From Individuals to Settlement Patterns.

Bridging the Gap Between the Living and the Dead in Early Medieval Populations

Using an Agent-Based Demographic Model

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Abstract

This thesis describes and contextualises the Population & Cemetery Simulator (PCS), which represents agent-based demographic modelling software that can be used to model living populations based on archaeological and historical data as well as their cemeteries. The data used by the PCS are demographic in nature, e.g. age and sex data generated by osteoarchaeologists from excavated cemeteries or historical demographic data. This thesis seeks to provide a methodological foundation for modelling the demographics of archaeological populations. It focusses on case studies using data from early medieval Anglo-Saxon (South England) and Alamannic (South Germany) cemeteries, although excursions into neighbouring periods and regions are included as validation studies. The case studies show how the PCS can be used in archaeological research and the software is presented as a solution to various problems caused by the difference between the living population and the 'dead' cemetery data in archaeology.

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(…) nothing in the history of mankind is ever repeated, things that at a first glance seem the same are scarcely even similar; each individual is a star unto himself, everything happens always and never, all things repeat themselves endlessly and unrepeatably.

(Danilo Kiš, The Encyclopedia of the Dead)

‘Well, suppose they do live three or four centuries – ’ ‘Hari. That’s ridiculous.’ ‘I’m saying suppose. In mathematics, we say “suppose” all the time and see if we can end up with something patently untrue, or self-contradictory. An extended life-span would almost surely mean an extended period of development. They might seem in their early twenties and actually be in their sixties.’ ‘You can try asking them how old they are.’ ‘We can assume they’d lie.’ ‘Look up their birth certificates.’

(Isaac Asimov, Prelude to Foundation)

INTRODUCTION

1 Introduction

This thesis describes how archaeological populations and cemeteries can be modelled in agent-based demographic simulations, provides open-access software called the Population & Cemetery Simulator (hereafter PCS) for such simulations, and shows how the model is applied in practice in early modern & medieval validation studies (c. 15th to 18th century) and early medieval case studies (c. 5th to 11th century). The demographics of small agricultural populations, the effects of demographic dynamics on life and social systems and the reliability and hidden complexities of burial data are explored. I argue that although archaeologists set out to describe the living populations which formed the archaeological sites in early medieval archaeology, they have in fact only managed to describe and compare cemeteries. While cemetery archaeology has developed, discarded and revived many theoretical approaches to the analysis of burials, including the assessment of the burial rituals, the role of the burying community and the complexities of the identities and social statuses expressed in the burials etc. (Dürr in Press; Härke 1989; Härke 1998; Härke 2000; Härke 2002; Härke 2005; Heilen 2012; Hills 2011; Johnson 2010; Parker Pearson 2003; Stutz and Tarlow 2013), the mathematical method of analysis has rarely focused on the living, and instead still works with what Peebles seminally described as “fossilised terminal statuses of individuals” (Peebles 1971, 69).

Fig. 1 illustrates the difference between the final-state cemetery data and the information defining a living population at one specific point in time. The dotted lines represent the lives of individuals buried in a cemetery at the point in time indicated by the rhombus. The excavated cemetery always records a final state (rhombus) whereas the individuals in the living population at a single point in time (A) are not only temporally delayed, but also likely to be in pre-final stages equal to a point on the dotted line before the final state rhombus. Consequently, an individual had a lower age during life, had not yet been infected or had not received a specific grave good at a specific point in time. Typical archaeological interpretation (B) using cemetery data is problematic, as it

(1) not only collapses the chronologically delayed signals onto one temporal signal, but also

(2) describes living populations incorrectly when only final state/rhombus data are used.

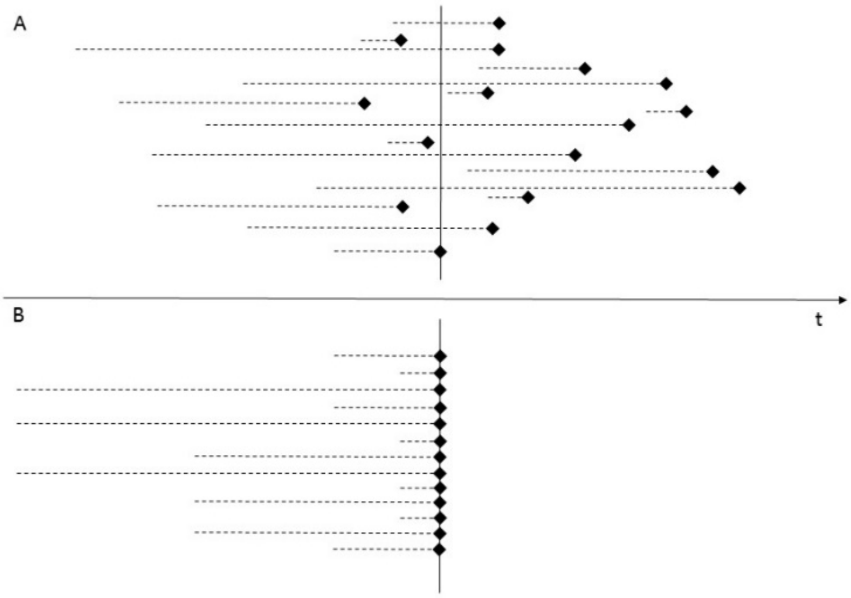

Fig. 1 The difference between living populations and their cemeteries. Horizontal axis: time (t), vertical axis: single point in time or transition from phase 1 and phase 2, A: phased, delayed reality, B: traditional archaeological interpretation using signals collapsed onto one phase or the final phase of a cemetery.

Instead of playing down this problem in the light of the already problematic burial data of the early medieval period, I will explain that it is in fact much more severe than the combined problems of sample bias, incomplete excavation and mixed preservation. Archaeologists almost always employ methods which incorrectly equate data deriving from the 'dead' population with the dynamics of a living community. Consequently, archaeological interpretations of single sites and regions which do not (conceptually or mathematically) model the dynamic living population and work with the static cemetery data only – no matter how well dated, phased, aged or sexed – most likely miss a range of equally likely scenarios or fall prey to simple category errors. This is not an entirely new claim (Wood et al. 1992, 343-344) and some archaeologists have realised and tackled the problem in various ways (e.g. generational chronologies in Anglo-Saxon Archaeology, Sayer 2010), but I propose a new solution to this fundamental issue of our field which is embedded in mathematics, bio-archaeology, demographics and relatively simple reproducible modelling. This thesis describes how scenarios of living populations can be modelled and their plausibility tested in relation to the excavated cemetery data.

My research was inspired by Kölbl's revolutionary Monte-Carlo simulations of the 'missing infant' phenomenon (2004), the famous model of the Anasazi population (Axtell et al. 2002) and Sayer's development of a generational approach to Anglo-Saxon cemeteries (2010). Their research introduces a mathematical framework of reasoning and interpretation in archaeology. Although my research questions are archaeological and, to a certain extent, historical, this research is based on interdisciplinary collaboration. The modelling4all project at the Oxford IT department led by Dr. Kenneth Kahn was fundamental to the development of the agent-based software, PCS. Mathematical elements of the modelling procedures and the independent cross-check which proves the reliability of the results produced by the PCS were developed together with Dr. Thomas Woolley at the Mathematical Institute, Oxford. I further draw on research in the fields of bioarchaeology, skeletal anthropology and historical demography.

Modelling is not undertaken in order to simply reconstruct possible past realities. Nor do I consider the claim valid that aspects of human populations are too complex to be modelled with a computer.[1] There are many other reasons for modelling in the social sciences, such as theory-building, understanding the parameters involved and learning to ask better questions (Courgeau et

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[1] Chapter 2.1 provides more material on my position in this debate.

al. 2016; Epstein 2008). Epstein, lists 16 additional reasons for modelling (2008, 1.9), including “the promotion of a scientific habit of mind”, challenging “the robustness of prevailing theories” and exposing “prevailing wisdom as incompatible with available data”. In our research on the Neolithic mass burial of Talheim, Kreis Heilbronn, Germany (Duering and Wahl 2014a; Duering and Wahl 2014b), the PCS was employed to challenge interpretations utilising virtual experiments. Models studying the impact and sensitivity of certain parameters might offer further interesting methodological insights. The PCS will hopefully contribute to an improved understanding of the data (age and sex, mortality, fertility, artefact frequencies, household composition, population size and composition) and the dynamic changes over time which ultimately form the archaeological material culture and skeletal populations excavated. Virtual experiments are employed in order to test hypotheses within a set framework. This allows the mathematical plausibility of certain demographic scenarios to be assessed within the limits of the often highly problematic archaeological data (Courgeau et al. 2016; Van Der Leeuw 2004; Verhagen and Whitley 2012). Regarding the incomplete and silent archaeological material, one might argue that there is little mathematical security obtainable at all. In such a context it is even more important to use an approach that links parameters – for instance, the influence of marriage ages on the reproduction rate and the chance of survival of small communities over long periods of time. Although the archaeological theory of community reconstruction based on the mortuary evidence is extensive and well-developed (e.g. Parker Pearson 2003), ‘mathematical’ concepts of plausibility and hypothesis falsification play a minor role in the archaeological research of cemetery populations. With the rapid growth of the importance of computer technology in every aspect of research and the growing amount of data from scientific analysis and database projects, this doctoral research seeks to fill the gap of the analytical data interpretation tools needed in cemetery archaeology. The expertise of archaeologists, historians, demographers, anthropologists, modellers and mathematicians can best be combined when software interfaces are used that permit results, data, interpretations and models to virtually interact. However, the thesis will also show that the palaeodemographic modelling approach PCS is ultimately unfinished. It will hopefully be checked, extended and improved in the future.

