0.899	0.847
25%	1.498	102%	2.427	63%	0.897	0.834
0%	2.243	202%	3.246	118%	0.747	0.683
Elderly underrepresentation						
75%	0.809	9%	1.382	-7%	0.895	0.871
50%	1.065	44%	1.360	−9%	0.886	0.877
25%	1.648	122%	1.636	10%	0.862	0.874
0%	3.377	355%	3.307	122%	0.731	0.750
Infant and elderly underrepresentation						
75%	0.744	0%	1.477	−1%	0.898	0.865
50%	0.758	2%	1.462	−2%	0.897	0.866
25%	0.829	12%	1.466	−2%	0.894	0.866
0%	1.455	96%	1.895	27%	0.733	0.707
Under-aged (15–19 years)						
75%	0.735	−1%	1.476	−1%	0.899	0.866
50%	0.730	−2%	1.463	−2%	0.901	0.868
25%	0.725	−2%	1.450	−3%	0.903	0.870
Over-aged (10–14 years)						
75%	0.748	1%	1.501	1%	0.895	0.862
50%	0.756	2%	1.512	1%	0.893	0.860
25%	0.764	3%	1.524	2%	0.891	0.857

* $p < 0.05$ for all correlations.

remained robust, even where 75% of individuals in the 10–14 years (over-ageing) or individuals in the 15–19 year (under-ageing) age groups were misclassified.

For the rate of natural increase, the correlation with the D0–14/D ratio was r = 0.864. Infant underenumeration had a minor impact on the correlation with the rate of natural increase, with 75%, 50% and 25% underenumeration producing correlations of r = 0.857, r = 0.847, and r = 0.834 respectively. The correlation remained above 0.800 until only 7.5% of infants were left. With infants omitted the relationship ceased to be of practical value (r = 0.683). For elderly underenumeration, there was no statistically significant difference between the wholly represented sample and the 50% and 25% underenumerated samples. With the elderly omitted, the correlation was r = 0.750. For both the infants and the elderly, there was no statistically significant difference between the whole sample, and the 75%, 50%, and 25% underrepresented samples. With only 2% of the elderly and infants represented, the correlation was r = 0.798 and with both omitted the correlation was r = 0.707. For the age estimation bias scenarios, the correlations with rate of natural increase were consistently strong.

4. Discussion

4.1. Preservation bias: Robusticity of palaeodemographic measures

In any scenario it is difficult to quantify the representativeness of the age-at-death distribution of a skeletal sample. The results presented here demonstrate that our palaeodemographic equations for total fertility rate and rate of natural population increase can be confidently used for samples where up to 25% of infants or the elderly (that is, one or the other) are missing.

But how accurately can we ‘eyeball’ good preservation? Skeletal completeness is one means by which the degree of preservation is estimated and, whilst it falls short of a percentage, it may be used as an indication of the sample representation (Domett and Oxenham, 2011). These results provide assurance that if good preservation equates to representation somewhere between 75% and 100% for either infants or the elderly, then these methods remain accurate and applicable without adjustment.

If one were to assume that preservation bias impacts infants and the elderly to a similar extent, as indicated by work by Walker et al. (1988), then the total fertility rate and rate of natural population increase equations can be applied to samples where as many as 75% of the infants *and* elderly are missing with only a minimal impact on the accuracy of the methods. This is the result of the reduction affecting both the numerator and denominator of the ratio. As previously noted, it is nearly impossible to quantify the degree of underenumeration without cemetery records, however, the accurate applicability of these methods on samples with just 25% representation should give bioarchaeologists confidence that these equations can be used where overall poor preservation (as opposed to complete omission via, for example, differential burial) is indicated, with no adjustments to the equations or estimation of underrepresentation necessary. This produces a far more accurate result than the tradition of deliberate omission of infants from palaeodemographic methods.