1.1 Research Objectives

This thesis explores the most fundamental agents and demographic parameters in order to provide a theoretical and practical basis for further population modelling in archaeology. The PCS should ideally be a building block of future bottom-up population models in archaeology. It became obvious that the focus of the following should be on three major problems in burial archaeology and the illustration of these problems in validation studies based on populations from periods with more available demographic data and case studies of Anglo-Saxon and Alamannic populations:

(a) The problems caused by *the difference between the living population*, i.e. the dynamically changing entity of individuals existing together at any point in time, *and the cemetery population*, i.e. the accumulating population consisting of all (or a selection of) the deceased that end up in the cemetery, and probably never coexisted at any point in time. The difference between living and cemetery populations pervades all archaeological and historical data interpretation as soon as a (living) society or community is described based on burial population data.

(b) The effects of *demographic dynamics*, such as the effect of population growth and changes of birth rates over time on the presence/absence and number of excavated artefacts in graves, are many. The final-state data in a cemetery often mask dynamics in the living community. This causes an equifinality problem as well as a complexity problem (described below, paragraph c).

(c) The network of variables involved in creating the final state cemetery populations can only be understood by using modelling software as they cause *complex inverse problems* – i.e. problems where we know the result – e.g. different numbers of buried adults in a population, but do not know the processes which led there – e.g. changing mortality over time.

1.2 The modelling software

The PCS allows archaeologists to model virtual populations and their cemeteries. By combining measured and extrapolated demographic parameters based on aged and sexed skeletal material as well as further archaeological and historical information, individual parameters (e.g. the probability of dying before the age 20, the average number of orphans per household, etc.) and the aggregate system (e.g. the development of the total population size over time) can be studied. Further, the demographic model is a basis for more complex further archaeological modelling, such as assessment of the influence of demographic dynamics on studies of artefacts, diseases, social structure and the burial ritual. In short, the modelling tool is employed to test hypotheses against a biological, demographic and mathematically consistent framework – a Petri dish for testing and interpretation of archaeological theory.

The PCS is an open-access toolkit with two interfaces:

The *first interface* represents a tool for data entry, parameter changes and simple modelling of populations for archaeological cemetery interpretation, including demographic research as well as research into artefact abundances and diseases. The first interface is somewhat limited to being a thinking tool and to prepare more precise experiments. It can further be used for teaching that employs game-like approaches to the understanding of demographics.

The *second interface* facilitates more fundamental changes in the modelling routine, as it fully employs the highly innovative Behaviour Composer developed by Dr Kenneth Kahn from the modelling4all initiative in Oxford (Kahn and Noble 2010). In the Behaviour Composer, the code is packaged in a mind-map-like structure which represents a visual network of the agent-based model. This intuitive way of visualising the programme facilitates teaching, sharing and adaptation. Archaeologists who have received no training in programming or do not understand the logic of an agent-based model are taught indirectly. The programme can be understood by everyone, runs on the web, can be easily shared and is adaptable to other research questions.

By downloading it into the NetLogo interface, its core programming language, analysts are able to repeat experiments thousands of times, record parameters and results in tables and spreadsheets and conduct sweeps over different parameter values utilising the BehaviourSpace provided by NetLogo. The NetLogo programming language is the most commonly used agent-based modelling platform available today (Wilensky 1999).

1.3 Validation and case studies

Although this thesis uses modern, historical (early modern and medieval) validation studies it is mainly targeted to understand early medieval cemeteries and their living populations with a focus on case studies in early medieval Kent in South England and the Alamannic territories in the South of Germany. Anglo-Saxon and Alamannic burial data are extremely well suited for showcasing the use of the PCS in archaeological research because of the abundance of graves and skeletal remains studied but additional data are necessary because of the incomplete and problematic archaeological record. Later medieval and early modern parish data, as well as a few excursions into other periods of time and regions serve as cross-checks and are designed to validate the modelling approach and put the early medieval demographic data into context. The dialogue with the field of historical demography cannot be underestimated when modelling populations in archaeology.

The case studies fall into the time of migrations of Germanic people into the British Isles and the south of Germany (called the Alamannia) between the collapse of the Roman Empire and the formation of the English kingdoms and Frankish dominion over the regions between the Upper Danube and the Rhine (Ade et al. 2008; Christlein et al. 1978; Hamerow 2012; Hamerow et al. 2011; Härke 2011). At least compared with the more complex populations in the validation studies, the Migration Period (c. 5th to 6th century) and the early medieval (to ca. 11th century) world have relatively uniform and simple agrarian community structures (Benedictow 1996; Hajnal 1965; Hajnal 1982). The earlier complexity of the Roman era is over and "Germanic" timber buildings, dispersed settlement landscapes and the pre-Christian burial ritual with inhumed and cremated human remains alongside a wealth of grave goods represent a unique database for studies of early medieval demography, social structure, migration etc. (Hamerow 2010, 71-72; Hamerow et al. 2011). Because of the scarcity of the written record in the early medieval period, the archaeological burial record is still the most extensive demographic dataset for the period between the 4th and 8th centuries AD. Although insights gained from settlements and landscape archaeology are becoming more numerous, most of the research still relies on the furnished and unfurnished buried dead, found in high numbers in relation to this archaeological period (Ade et al. 2008; Hamerow 2002; Kokkotidis 1999). This research is undertaken in order to improve our understanding of the burial data which are integral to understanding of this period of human history.

1.4 Structure

The thesis first describes background and context before introducing the method, i.e. modelling with the agent-based software PCS. Following this, specific parameters and their relative importance are discussed in hypothetical scenarios. Then, better documented, mostly historical validation studies are presented, to set the stage for early medieval case studies of populations from England and South Germany.

After the introduction and background in chapter 2, I will discuss the development of demographic modelling in archaeology. The data employed are mostly bio-anthropological, most importantly age and sex. These datasets have their own intrinsic problems discussed between 1970 and the early 2000s, which led to a general frustration about the reliability of palaeodemographic studies (Hedges 2011). In chapter 3, new and old methods are compared in a review of the literature to demonstrate the potential of palaeodemography to resolve archaeological questions and the limitations of the data employed in archaeological demography and palaeodemography.

The PCS software is described in the method chapter 4, in which I focus on how human populations can be modelled based on archaeological data, the programme and the mathematics. The PCS models archaeological populations bottom-up, i.e. starting with single individuals, reconstructions of family sizes and compositions, households and communities.

In chapter 5, the data that are used in PCS models are discussed. The archaeological and historical source material is presented and information about independent mathematical model validation are given. Further, the biological basis of how populations work and the general parameters, e.g. fertility and mortality, are described and their sensitivity with respect to the whole system and each other is analysed. A theoretical conclusion which sums up the methodological insight and the sensitivity of the parameters involved sets the scene for the following validation and case studies.

Chapters 6 and 7 present validation studies of the PCS as well as hope to demonstrate the interrelatedness of historical demography and palaeodemography. Chapter 6 focuses on the impact of a single demographic parameter, i.e. female marriage ages, on fertility and population survival using medieval population data. Chapter 7 uses a mix of historical data and archaeological inference to study the population dynamics of a medieval parish is South Oxfordshire. Chapters 8 and 9 include case studies which demonstrate the use of the software in archaeological practice. Kentish and Alamannic early medieval individuals, families, site-specific populations and regional populations are modelled to show the PCS at work. None of the validation and case studies seek to find definitive answers as this is not the objective of the game-like approach advocated here. It is therefore allowed to model both possibly realistic mortality profiles and parameter combinations as well as old and unreliable data or information taken from different periods and regions. Exploring the possibilities of the PCS is the main objective of chapters 6 to 9.

In chapter 9 pure demographics are transcended and the world of archaeological material culture entered by showing how demographic dynamics and effects influence artefact frequencies in living populations and their cemeteries. When more complexity is added, e.g. by modelling the presence or absence of certain artefacts, the modelling technique presented reaches the truly interesting stage at the centre of interpretation of the material culture in the grave – the point at which the archaeologist seeks to get a glimpse of lives lived in the past by looking into the grave.

Finally, chapter 10 concludes the thesis and provides an outlook. The PCS's programming code as it appears in NetLogo is attached at the end of the thesis.

This research required the author to devise a way of presenting experiments in a way which simplifies remodelling of the virtual experiments that are designed to represent a basis for more complex and specific modelling research in the future. Experimental setup, parameter sets and the results of thousands of lines of numbers in spreadsheets need to be presented in a consistent and useful way. With the following PCS-specific data entry sheet for virtual experiments (Tab. 1) long data appendices are replaced which would ultimately only show thousands of pages of virtual data for virtual populations that cannot be provided in hard copy. Using this tool, all the experiments described can be repeated for validation and cross-checking purposes.

PCS DATA SHEET VIRTUAL EXPERIMENT NO ___

Research Question	Observed Parameters	Number of Repetitions
		Time / Duration of Run

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age

Catastrophes		
On/Off	Delay	X Mort

Mortality (qx)	
0-4	
5-9	
10-14	
15-19	
20-24	
25-29	
30-34	
35-39	
40-44	
45-49	
50-54	
55-59	
60+	
Mortality based on:	

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1				
P1 to P2				
Migrant Age	Min	Max	Min	Max

Tab. 1 PCS data sheet for virtual experiments.

2 Background

2.1 Archaeological background

The ‘Dark Ages’ are known for both their absence of written sources and the relative absence of the material culture of the living. The multitude of Roman buildings, pottery and objects representing diverse aspects of human life such as villas, hypocaust heating, tools, traded pottery, statues, ritual objects, mosaics etc. are replaced by a dramatic reduction in finds of material culture representing everyday life. From roughly AD 450 to 700, material from burial places, i.e. the Migration Period cemeteries, starts to dominate the archaeological record, and although landscape archaeological data and a revival of an interest in settlements have filled some of the knowledge gaps (Hamerow 2010), most interpretations of the early medieval period are still based on graves and the objects found in them. The Germanic population (independent of how many actually immigrated to the Anglo-Saxon and Alamannic regions and what proportion of the population comprised the original inhabitants) overrides the archaeological record of its predecessors and replaces it with a material culture of the grave. The break in the material culture at this point in time creates an impression of changing times, marking a turning-point in history which still defines the subdivisions of the fields of history and archaeology today. The extent of the *caesura* between actual life in the Roman provinces before 450 and life in an Anglo-Saxon or Alamannic settlement is a hotly debated subject. Research trends oscillate between stressing the links between the Roman Empire and the Dark Ages and stressing the contrasts of the archaeological record before and after the fifth century AD (Härke 2011; Hodges and Whitehouse 1983; Ward-Perkins 2006). Everyday human biological life in rural settlements might not have changed as drastically whereas, in parallel, economic collapse and a considerable drop in living population size can definitely be observed, such as the unmistakable implosion of urban centres (Astill 2011; Hamerow et al. 2011; Hedges 2011). In this thesis, I will illustrate some aspects of population change and describe human populations and demography as evidenced in the archaeological cemetery data. Understanding the limits of cemetery data when one wishes to learn of people's lives has direct implications for the interpretation of the *caesura* between late antiquity and the medieval period.

For the early medieval period, archaeologists set out to describe the living conditions, social system, wealth etc. of the populations which existed at specific points in time as well as changes of these aspects over time. Archaeologists almost never describe the excavated material as an entity which is unrelated to the people who produced it. A description of a cemetery or grave in archaeology without relating the data to interpretations about dynamic processes during the lives of the deceased would equal a 'silent' list of objects and contexts found. Likewise, studies of cemeteries which examine the burial ritual deal with the agents in the system, which are the living people burying their dead and not the deceased in the graves (Härke 2000; Härke 2002; Härke 2005; Härke 2014; Parker Pearson 2003; Williams 2006). Early medieval archaeologists often focus on a fine phasing of objects in graves in order to get as close as possible to human generation lengths, thereby hoping to distil the aggregate cemetery data into subpopulations representative of the living at any point in time. Information on the limitations of dating in archaeology are abundant in the literature and cannot be the focus here (Bayliss et al. 2013; Sayer 2010). Fine dating of artefacts does not completely achieve the sought-after effect of getting hold of the living. The deceased in a grave belongs to a final state which is distinct biologically, demographically and archaeologically, from the changing states of the individual during his or her lifetime (e.g. his or her age-at-death always equals the highest possible age of the individual). At the time of death, the individual is removed from the group of the living and is, therefore, not part of the living community anymore. This process of burial in a living population is comparable to photo negatives taken at specific points in time (whenever someone in the group dies), while at the same time the actual lives of the individuals in the imagined population are recorded in a continuous colour film. A lot of the information on the colour film is lost in the photo negatives – for instance, the things which happened in between two photos. Therefore, multiple colour films fit a single photo negative series.

In an archaeological population, for instance, multiple surges of an infectious disease might be interpreted as only one catastrophic event because of the incomplete chronological information usually obtainable for ancient burials. Cemetery site interpretation is an inverse (i.e. negative final state instead of dynamic colour film) probabilistic modelling problem, with a multitude of likely scenarios limited by the probability of producing the excavated 'final state' data. In order to achieve the modelling of different possible living populations for one cemetery site, demographic information about death rates and reproduction rates, growth etc. are required.

Early medieval archaeology is well positioned to integrate demographic modelling techniques which ultimately represents the only way to make sense of their major source material – burial data and hundreds of excavated cemeteries. Neolithic populations and hunter-gatherer groups were modelled much earlier although far fewer data on them exist (Bocquet-Appel 2008a; Chamberlain 2006). Demographic modelling further profits from data produced by bio-archaeological approaches: both the standard age and sex data estimated using skeletal material and the stable isotope and genetic information on migration, weaning and nutrition provide valuable demographic information (Benedictow 1996; Grupe et al. 2013; Hedges 2011). Historical demography of periods for which more written sources are available and ethnographic comparisons can help in calibrating models based on archaeological material.

The link between settlement dynamics and the burial record is one of the subsequent problems in both Anglo-Saxon and Alamannic archaeology to be caused by the difference between living population and cemetery data. Richard Bradley's observation in 1980 that Anglo-Saxon archaeology has failed to integrate settlement and cemetery studies has lost none of its actuality (Bradley 1980, 171-178, specifically, 172). Helena Hamerow writes in 2012: "..., yet, despite its importance, the relationship – spatial and symbolic – of rural settlements to cemeteries has still to receive extended treatment" (Hamerow 2012, 120). As settlements are the direct relics of the living communities, they reflect the past in a mathematically straightforward manner, despite the problems of phasing and building identification where high numbers of post holes were excavated (Hamerow 1993; Stork 1998). Cemetery data, on the other hand, need to be transformed, as the dead population does not directly reflect the past realities of living communities. The excavated record rarely allows for direct comparisons between the two categories of sites, as there are still many more excavated cemeteries than settlements. Furthermore, sites such as Mucking, Essex, where both the cemeteries and the settlement are recovered and published, are rare. However, Helena Hamerow observes, “Despite the small numbers of settlements that have been excavated in tandem with associated cemeteries, enough evidence exists (albeit primarily from southern and eastern England) to examine the development of this relationship from the fifth to the mid ninth centuries ...” (Hamerow 2012, 120-121). The same problem exists in the Alamannic region. Settlements were long neglected as a source of archaeological information, because postholes and crude local ceramic production were rarely collected or thought informative enough to be extensively excavated and studied. In contrast, the eye-caching artefacts from cemeteries roused interest much earlier in the history of our field, and the link with the ‘Germanic ancestors’, the Alamanni, was established as soon as the 1830s and -40s although the *Altertumsvereine* first mostly focussed on Roman history and archaeology. The important excavations at Oberflacht, Kreis Tuttlingen, where c. 50 graves with a multitude of artefacts were uncovered, set early medieval archaeology in motion in the German south-west. The waterlogged conditions at the site made it possible to recover wooden objects (bows, shields, coffins, chairs, etc.), and in Hans-Otto von Ow-Wachendorf’s diary we can read that even neatly folded textiles were witnessed by the excavators who were unfortunately unable to conserve the organic materials (Ade 2008; Ade et al. 2008). The pivotal find led to a focus on cemetery material from the early medieval period and the material culture associated with the dead. Although Christlein used the sub-title of ‘Archäologie eines lebendigen Volkes’ (Archaeology of a living people) in his 1978 standard volume on the Alamanni, his sources are almost entirely associated with graves (Christlein et al. 1978). But since the pivotal excavation at Lauchheim, Mittelhofen, where a complete cemetery and the associated settlement (with manor-house complex) were found (Stork 1998), the trajectories research interests have since started to shift towards stronger inclusion of settlement archaeology (Schreg 2006).

The trend towards integrating settlement and cemetery data, coupled with an ever-growing interest in bioarchaeological methods such as genetic and stable isotope migration studies, inevitably lead to demographic modelling. Families, households, kinship groups, inhabitants of dwellings and settlements are demographic entities, and archaeologists need to become more familiar with the demographic side of the material they research.

Direct comparisons between burial numbers per period and the respective development of the settlement landscape have been conducted for both Kent and the Alamannic region (Brookes 2010; Kokkotidis 1999; Richardson 2005) and provide the background for the case studies in the thesis. More detailed regional studies, landscape archaeological approaches using agricultural data, and spatial and topographic relationships provide future routes for the PCS models. Populating ecological and agricultural models of land use and technological change can enhance our understanding of the settlement landscape.

2.2 The areas of study: Kent and central Alamannia

The case studies of chapter 9 are situated in two both different and similar regions of early medieval Europe: Anglo-Saxon Kent and the inner Alamannic region in south-west Germany, more specifically the Upper Danube region and Neckar valley. Both areas were first occupied and subsequently left by the Roman Empire and were reorganised in a Germanic tradition that assimilated older populations but was politically dominated by immigrants or invaders. Although still present, the older Roman centres did not play as important a role as in France, the Rhine valley, Iberia, or northern Italy (Ade et al. 2008; Christlein et al. 1978; Hamerow et al. 2011). In both regions, the fifth and sixth centuries AD were crucial for the formation of a settlement structure that led to population growth, diversification and, ultimately, the villages and towns which are so characteristic of the Middle Ages and our modern way of life (Brookes 2007; Brookes 2010; Brookes and Harrington 2010; Schreg 2006). The Alamannic region and Kent represent Petri dishes for the starting-point of the study of medieval population dynamics, in which the ideal of linking simulations with more or less realistic points of data draws very close, and certainly closer than in many other archaeological periods and parts of the world. However, the lack of written sources makes it necessary to contextualise the archaeological information available with validation studies of other regions and periods.