For the total fertility rate, 25% underenumeration of infants or the elderly, and 75% underenumeration of infants and the elderly, increased the SEE by between 9–11%. For the rate of natural increase, the error increased by 11% with 25% underenumeration of infants, decreased by 9% with up to 50% underenumeration of the elderly, but subsequently increased by 10% with 75% underenumeration. For both infants and the elderly, SEE decreased by 2% with 75% underenumeration. These error rates suggest that not only does the relationship between palaeodemographic measures and the D0–14/D ratio remain robust, but that the ratio remains stable enough for use in our existing equations in a range of sample-bias scenarios.

The acceptable rate of error should be evaluated on a case by case basis and it is necessary with all methods to calculate standard error based on sample size. Paine and Harpending (1998) argued that error rates in the range of 10–20% was unacceptable. Whilst in isolation these rates seem high, to outright reject such error contradicts the accuracy one can hope to achieve with palaeodemographic measures even in the best-case scenarios. As observed by Wood et al. (2002), there are limits to the detail researchers may credibly obtain from the age-at-death distribution. Further, even modern demographic predictions experience significant error rates despite being based on large volumes of data, living populations, and often complex calculations (for example, Khan and Lutz, 2007; Office for National Statistics, 2015). We suggest that the acceptability of such error should be evaluated on a case by case basis, in the context of the sample, interpretive framework, and research aims.

4.2. Missing Infants and the invisible elderly: Selective burial practices and recovery bias

Where representation for either age group (but not both) is below 75%, the correlations with total fertility rate and rate of natural increase remained significant, but the SEE was too high, in our opinion, for the existing equations to be used. In order to overcome this issue, we would need to be able to confidently estimate the percentage of representation we are dealing with in order to create a bespoke predictor, however, this is a highly unlikely scenario. We do not recommend our measures be applied to samples where infants appear to be significantly underrepresented, or the elderly appear to be significantly underrepresented. Scenarios where one of these age groups may be misrepresented, but not the other, include differential burial practices and recovery bias. In both cases, infants and juveniles are the more likely candidates, due to the known occurrence of child cemeteries (Milner et al., 2008) and small bones being more susceptible to recovery bias (Pokines and Paz, 2016). Where infants are seemingly well represented and there are low numbers of elderly individuals, it would be necessary to consider all potential explanations before pursuing a methodology. One such scenario that should be considered is lower overall life expectancy, which could mean the apparently low representation of elderly is a true reflection of the age-at-death distribution. Notwithstanding, the potential impacts of age-estimation bias against the elderly should not be ignored (see Cave and Oxenham, 2014).

Where infants, the elderly, or both are entirely omitted from the burial samples, the proposed palaeodemographic equations are not suitably accurate for use. For infant omission or significant underenumeration (a commonly seen phenomenon), we recommend the use of the following equations, noting the correlation is reduced to $r = 0.747$ for total fertility rate and $r = 0.683$ for the rate of natural increase:

$$\text{Total fertility rate} = (32.225 \times \text{D5–14/D5+}) + 3.028$$

$$\text{Rate of natural increase} = (17.708 \times \text{D5–14/D5+}) + 1.259$$

These equations were developed using the dataset of the present study and the same methodology as McFadden and Oxenham (2018a, 2018b), and where D5–14 is the number of individuals age 5–14 years at death and D5+ is the number of individuals aged 5 years or over at death. For elderly omission or severe underenumeration, or dual infant and elderly omission, linear regression may similarly be used to develop alternative equations which exclude these age categories, though accuracy of such equations will also be reduced.

4.3. Age-estimation error

In all age-estimation scenarios evaluated, the impact on accuracy was negligible. Both over- ageing and under-ageing of individuals within the range of error for the 14 years of age demarcation point does not appear to adversely impact upon the methods for estimating total fertility rate or rate of natural increase. This should provide researchers with confidence that the methods can be applied to samples of diverse origins and using a variety of age- estimation approaches.

5. Conclusion

Infant and elderly underrepresentation and age-estimation have historically been problematic for palaeodemography, with the traditional approach being to intentionally omit infants from palaeodemographic measures. The results reported here show that correlations between the total fertility rate, rate of natural increase and the D0–14/D ratio remain robust even with minimal representation of each age category, however, this alone does not mean our methods (McFadden and Oxenham, 2018a, 2018b) are suitable for underrepresented samples. In terms of practical application, where infant underenumeration *or* elderly underenumeration is suspected our palaeodemographic equations maintain accuracy when up to 25% of the sample is missing, based on the results of the standard error estimates. This may be applicable for samples where good, but not complete, preservation is indicated. Age estimation error for the relevant demarcation point (14 years of age) was found to have a negligible impact on palaeodemographic methods. An anomaly was observed where SEE was reduced by underenumerating the elderly by 25–50%, and it is suggested the theoretical cause of this be explored in further research. If both infants *and* the elderly are underrepresented, the D0- 14/D ratio remains relatively stable when as many as 75% of individuals are missing from the sample, and as a result our equations remain sufficiently accurate for use. A potential application of this is where preservational bias against those with low bone density is suspected. Where either infants or the elderly have been omitted from the burial site via differential burial rites, or where they have been significantly underrepresented due to factors such as recovery bias, alternative measures may be required. This study has highlighted the need for further experimental research into differential preservation of infants and, particularly, the elderly. Infant underenumeration has been a concern for palaeodemographers for some time, however, our results indicate that elderly underenumeration should be of equal concern. Ultimately, this study has shown palaeodemographic methods derived from the D0- 14/D ratio to be robust and stable in a variety of sample bias scenarios.

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Appendix 4 – Published copy of ‘Detection of temporospatially localized growth in ancient Southeast Asia using human skeletal remains’

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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