Kent represents an early medieval landscape which has an exceptionally rich early Anglo-Saxon material culture and is very well studied, including overview studies of early medieval economic, population structure and overall settlement development (Brookes 2007; Brookes 2010; Brookes and Harrington 2010; Harrington and Brookes 2012; Richardson 2005). The Anglo-Saxon Kent Electronic Database (ASKED) represents a collection of data which can be used in PCS models (Harrington and Brookes 2012). On the other hand, Kent lacks highly detailed palaeodemographic and palaeopathological studies for individual cemeteries. The scarcity of fully excavated and published settlements in the area will force me to include data from sites excavated in regions nearby, such as Mucking, Essex (Hamerow 1993) and Wharram Percy, Yorkshire (Mays 2004; Mays et al. 2007).

This situation is very similar in the Alamannic territories (Ade et al. 2008; Schreg 2006). The Alamannic sites I will include here will partly supplement the missing osteoarchaeogical insights in Kent. Thousands of well-preserved aged and sexed human remains in early medieval cemeteries are available for the Alamannic region, and some of the data have already been synthesised (Kokkotidis 1999). Currently, further database projects are in preparation at Tübingen University and will provide data for future applications of the PCS.

The study of both regions also leads to interesting observations in terms of methodology. The Anglo-Saxon theory-laden approaches balance out the ‘theoretical illiteracy’ of the south German ‘data collectors’. Alamannic sites are still mainly analysed based on the methods developed by Christlein in the 1970s and -80s (Christlein et al. 1978), where artefacts are dated based on their typologies and grouped in ‘Qualitätsgruppen’ that are thought to represent social strata within the society. Anglo-Saxon sites have been studied under the influence of new paradigms, e.g. Parker Pearson’s interest in the burial ceremonies (2003), Williams’ focus on memory (Williams 2006) or Brookes’ detailed analysis of different ways of interpreting wealth and changing economies based on grave assemblages (2007). Duncan Sayer's development of generational chronologies (2010), for instance, is very interesting from a modelling perspective. He devised a formula with which social data from cemeteries can be evaluated at the level of mean generation lengths, and therefore made the first move towards bridging the chasm between the living and the buried individuals. If simulated by a computer, Sayer's theoretical concept can be emancipated from the static cohort approach on which his formula is based. He addresses knowledge transfer from one generation to the next and elaborates how many generations of individuals were present at any one point in time and, hence, were able to interact as a community. In a cohort-based approach, every individual in one generation has the same age. But in reality, individuals in populations are aged differently, with ages delayed according to the mortality pattern of the population. Virtually simulated populations can produce individuals of different ages by randomising the starter age of each individual and recording each lifetime individually. Once complex continuous dynamics can be modelled with the PCS, rendering static calculation approaches unnecessary.

2.3 The early medieval settlement pattern

How can demographic studies of complex late medieval and early modern landscapes, with towns, monastic sites, royal sites and elite centres, be conducted successfully without having understood the starting-point of what defines the nuclei of our modern landscape until the present day: the rural settlement? The Germanic settlement landscape of the fifth to seventh centuries is structured relatively uniformly in comparison with earlier Roman or later medieval settlement landscapes in Western Europe. The old Roman towns and nuclei had vanished, and new medieval foci such as churches or monastic sites had not yet been established (Ade et al. 2008; Hamerow et al. 2011). The fifth to seventh centuries represent a historical window of continuity, which makes it easier to apply numerical approaches. The size of communities is estimated to c. 50 individuals present on average at any point in time "to within a factor of two" (Hedges 2011, 81). The impression of a "remarkable geographical uniformity of building traditions across much of south-east England during the fifth to seventh centuries" (Hamerow 2012, 31) is based on the observation of often standardised dwelling sizes (Blair 2013) and that the rectangular posthole buildings and sunken featured buildings known as *Grubenhäuser* form an integral part of the settlement landscape everywhere in the regions.

The posthole buildings are regarded as mainly dwellings, whereas the *Grubenhäuser* might have had more to do with economic activities, such as weaving, and storage (Christlein et al. 1978; Hamerow 2002; Hamerow 2012). The communities appear to be ranked internally, and social differences "were largely expressed within households rather than between them" (Hamerow 2002; Hamerow 2012, 72; Härke 1997). This absence of any clear settlement hierarchy is a problem for archaeologists searching for evidence of elites, social organisation and identity; it is, however, an opportunity for palaeodemographers who are looking for repetitive patterns.

Linking household units and the burial record has a long history in Anglo-Saxon and Alamannic archaeology but the definition of the terms used such as nuclear family or household remain unclear. Approximately 12 individuals formed one household, based on data from West Heslerton, Yorkshire, and Mucking, Essex (Hamerow 2012; Hamerow et al. 2011; Härke 1997; Sayer 2010). Donat and Ullrich suggest that the average household in the Merovingian context was of a size of

c. 8 individuals (Donat and Ullrich 1971). In contrast, Benedictow has calculated an average nuclear family unit of 4.5 for early medieval Scandinavian households (Benedictow 1996, 175) and the historical demographic literature likewise multiplies Domesday Book (heads of) households by a factor of 4.5 or 4.75 in order to achieve a population size estimate (Hinton 2013, 148, footnote 11). But which estimate is the most useful in the Anglo-Saxon and Alamannic context, what do we learn about the composition of an early medieval family and household, and is there a difference between Kent and the Upper Danube region?

The evidence that the majority of Anglo-Saxon buildings were used for twenty to forty years and were often abandoned while still habitable leads to a further interesting theoretical consideration. It was suggested based on a lack of evidence for repairs that many early Anglo-Saxon dwellings have been “single generational, established upon marriage, occupied throughout the lifespan of the head of the household and his or her spouse, and abandoned upon their deaths” (Brück 1999, 149; Hamerow 2012, 34). This cries out for a parallel simulation of populations, households and burials.

Settlement forms and the organisation of rural landscapes diversified after c. 600 AD, and the mid-Saxon period saw the intensification of farming methods and pronounced population growth that included grid systems and planned settlements (Blair 2013; Hinton 2013). The PCS can combine data from cemeteries with evidence for changes in population density.

Very similar processes and the same dispersed, broadly uniform settlement structure can be observed in the Alamannic region, based on the few, but steadily growing, reports of settlement sites (Ade et al. 2008; Schreg 2006). The size of most communities probably did not exceed that of Mucking, for instance, with its approximate average living population size of 90 to just over 100 (Hamerow 2012; Hirst and Clark 2009; Sayer 2010). The stable outline and size of the houses and the dispersed structure of the settlement pattern alongside its stability are extremely parallel to the situation in early medieval England. The posthole buildings of the populations living in the Germanic tradition in the north of Germany, the Netherlands and Denmark (e.g. Dalem, Vorbasse (Hamerow 2002)) can be much larger than in the Anglo-Saxon context, whereas the longhouses of the Alamanni are only minimally larger (6-7m in breath and up to 18 m in length (Willmy 2008, 80)) than the average Anglo-Saxon posthole buildings (4-5m in breath and 8-10 in length (Hamerow 2012, 17)). A further caveat is that there is good evidence that Alamannic longhouses had internal space for livestock, shown in the archaeological record through raised levels of phosphate in the soil of one part of the houses (Schreg 2006; Willmy 2008). It is less clear weather animals were also sheltered within Anglo-Saxon houses but theoretically possible (Hamerow 2012). The size of the dwellings, consequently, does not in itself suggest a specific (maximum) number of inhabitants. There is certainly enough space for twelve or more individuals. A change in population size will therefore be initially absorbed by less or more closely crowded people in the same number of houses, and the population dynamic might therefore be delayed by approximately one to one-half of a generation, until the houses are abandoned in declining populations or new buildings are erected by newly founded families/households in growing populations. The relationship between houses and people is probably both partly decoupled and – most certainly – time-delayed. A close examination of the demographic information contained in temporal and regional differences of longhouse sizes and agricultural specialisation of populations coupled with modelling will be a fruitful approach for future research (Schreg 2006; Zimmermann et al. 2009).

Social reorganisation in the seventh and eighth centuries (Hamerow 1991; Hamerow 2002; Hamerow 2012), the migration debate (Härke 1998; Härke 2000; Härke 2011; Hedges 2011; Thomas et al. 2006; Thomas et al. 2008) and the unresolved role of the indigenous populations (Ade et al. 2008; Hamerow 2012; Hedges 2011), however, represent blurring factors that must not be neglected in both regions. The complexity of the ‘ethnogenesis’ (Härke 2011) is a similar problem in the Alamannic region (Ade et al. 2008). The fourth and fifth centuries saw the immigration of Germanic people to an unknown extent and the assimilation of immigrants and local populations

(Hakenbeck 2007; Härke 1998; Härke 2011; Leslie et al. 2015; Pattison 2008; Pattison 2011; Thomas et al. 2006; Thomas et al. 2008). And, finally, catastrophic events, such as the Justinian Plague fall into the study period (McCormick 2015). Archaeological cemetery research is needed to calibrate bio-archaeological approaches using genetic and stable isotope methods (Hills 2009) and the aforementioned extraordinary situations can best be understood on the basis of robust models of ‘every-day’ demographics.