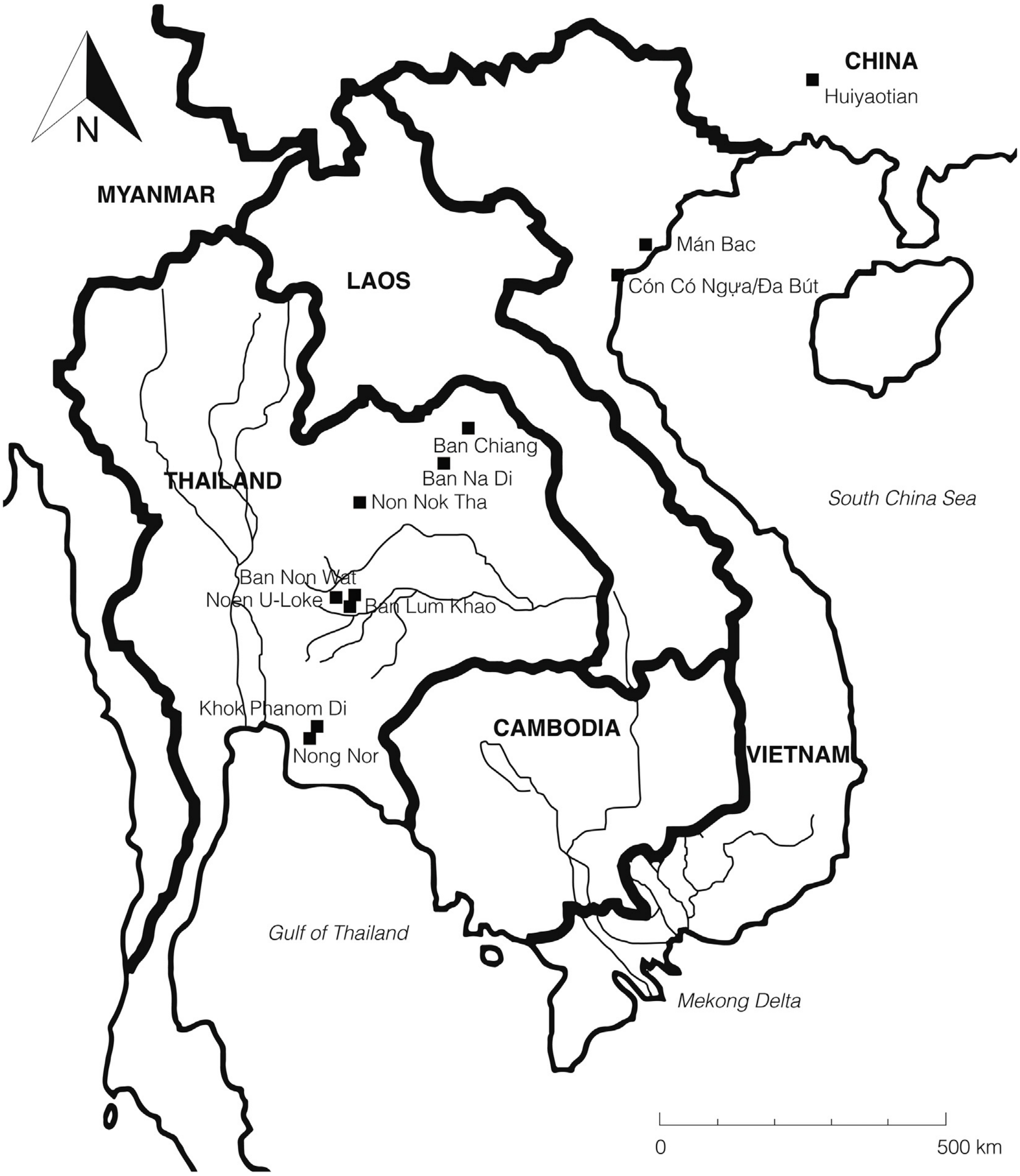

Fig. 1. Map of Sites in Southeast Asia, adapted from Sarjeant (2017).

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

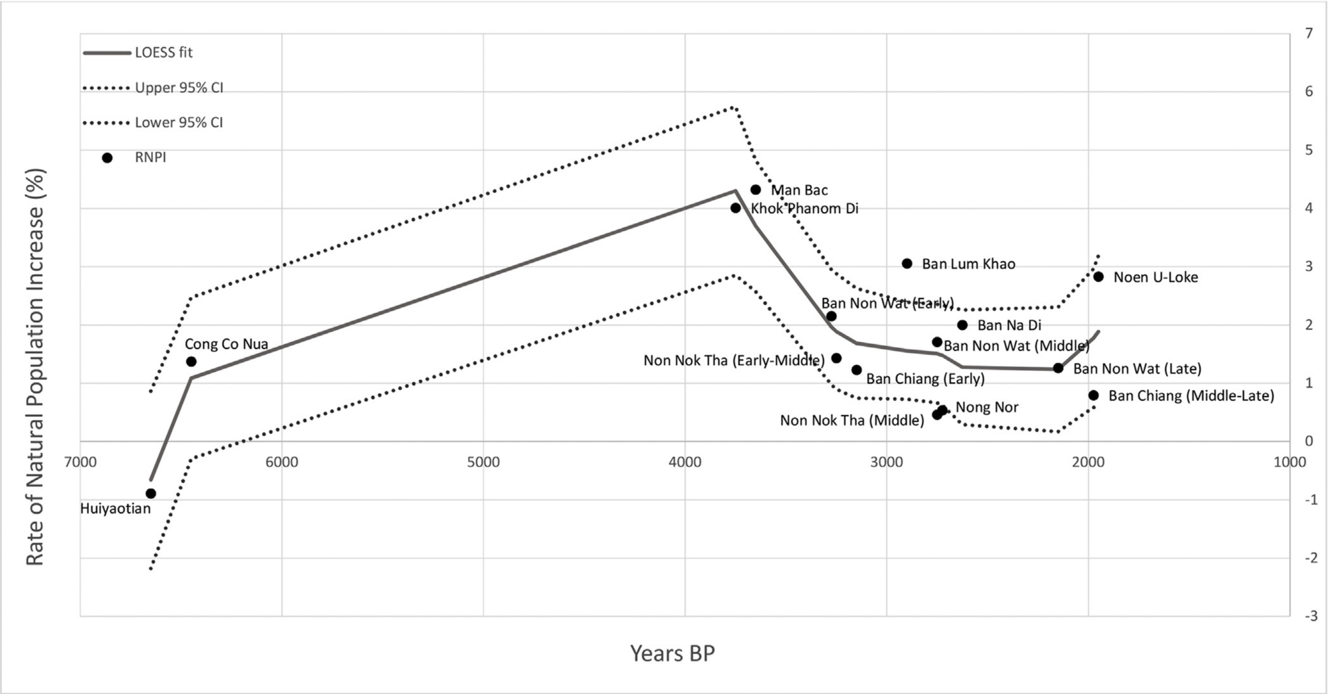

Fig. 2. Rate of natural population increase (per annum) for 15 ancient Southeast Asian samples (LOESS fit with 95% CI).