2.4 Research questions

2.4.1 How can archaeologists, osteologists and historians model early medieval populations?

> *“Why model?” Imagining a rhetorical (non-innocent) inquisitor, my favorite retort is, “You are a modeler.” Anyone who ventures a projection, or imagines how a social dynamic—an epidemic, war, or migration—would unfold is running some model.*
> *But typically, it is an implicit model in which the assumptions are hidden, their internal consistency is untested, their logical consequences are unknown, and their relation to data is unknown. But, when you close your eyes and imagine an epidemic spreading, or any other social dynamic, you are running some model or other. It is just an implicit model that you haven't written down (…).*
> *This being the case, I am always amused when these same people challenge me with the question, “Can you validate your model?” The appropriate retort, of course, is, “Can you validate yours?” At least I can write mine down so that it can, in principle, be calibrated to data, if that is what you mean by “validate” (…)*
>
> Epstein (2008, 1.2-1.4)

At a stage at which data are incomplete and problematic, playful, scenario-based, and exploratory approaches can lead to a better understanding of the data and the parameter system. If numerical data are available, for instance, phased, aged, sexed (all numbers!) graves, falsification procedures can be used to identify unlikely parameters and interpretations, often depending on a range of assumptions made. Ideally, models work with discreet mathematical data, simplify reality according to the stated preconditions and wait to be falsified/replaced when new, more, better data are available. Agent-based models such as the PCS can be validated against their internal mathematical integrity, can be tested against well-known demographic data but are *a priori* only as 'realistic' as the data used as input. The development of agent-based modelling approaches in archaeology has a history and the PCS is a stepping-stone in the process of developing more and more software which help archaeologists to understand the past.

Historical models of medieval populations are generally Malthusian macro models, which aggregate the population of whole countries and regions (Hatcher and Bailey 2001; Wrigley and Schofield 1989). Mortality or fertility changes are, for instance, compared with other aggregate data, such as the fluctuation of wages in the late medieval period (De Moor and Van Zanden 2010; Hajnal 1965; Hajnal 1982; Kelly and Ó Gráda 2012). Such models work with a range of general assumptions, e.g. patrilocality, and they do not build up the populations from the bottom up. Sub-regional differences, social strata within the populations or even single households, nuclear families etc. make up these populations in reality, but are not represented in aggregate models. Hatcher and Bailey (2001) state that the future in historical modelling will be the route of micro models – a shift from the large scale to a scale more suitable for comparisons with fragmented archaeological data. Historical models employ data from tax polls, parish registers and modern ethnographic parallels (Engelen and Puschmann 2011; Schofield 1985a; Wrigley and Schofield 1983). The archaeological burial data, especially the skeletal data on age and sex (Benedictow 1996; Grupe et al. 2005), are seldom compared with the historical results, which can be explained by the pessimistic trends in archaeological demography in the last decades (see chapter 3) and the fundamental change from prehistory to history, i.e. few written sources to an abundance of written sources, which is a characteristic of the difference between early and late medieval research. This thesis hopes to show that there is untapped potential for collaborations between osteological and archaeological researchers and historical demographers.

In parallel and relatively independently of historical demography, anthropologists have modelled populations of the present and the past based on ethnographic observations and skeletal remains since the 1970s (Acsádi and Nemeskéri 1970; Bocquet-Appel 2008a; Howell and Lehotay 1978). Since then, a lot of problems have been described which complicate population modelling based on skeletal samples (Hoppa and Vaupel 2002a; Wood et al. 1992). These problems are described in detail below. The anthropologists and osteologists mostly employ equation-based mathematical models which require aggregate data (Bocquet-Appel 2008b). Whenever differences in subpopulations complicate the acquisition of aggregate data, agent-based models such as the PCS, which model populations bottom-up, might once again, offer an alternative.

This leads to an important distinction between two kinds of models: continuous and stochastic models. Continuous models are based on mathematical equations and represent formulas that can be solved for single parameters in the system. They produce discrete results and are generally very well suited for large-scale data where the individual is unimportant. The more complex the modelled system becomes, however, the more complex the equations. Solving the equations can become almost impossible after only a handful of parameters. As ‘realistic’ systems are influenced by many parameters, the continuous models must always remain abstract and simplified. The advantage of continuous models is that they are the most transparent and ‘mathematically beautiful’ way to express the relationship between parameters and the system (Courgeau et al. 2016). A mathematical model (developed by Dr Thomas Woolley and Rosemarie Leaman, Mathematical Institute, Oxford) is used to test the general behaviour of the PCS in chapter 6. For instance, while it is possible to solve the mathematical model for certain parameters, only the female population is modelled and only three age categories are used. This makes it tidier than the PCS, but also less versatile, e.g. in cases the male population is of interest.

Stochastic models, on the other hand, are mostly computer-generated models such as the PCS. Their build-up is more complex than equations, and might even include some equations to control parts of the system (Courgeau et al. 2016). In the PCS, 'actual individuals' are created and changed over time. They reproduce and die according to a temporal clock that delays events. The interactions and behaviours are expressed as computer code (do-if, do-when…), and some events are randomised and only occur under certain conditions. Unlike the equation-based models, results are dependent on contingency. The probability of specific scenarios can only be tested by repeating the experiments multiple times, which sometimes increases the modelling time to hours depending on how many individuals are modelled, how complex the modelling environment is and how many repetitions are required. The smaller the modelled populations, the higher the influence of chance, such as the probability that a certain event occurs, e.g. the probability that small populations will die out due to 'bad luck' is greater than in large populations which can absorb single adverse events. In micro-model scenarios, the stochastic approach is the more realistic one. Multiple parameter combinations can be tested against the probability that they lead to a specific outcome (here mostly the excavated cemetery sample) and this produces an understanding of the range of possible scenarios.

Agent-based models are becoming more and more important in the social sciences in general and archaeology in particular (see chapter 3). The sub-regional, scattered, fractionated, individual datasets in archaeology, such as the many incompletely excavated cemeteries in early medieval archaeology which represent one or two households instead of regional populations or countries, are much better suited for small-scale agent-based micro models than aggregate modelling procedures (Hatcher and Bailey 2001; Van Der Leeuw 2004; Verhagen and Whitley 2012). On the small scale, the biological is also often strongly influenced by social behaviour and society. 'Agents' in such models can have individual properties and agency which allows models of the interaction between individual and environment (Axtell et al. 2002; Griffith et al. 2010) or individual and economy (Wilkinson et al. 2013). In order to be able to compare such models of living populations and their interactions with cemetery data, i.e. burials of single individuals in cemeteries, the PCS models both the living and the cemetery.

All archaeological interpretations employ some kind of model and being explicit about the pre-conditions and parameters in the system helps in the cross-checking and falsification process which ultimately advances the field (Courgeau et al. 2016). The PCS is a stochastic agent-based model which enables researchers the study of both the macro and the micro world, such as single families or household systems. It can be used for both game-like exploratory modelling and more rigorous testing of interpretations against data.

2.4.2 Do we have enough data for the modelling of early medieval populations?

It is sometimes stated that there is not enough sufficiently robust data to reconstruct early medieval population dynamics (Hedges 2011; Hirst and Clark 2009). Data on early medieval demography are generally believed to be problematic both in quantity and quality. In his chapter on Anglo-Saxon migration and the molecular evidence, Hedges concludes that the bioarchaeological methods "(…) owe their interest to their potential rather than their achievements so far" (Hedges 2011, 80). However, the quantity of the cemetery and burial data already studied is immense. Many thousands of early medieval burials (inhumations and cremations) have been excavated, and studied. The North European early medieval burial record is certainly one of the most extensive archaeological datasets in the world – in terms of bone preservation, numbers and quality of artefacts. Their number, date, age and sex constitute the demographic data which are so often criticised. Some burials also include evidence on society, social ranking, burial rituals etc. Of the diverse demographic data, some are easier to study than others:

For instance, estimations for total population of Britain exist. The population in third and fourth century Britain is believed to be 2 to 4 million, and that of east and south-east England in the fifth century c. 1 million people (Hedges 2011, 81; Millett 1990). Hedges states that the numbers are generally 'realistic' as they can be validated by the population size calculated on the basis of the Anglo-Saxon settlement density in south-east England (c. 250,000), assuming that there was a settlement of a size of c. 50 individuals every 2 to 4 km (Hamerow 2005). Härke's estimates are relatively similar, both in earlier studies and in recent genetic projects (Härke 1997; Thomas et al. 2006). Large population studies such as these receive the most attention (Leslie et al. 2015) but can we actually understand early medieval populations on such a large scale, especially as modern concepts of countries and borders might have little to do with past regional divisions and populations? The analysis of sub-regions and single communities is believed to be more problematic, for instance, because in archaeology we "(…) lack a sufficient number of children to represent a demographically realistic population (…)" (Hedges 2011, 81). Hinton, for example, stresses that although we know that Domesday Book underrepresents certain parts of the population (e.g. fishermen), he believes that any attempt of estimating how many are omitted is impossible due to the variations observed between regions (Hinton 2013). I agree with Hinton that such large-scale populations cannot be understood without knowing the substructure of the aggregate. This is consistent with the observation by Hatcher and Bailey (2001) that micro-models are needed along with these macro approaches in historical demography (see above). Further, at the level of the data at hand, I also believe that the focus should be changed from large-scale to small-scale given that the archaeological data are made up of single burials in cemeteries which belong to small subpopulations. The macro picture should therefore be an emergent entity based on an aggregate of the substratum. This does not mean that results of archaeo-demographic models should not be described in simple and clear mathematical functions (Courgeau et al. 2016) if they can ultimately be found.