(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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Appendix 5 - Australian National University Thesis by Compilation Policy

Australian
National
University

Procedure: Higher degree by research – thesis by compilation and thesis by creative works

Purpose

This document outlines the content, format, and approval process for an HDR Thesis by Compilation or Thesis by Creative Works submission.

Procedure

1. This document is to be read in conjunction with the Research Awards Rule.
2. This procedure supplements the information provided in the *Higher Degree by Research Submission and Examination of Theses Procedure*. Where information is not varied or detailed in this procedure the *Higher Degree by Research Submission and Examination of Theses Procedure* prevails.

Thesis by compilation

Content

3. A thesis by compilation includes papers (e.g. articles, chapters) where the student is the sole or joint author that are in the process of being prepared or approved for publication, have been accepted for publication, or have been published.

4. A thesis by compilation contains
   a. An introduction to the field of study and the hypothesis or research questions, how these are addressed through the ensuing chapters, and a general account of the theory and methodological components of the research where these components may be distributed across separate papers/chapters.
   b. Linking text to establish the relationship between one chapter and the next, such as through a foreword to each chapter.
   c. A conclusion drawing together the published papers or works in a cohesive manner, and addresses how the individual publications link to the theory and methodology adopted and evaluate the contribution that the research in the submitted publications makes to the advancement of the research area.

5. Papers evidenced as in the following categories may be included with each presented as an individual chapter in the thesis:

   a. Published papers
   b. Manuscripts accepted for publication
   c. Manuscripts submitted and under review by referees;
   d. Manuscripts under revision following referees reports; and
   e. Manuscripts in preparation for submission.

6. Unless otherwise approved by the Delegated Authority, a thesis by compilation consists primarily of published papers and manuscripts accepted for publication, and not primarily of manuscripts submitted and under review by referees or manuscripts under revision following referees reports.

7. A thesis by compilation may also include video recordings, film or other works of visual or sonic arts, computer software, digital material or other non-written material for which approval has been given for submission in alternative format.

8. The papers must have been researched and written during the course of the candidature, except in the case of students admitted to a PhD program as a staff member under the Research Awards Rules.

9. The scope and quality of a thesis by compilation is commensurate with the contribution to knowledge expected of a candidate for the relevant degree. The numbers of papers that constitute this requirement may vary between a single long monograph in disciplines such as mathematics to four to five peer*reviewed papers in other disciplines.

Format

10. A thesis by compilation includes a signed declaration that specifies:

    a. Title, authorship and publication outlet of each paper.
    b. The current status of each paper (In press, Accepted, Under Review, In preparation).
    c. The extent of the contribution of the candidate to the research and the authorship of each paper.

11. For each paper where the candidate is not the sole author, either:

    a. The collaborating authors sign the declaration; or
    b. A senior author signs the declaration on behalf of the collaborating authors

12. The thesis may also include relevant appendices containing additional papers that are not related to the main thrust of the thesis, raw data, programs, questionnaires and other material as deemed appropriate for each discipline.

13. The thesis is otherwise formatted as per the Thesis in Standard Format Section in the *Higher Degree by Research Submission and Examination of Theses Procedure*, although journal formatting can be preserved for appropriate sections.

Process

14. Students submitting by compilation will normally obtain endorsement from their supervisory panel about the format of their thesis more than 12 months prior to submission, and no later than 6 months prior to submission.

15. In considering the request the supervisory panel provides the student with discipline*specific guidance on the appropriate quantity and quality of papers for submission as a thesis, as well as practical guidance about realistic peer*review and publication timeframes in their discipline.

16. Subsequent to endorsement by the supervisory panel, submission of a thesis by compilation requires approval by the Delegated Authority.

17. The Delegated Authority may permit the approval of a thesis by compilation and the composition of that thesis later than 6 months prior to submission in exceptional circumstances.

18. Following submission of the thesis the standard ANU examination procedures will apply.

Other

19. Students who are undertaking a thesis by compilation ensure publisher's agreements do not preclude the inclusion of the published work in their thesis.

20. Only in exceptional circumstances will approval be given to a candidate for a Master of Philosophy or Professional Doctorate to submit a thesis by compilation.

Thesis by creative works

Content

21. A thesis by creative works is an original work which includes one or more of the following: a multimedia or digital work, a film, an exhibition, a performance, a musical composition, a novel, a play, a series of poems, creative art work or other works considered acceptable by the Delegated Authority.

22. The written thesis accompanying the creative work may be a dissertation or an exegesis or a combination of both as approved by the Delegated Authority.

23. The exegesis details the development of the creative work over the duration of the course of study, and provides the broad context for the ideas and precedents which inform the development of the research program. The exegesis enables the candidate to present an account of the research, demonstrating how the work addresses the objectives of the approved research project, and how the topic(s) of the dissertation or coursework have informed the creative work-based research.

24. For the dissertation, candidates present a substantial academic essay on a topic of relevance to the objectives of the creative work-based research project. The candidate presents a standalone paper or one that supports a lecture recital that is framed within appropriate academic methods through research, documentation and theoretical and conceptual discourse in a form that is relevant to the topic in question.

Length of thesis

25. In the case of a combined body of a Thesis by Creative Works PhD, the written work for a PhD must be a substantial work of 30,000 to 60,000 words that complements the other work submitted.

26. In the case of the combined body of a Thesis by Creative Works MPhil, the written work for an MPhil must be a substantial work of 15,000 to 30,000 words that complements the other work submitted.

27. The additional material submitted or presented in the form of a public recital must be:

a. A substantial and genuine contribution to research; and

b. A work of equivalent quality to a written thesis using criteria appropriate to the particular medium in which it is submitted.

28. The submission as a whole must be a coherent contribution to the advancement of knowledge and a pass standard must be achieved in all components.

29. In the case of resubmission being required only that component that has failed to meet the appropriate standard is required to be revised.

Examination of creative work other than a written thesis

30. The final outcome of the creative work component of the thesis is presented for examination in the form of an exhibition, or audio-visual presentation, recital, lecture recital or in such other form as had been approved by the Delegated Authority in the candidate's research program.

31. The Delegated Authority approves whether artistic practice is examined by a theoretical dissertation or by creative work and written thesis. If a creative work and written thesis is approved, they are be examined as an integrated whole.

32. In cases where the creative work is presented in the form of an exhibition, audio-visual presentation, recital, lecture recital etc., the written thesis is made available to the examiners at least one month before the presentation of the creative work so that the examiners are fully aware of the context of research which has led to the work in the final presentation. Any additional items such as video of the performance, visual presentation of artwork, recording, are either:

a. supplied to the examiners with the written thesis; or
b. supplied to examiners as soon as the documentation is available.

Document information

Title	Higher degree by research - thesis by compilation and thesis by creative works
Document Type	Procedure
Document Number	ANUP_003405
Version	12
Purpose	This document outlines the content, format, and approval process for an HDR Thesis by Compilation or Thesis by Creative Works submission.
Audience	Staff-Academic-Research, Students-Graduate-Research, Students-Graduate
Category	Academic
Topic	Students
Subtopic	Higher Research Degrees
Effective Date	21 Dec 2018
Review Date	21 Dec 2021
Responsible Officer	Dean, Higher Degree Research (dean.hdr@anu.edu.au)
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Contact Area	Office of the Dean, Higher Degree Research (dean.hdr@anu.edu.au)
Authority	Research Awards Rule 2017
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