In order to model a population, more than the absolute numbers of individuals and their migration dynamics are needed. We also need some basic information about the age-specific probability of dying (mortality) and the reproduction rate of the population (fertility). Thereare a large number of excavated burial sites in early medieval archaeology; although the complete living population discussed above is clearly not represented in the burial record, specific subpopulations might be relatively well represented. Hedges states that roughly 10,000 'early' Anglo-Saxon inhumations and cremations have been recovered (Hedges 2011, 80) – probably an underestimation in the light of the recent big data projects and the grey literature. Some of the recovered burials do not represent complete datasets and most cemeteries are not complete. Sometimes a number of the skeletal remains were not recovered, or the preservation conditions render age and sex estimations impossible (Hoppa 1996). It is also easier to study demographics in archaeology when the majority of individuals were inhumed instead of cremated. Therefore, some regions with according burial customs in Anglo-Saxon England are more suitable for population analysis than others. The Alamannic cemetery sites are equally numerous and contain mostly inhumations (Ade et al. 2008; Christlein et al. 1978; Wahl 2007). Kokkotidis (1999), for instance, collected detailed age and sex data for just under 7,000 inhumations. I will focus on regional patterns and single sites where relatively good demographic information is available. In doing so, I am aware that the results obtained may not be valid for other regions and sites; however, as early medieval communities and the settlement pattern appear to be relatively uniform (small agrarian populations) compared to the Roman period (villa, vicus, civitas etc.) or the later medieval period with its monasteries, towns etc. , the demographics might show a similar tendency towards uniformity despite the undeniably regional patterns at the level of differently organised small agrarian populations changing with different speeds over time.

2.4.3 Defining the term 'population'

The term 'population' is rarely clearly defined. With a few exceptions, researchers writing population histories mostly talk about the general population, in a 'typical' village or early medieval community (Benedictow 1996; Campbell 2000; Dyer 2001; Gilchrist 2012; Hajnal 1965; Hatcher and Bailey 2001; Hinton 2013; Schofield 1985b; Wrigley and Schofield 1989). They set out to present global overviews which are based on individual case studies, but talk about life in a medieval village or community in general. These 'general' populations are mostly loosely defined through either modern country borders or medieval kingdoms, such as 'the English population' or the 'north European population'. Historians therefore voluntarily or involuntarily often imply the uniformity of medieval demography.

By contrast, today's early medieval archaeologists mostly focus on the local burial community or the ritual community responsible for the development of a specific site and/or small region (Blair 1994; Boyle et al. 2011; Brookes 2007; Brookes and Harrington 2010; Groove 2001; Härke 2001; Hirst and Clark 2009; Sayer 2010; Sayer 2014). The site is generally not used as a proxy for the total population, and individualities and regional differences are stressed. In Anglo-Saxon burial archaeology, the most prominent regional variance often referred to is the difference between the large ancestral multi-community cremation cemeteries roughly in the north-east of England, such as Spong Hill or the Lincoln area and the smaller sites dominated by inhumations in the south-west and Kent (Brookes 2007; Chadwick 1958; Ford 2003; Hedges 2011; Hills and Lucy 2013). The populations described in archaeological research are consequently much smaller and more individualistic entities, village, or burial communities. Current interest in sub-populations within a burial community proves this trend (Sayer 2010; Sayer 2014). The idea that burial communities might not be entirely identical with the excavated number of individuals per site (Parker Pearson 2003; Sayer 2014) is a concept which has not yet become a particularly influential idea amongst archaeologists studying Alamannic sites. Their concept of populations is strictly site-specific and refers to the excavated and estimated total of buried individuals recovered from a cemetery, almost always equating the cemetery and the envisaged settlement community (Ade et al. 2008; Christlein et al. 1978; Groove 2001; Kokkotidis 1999).

This is similar to but does not equate with the bioarchaeological/osteological population definition. Skeletal studies treat the skeletal sample as a direct representation of the population, i.e. its living conditions, demographics and health status (Chamberlain 2006; Duering 2014; Hirst and Clark 2009; Hoppa 1996; McKinley 1994; Roberts and Cox 2003; Wahl et al. 1998). Although caveats are often cited, e.g. the ‘Osteological Paradox’ (Wood et al. 1992) which will be explained below, the most common research routine is the comparison between ‘populations’, meaning the comparison between skeletal samples made up of the excavated skeletal remains from one site – skeletal-population-based palaeoepidemiology (Waldron 2007; Waldron 2009). It is often clearly stated that the population used is only the sample from which quantitative inferences are possible but in interpretations it is generally the case that it is used as a proxy for the population from which the mortuary sample is drawn. This inference step often cannot be avoided. However, it is important to stop there and not also equate it to the once-living sample of individuals represented in the cemetery assemblage.

An initial step towards a more transparent definition of ‘population’ is the strict differentiation between living populations and cemetery populations advocated in this thesis. Historians define populations mostly as living communities, while osteologists instead talk exclusively about the cemetery population. Archaeologists alternate between the two depending on the context. Avoidance of confusion between these strongly different entities is imperative in early medieval archaeology. But even in this thesis, the biological, social or statistical meaning of the word population remains often loosely defined. Context matters, as demographic entities often contain both biological and social elements.

2.4.4 The relationship between the cemetery and the community living in the settlement

Populations can further be differentiated in terms of their size and elements:
The smallest unit is the *individual*, defined by age, sex, gender, social status etc. The individual is therefore linked in a network with other individuals from different strata of individuals within a population.

The *nuclear family* is the next biggest unit, consisting of the brothers and sisters, children and biological parents of an individual. This small unit was relatively unstable due to high death rates, and widows and orphans were not uncommon. How big was the social problem numerically caused by this kind of demographic frailty?

The *household* is a term which is especially important in early medieval archaeology. It comprises a wider (though not clearly defined) kinship group, likely to be made up of more than one nuclear family unit. Serfs, slaves and other dependants can also be part of the same household. Theories about a household's relation to posthole buildings, socio-political organisation, legal practices, power and gender represent a substantial part of early medieval history and archaeology (Ade et al. 2008; Christlein et al. 1978; Donat and Ullrich 1971; Hamerow 2012; Härke 1997; Härke 2005; Härke 2014). The Anglo-Saxon and Alamannic household will be studied in detail in various chapters within this thesis. Micro-population models have the power to yield much information about their possible demographic structure.

At the same sub-regional and size level there are two related types of populations which sometimes overlap completely, for instance if one village population buried their dead in one communal cemetery but which can also represent distinct groups: the *burial community* burying their dead in one specific cemetery and the s*ettlement community*, i.e. the living population which is organised in a hamlet, village or dispersed settlement structure with legal and/or social ties of families and households. There are various examples in early medieval archaeology where ritual burial community and the settlement population are not the same (Hamerow 2010; Sayer 2014). For example, the important reference site of Mucking, Essex, is interpreted to either consist of one dispersed multi-core settlement with two distinct cemeteries or two settlement nuclei according to another interpretation of the archaeology (Hamerow 1993; Tipper 2004). In the Alamannic site of Lauchheim, Ostalbkreis, some of the individuals were buried in a large communal cemetery whereas others were buried in small groups of graves next to posthole buildings within the settlement (Ade et al. 2008; Stork 1998). These observations complicate comparisons between the virtual living population modelled on the basis of cemetery data and the settlement record, e.g. the number of posthole buildings present at one site. Regional and temporal trends further exacerbate this problem, e.g. the reorganisation of the settlement landscape due to socio-political changes in the seventh and eighth centuries, the final phase of the pre-Christian cemeteries and the establishment of church graveyards (e.g. Bärenthal, Tuttlingen) all fall into the period of study (Duering 2014; Hamerow 1991; Hamerow 2010; Lohrke 2004; Sayer 2013). Models of both living and burial communities will be used in the following to study the relationship between the archaeological settlement and cemetery record.

At the next level, there are *regional settlement networks* which might overlap with the multi-focal dispersed settlement structures that were integral to the settlement landscape of the early phases in both the Anglo-Saxon south and the Alemannic study region (Hamerow 2002; Hamerow 2012; Scholkmann 2009; Schreg 2006). *Larger burial communities* are again the 'cemetery' parallel at the same size level, but might not be a mirror image of the settlement networks in the same region. The large site of Spong Hill, Norfolk, is an example where it seems unlikely that one settlement constituted the living population responsible for the cemetery. It is suggested that a network of smaller settlement sites used one communal cemetery, and/or that sub-groups of living populations of wider area buried their dead in the cremation cemetery due to social or ritual behaviour and that other parts of the population buried their dead in smaller local cemeteries (Hills and Lucy 2013; Sayer 2014).

Large geographical areas such as the Thames valley or the Danube valley, one or more kingdoms, large area of similar traditions, e.g. the Anglo-Saxon kingdoms or the Welsh kingdoms, and even supra-areas such as the regions of ‘Germanic’ tradition constitute macro-populations. Despite the relative complexity of the substructures, demographic information is sometimes available for early medieval ‘England’ (Hedges 2011; Leslie et al. 2015), ‘Scandinavia’ (Benedictow 1996) or even ‘Europe’ (Hajnal 1965). Such overall data can be used to understand averages and the variance between the macro picture and smaller populations.

2.4.5 How representative are cemetery populations of past dynamics of living communities?

Sample bias because of differential preservation, poor recording or incomplete exacavation represents a problem which dominates the literature on the representativeness of sites in the archaeological literature. In addition, the complex relationship between settlement and cemetery (discussed above) is often mentioned in early medieval case studies. However, there are additional problems which are often overlooked.

A cemetery represents the final state of a dynamic process. The dynamic sequence of burials is studied by trying to phase burials and grave goods as closely as possible. However, the dynamic living population is still different from the sequence of the individuals removed by death that end up in the burial ground. As soon as an individual dies, he or she is not part of the living population anymore. Therefore, the deceased in a cemetery represent a different entity which might not closely reflect the living population. The difference is temporal (static vs. dynamic) and mathematical (different parameters, delayed reaction to parameter changes etc.) in nature. For example, the effect of demographic change might change living conditions in the living populations quite quickly, whereas it takes some time until a representative number of individuals affected by the new conditions have died so that the changes become visible in the cemetery, and short-term changes in the living group might not be translated into the cemetery record at all. The analysis of these temporal delays requires demographic models such as those that are the focus of this thesis.

Further, as the data are sketchy and problematic, multiple scenarios of interpretation are possible. Early medieval archaeologists need a tool that allows for a more stringent analysis of equifinality. Multiple dynamic living populations with different demographic parameters could have formed the final state cemeteries in our record. Explorative modelling of minimum and maximum scenarios can show which parameters belong to a possible parameter set that could reproduce the excavated site. If all parameter combinations could reproduce the excavated site, the excavated data consequently contain limited demographic or social information; if certain scenarios can never reproduce a site, they can be excluded from the list of possible scenarios, and so forth.

2.4.6 Parameters influencing the growth of a population

Let us first look at the parameter population growth. Acsádi and Nemeskéri (1970) made us aware of the fact that modern dynamically growing populations (e.g. India and China) are not representative of the prehistoric past. During most of the prehistory and history of humanity, growth rates were relatively low and population sizes were dependent on new technologies in agriculture and urbanisation processes, so that demographic dynamics of archaeological populations are relatively small. While this might be correct for the macro-population, it certainly underrates regional differences and short-term changes. The pronounced population collapse after the end of the Roman Empire and the growth of the population during the early medieval period up to the point when urbanisation processes could take hold represent decisive dynamics that should influence how we study medieval populations. Benedictow (1996) estimates that the populations of Scandinavia grew by approximately 2% annually between 750 and 1300. This equals a tripling of the population within a sub-phase of the medieval period. Hedges’ (2011) and Härke’s (Thomas et al. 2006; Thomas et al. 2008) data on the growth of the Anglo-Saxon population in the early medieval period also reveal that static populations might not represent a good proxy for the study period. Populations grow when mortality and fertility rates are not equal. Constant migration might also explain growth. Despite the long tradition of studying fertility in historical demography for precisely that reason, archaeologists are often unaware that fertility is at least as sensitive to social and economic changes than mortality (Bumpass 1969; De Moor and Van Zanden 2010; Engelen and Puschmann 2011; Frier 1994; Hajnal 1982; Kelly and Ó Gráda 2012). Populations might grow and decline because of changes in female reproduction, and not because more or fewer people die per year. Further, the regularly invoked migration scenario to explain population change and make-up in the early medieval period (Leslie et al. 2015; Thomas et al. 2006) limits interpretations to the historical ‘Migration Period’ narrative. More research is needed to assess whether the considerable growth rates of early medieval populations are governed by migrations or intrinsic factors such as changes in agriculture.

2.4.7 How stable was an isolated small early medieval population?

Not all sites exist for long periods of time and represent success stories such as Mucking, Essex, which was occupied for some 300 years (Hamerow 1993; Hirst and Clark 2009). Other sites were relatively small and existed for only a fraction of the time, e.g. the Anglo-Saxon cemetery of Stretton-on-Fosse, Warwickshire, which was in use for a maximum of 140 years (Ford 2003). Extrinsic factors such as raids, crises or relocation are often quickly invoked as explanations for short-lived sites. But there are other things to consider, such as the relative stability of a very small population. Models in this thesis will analyse the effect of small numbers on the survival probability of small communities. This will be linked with the question of how isolated such populations were. Were sites part of a large and interacting network, or was there a degree of inhibition of population flow between communities? Does interconnectivity have a strong effect on the stability of small dispersed settlements and communities and is the apparently uniform average group size of c. 50 identified by Hedges (2011) a coincidence?

2.4.8 How do single sites interact with the regional aggregate population?

The patrilocal household structure (Hajnal 1982) suggests that females regularly transitioned between households and communities for marriage. Sayer argues that women and their children kept social and ritual ties to the mother's family and were often buried in their ancestral cemetery instead of in their new husband's cemetery (Sayer 2014). It is therefore advisable to model early medieval demographics in a regional approach instead of putting the emphasis on single 'sites' and 'populations' in cemetery archaeology and osteoarchaeology. The pure size of regional populations further leads to more stability in parameter estimations, which is why a balance between a bottom-up and a top-down approach has to be found.

2.4.9 The influence of demographic change on other archaeological data

As demography includes more information than merely age and sex, the influence of demographic change on artefact and disease rates will be analysed. For example, growing populations have more children than static populations that have the same mortality characteristics. The numbers of buried children and the artefacts associated with them might therefore differ between sites because of different growth rates even if the underlying social and ritual behaviour was exactly the same.

Furthermore, selective effects of mortality (Wood et al. 1992) influence how many individuals transition from the living population into the cemetery population and are then buried with a specific grave good or bone lesion. Individuals with rich grave goods might have slightly better living conditions and therefore lower probabilities of dying at any given point (decreased individual mortality rates/the chance to die at older ages) compared to lower ranks in the population. Due to this difference in risk, the proportion of individuals buried with rich objects might decrease in the cemetery compared to the rate of survivors in the living population. Consequently, cemeteries might underestimate individuals with a net advantage in survival probability, compared to the living populations which we set out to study in archaeology. This thesis will put the Wood et al.'s findings into a wider archaeological context and demonstrate that early medieval graves can only be used as proxy for their living populations if demographics receive focused attention.

3 Demographic modelling in archaeology and history

3.1 Palaeodemography & the principles of demographic modelling

3.1.1 The crisis of palaeodemography

Archaeological demography depends heavily on skeletal data from cemeteries. Whenever archaeologists use age estimates of individuals buried in graves for artefact distributions, the analysis of social strata, changes of grave goods over the age of individuals etc., they depend on the accuracy of palaeodemographic data. It is important to understand the developments within this sub-field to correctly assess the quality of material available in publications and the trends in archaeological demography. I will also address why palaeodemographic results are believed to be unreliable in archaeology.

Human longevity had been described in occasional research since c. 1900, and Angel's early papers of the late 1940s (e.g. Angel 1947; Angel 1969) represent the starting-point of sub-specialisation within the field of physical anthropology (Hoppa 2002; Konigsberg and Frankenberg 2002). Palaeodemography emerged as a sub-discipline of both archaeology and physical anthropology in the 1970s, culminating in the publication of Acsádi and Nemeskéri's "History of Human Life Span and Mortality" (Acsádi and Nemeskéri 1970) in which the life table, a modern demographic tool, was adapted for use in archaeological research. Since Chamberlain argued for a more broadly defined palaeodemography, palaeodemography and archaeological demography have been used interchangeably although the former puts an emphasis on skeletal human remains whereas the latter includes more archaeological data, e.g. from landscapes and settlements. An archaeological demography independent of the biological source material does not really exist (Chamberlain 2009; Chamberlain 2006). Based on 'life tables' or 'mortality tables' – which are tools employed by insurance companies and national institutions to predict mortality trends and population growth – skeletal populations were transformed into demographic entities with specific mortalities and life expectancies, which could yield information about the past through comparison between skeletal populations and parish registers (Bocquet-Appel 2008a; Chamberlain 2006; Imhoff 1990). Historical demography and physical anthropology, however, developed into different fields with little overlap, as palaeodemography was mainly interested in prehistoric archaeological material while historical demographers were limited to the late medieval and modern period by the nature of their sources (Benedictow 1996; Hatcher and Bailey 2001; Hoppa and Vaupel 2002a; Schofield 1985b). For instance, skeletal and archaeological data are not even mentioned in the demography section of "Modelling the Middle Ages" by Hatcher and Bailey (2001) and skeletal data do not play any role in the seminal 'Population History of England' (Wrigley and Schofield 1989). As the archaeological data are much more relevant than the historical for the early medieval case studies presented later, I will focus on the development of archaeological demography.

A standard palaeodemographic method based on skeletal populations soon emerged, culminating, for instance, in the publication of the Libben Site demographics (Howell 1982; Lovejoy et al. 1977) and, more relevant here, in the overview of Alamannic demography by Kokkotidis (1999). According to this method, the ages and sexes of the skeletonised archaeological individuals are estimated by osteologists and sorted into age groups. The ratios of individuals who died per age group are then added into a life table calculation that transforms the totality of the buried individuals of a cemetery into a dead cohort and calculates mortality rates, survivorship curves and life-expectancies per age group. Chamberlain (2006, 27-31) describes in detail how a life table is calculated. Examples of life tables I have calculated are available for the early medieval site of Bärenthal, Kreis Tuttlingen, and the Neolithic massacre site of Talheim, Kreis Heilbronn, (Duering 2014; Duering and Wahl 2014a). Acsádi and Nemeskéri had already described some of the shortcomings of life tables, i.e. they were aware that the calculated demographic data were only correct when the populations studied had remained relatively stable over long periods of time (Acsádi and Nemeskéri 1970). Soon Howell, employing demographic modelling software, noticed further problems with the life table technique and addressed issues of the underlying ageing methods and the in-built requirement of static behaviour for populations whose data are entered into a life table (Howell 1982; Howell 1986; Howell and Lehotay 1978). Growing or declining populations do not produce correct results in a life table, which ultimately treats the skeletal population as belonging to one single cohort while, in reality, the individual's births fall on different points in time (Kölbl 2004; Moore et al. 1975; Paine and Boldsen 2002; Roth 1992; Williams 1992).

In the 1980s and 1990s a debate was unleashed, between 'traditionalists' employing life tables on the one hand and a new generation of palaeodemographers on the other who started to doubt the statistical procedures behind ageing methods. Papers with titles such as 'Farewell to Palaeodemography', 'Palaeodemography: Expectancy and false hope', and 'Paleodemography: Not quite dead' (Bocquet-Appel and Masset 1982; Bocquet-Appel and Masset 1996; Konigsberg and Frankenberg 1994) were published. In 2002, the discourse resulted in the formulation of the 'Rostock Manifesto', an iconic statement on the methodological fallacies of past demographic studies (Hoppa and Vaupel 2002a). The 'manifesto' is seen as a decisive step by the critics (Séguy and Buchet 2013; Séguy et al. 2013) but given that, unfortunately, only a small group of specialists are now using the new methods proposed in the 'manifesto' with relatively few articles published which apply the new approaches (Milner and Boldsen 2012b; Séguy et al. 2013), the victory might have come at a high cost. The wider osteoarchaeological and archaeological community was lost in the process of the debate: they merely said 'Farewell to Palaeodemography' sometime between 1990 and 2000 (Bocquet-Appel and Masset 1982), which resulted in statements such as that of Hedges in the Handbook of Anglo-Saxon Archaeology that we know almost nothing about the palaeodemography of the Anglo-Saxons (Hedges 2011, 80-81). This stance is particularly problematic as the many thousands of burials excavated and analysed continuously form an important corner stone of the archaeology of the early medieval period.

Another seminal challenge of traditional palaeodemography was put forward in the "Osteological Paradox" (Wood et al. 1992) which transcends the problems of ageing populations and includes challenges to the study of ancient disease which have not been properly addressed until now (Cohen et al. 1994; DeWitte and Stojanowski 2015; Jackes 1993; Siek 2013; Wright and Yoder 2003). Both the Rostock Manifesto and the Osteological Paradox are explored in detail below. Detailed overviews including more information on the history, methodological developments and various 'revolutions' and 'manifestos' in palaeodemography are available (e.g. Bocquet-Appel 2008a; Bocquet-Appel 2008b; Buikstra and Konigsberg 1985; Caldwell et al. 1987; Chamberlain 2009; Chamberlain 2006; Hoppa 2002; Howell 1986; Konigsberg and Frankenberg 2002; Meindl and Russell 1998; Séguy and Buchet 2013; Wittwer-Backofen et al. 2008).

Why are these developments in osteoarchaeology important in the context of early medieval archaeology? Age data are employed all the time, especially individual age estimates which are used to understand individual graves, the burial ritual etc. While both the 1992 and the 2002 publications (Devlin and Herrmann 2008; Hoppa and Vaupel 2002a; Wood et al. 1992) describe better statistical approaches and modelling methods that researchers can employ, many have reacted conservatively. Some dismiss archaeological demography, focussing only on simple bar-chart statistics of skeletonised material assigned to wide age ranges (such as sub-adult, adolescent, young adult, old adult) (Buikstra and Ubelaker 1994; Roberts and Council for British Archaeology 2009) and other focus on the improvement of ageing methods (Milner and Boldsen 2011; Milner and Boldsen 2012a; Milner and Boldsen 2012b). Statistical and modelling approaches in palaeodemography are now a highly specialised sub-field, applying methods which are almost never used in standard osteoarchaeological work. The problem is exacerbated as ageing and sexing of skeletal material happens all the time, especially in commercial archaeology. Physical anthropologists have even disassociated ageing from more general demographic approaches, so that age estimation and sex determination are now used interchangeably with the term 'palaeodemography'. Instead of addressing all the major problems involved, such as the influence of sample bias (e.g. missing infants), heterogeneous population make-up, growth and migration, as recommended in the seminal publications, osteologists and archaeologists have reacted counterintuitively and retreated into an even more simplistic way of approaching demography than before. But bridging the widening gap between specialist palaeodemography using relatively complex mathematical approaches and standard early medieval archaeology constantly working with age and sex data from cemeteries is a big challenge. In a recent symposium on biological age estimation in Oxford (December 2014), the various camps of bioarchaeologists have made tentative approaches towards method unification (Buckberry 2015; Konigsberg 2015; Mays 2015; Wittwer-Backofen et al. 2008). Trends reversing the fragmentation into specialised sub-disciplines give hope for future collaborative research projects in archaeological demography.

3.1.2 Unlocking the potential

Notions pervading research in current archaeological demography can be summarised in five points:

1) Ages of skeletons must only be given as ordinal categories such as infant, sub-adult, adult and old adult, and not as numbers in years.
2) Old individuals are consistently under-aged.
3) Sub-adults must remain unsexed.
4) Sub-adults are missing in unknown quantities in the cemetery samples.
5) More complex statistics are unreliable and there are far too many unknowns in the system.

1) Osteoarchaeological researchers of Anglo-Saxon populations offer skeletal age data as deliberately vague ordinal age stages instead of numbers with mean or ranges (e.g. 40 to 50 years or 45±5 years). Hazard mortality models as advocated in the Rostock Manifesto are virtually non-existent for the regions and periods relevant in this thesis (Hoppa and Vaupel 2002a). This leads to

the problem that data cannot be readily compared. Authors tend to use different stages and seldom clearly define the stages they use, e.g. 'old adult' might mean individuals aged 45 and over in one publication and 40 and over in another. Age stages further include different numbers of years, i.e. different lengths of time during the ageing process. Direct comparisons of age categories of different lengths of time, for instance, in the ever-present bar charts, are highly problematic. In such cases, age ranges, including a higher number of possible ages (e.g. 'old adult') are overrepresented compared to an age category including only a few years (e.g. 'infant'). The practice of giving ordinal (i.e. word-based) age ranges instead of absolute numbers is probably a relic of old physical anthropology that used the terms *neonatus, infans I, infans II, juvenis, adtualtus, maturitas,* and *senilis* to define age groups in a population (Buckberry 2015; Martin 1914). Numbers remain a much more precise and accurate way of presenting the continuous numeric ageing process measured in years. Osteoarchaeologists sometimes stress the importance of differentiating between chronological age and biological ageing as, as these terms do not always represent the same thing (Buckberry 2015; Grupe et al. 2005; Wittwer-Backofen et al. 2008; Wood et al. 1992). The ordinal stages are then used to make clear the difference between chronological and biological age. But biological ageing is as continuous a process as chronological ageing and can best be expressed in a numeric way. Numbers facilitate further statistical and comparative research. Another problem of age stages is the transition between one and the other (Milner and Boldsen 2012b). It might be correct that ageing is not as accurate as one might wish and that some individuals can only be put in categories such as 'young adult' and 'old adult'. But making sacrifices on the side of precision to maintain accuracy does not solve the problem at points of transition: the key issue is to make a decision about individuals with acquired skeletal traits of both the younger and the older age category in question. In such cases, decisions similar to giving numeric ages have to be made, e.g. weighing traits and methods and including contextual considerations that might hint towards the older or younger age range. In cases of bad bone preservation and ambiguous skeletal traits, giving a numeric age allows for long age ranges as well as exact lower and upper age limits. It took very long to standardise the age estimates used in this thesis, which differed between authors and sites, and the interpretation of vague age data introduces an unnecessary source of error. An altogether different theoretical option for presenting skeletal age information is to suspend judgement on actual age completely and only collect and present observed skeletal age stages. This would represent a corpus of data readily available for probabilistic approaches such as maximum likelihood methods, Transition Analysis and Bayesian approaches (Konigsberg 2015; Séguy and Buchet 2013; Séguy et al. 2013). However, production of raw data without interpretation in such a way is currently unrealistic in archaeology. Data presented is the described way is also not available for early medieval Anglo-Saxon and Alamannic populations and therefore remains a future ideal.

2) The consistent under-ageing of old individuals is an often-stated observation and because of the asserted inaccuracy of age estimates of old adult individuals, osteoarchaeologists commonly stop at c. age 50 and include all older individuals in a collective age category. Specifically, the methods which utilise degeneration of articulate surfaces on the human pelvis (Pubic symphysis and Auricular surface) tend to under-age specimens (Buckberry 2015). In a recent research project in which Janamarie Truesdell collected CT data of modern patients at the Churchill Hospital in Oxford and reviewed the ageing methods developed by Suchey and Brooks (Brooks and Suchey 1990; Suchey and Katz 1986) and Hartnett (Hartnett 2010), a significant under-ageing effect of 8 to 10 years was found (increasing from 8 to 10 between the young and the old adult age ranges) compared with the known-age patient data. Truesdell has therefore proposed a new (more continuous) ageing method which might eliminate the under-ageing effect and significantly improve ageing precision and accuracies including individuals of ages between 60 and 90 years (Truesdell and Duering forthcoming). But when other skeletal regions than the pubic bone are used to infer age, the effects of old age are more complex. Milner and Boldsen (2012b, Fig. 10) noticed that the greatest discrepancy occurs between the ages of 40 years and 70 years; age estimates beyond 70 become more accurate again. Milner and Boldsen therefore think that we should place

more trust in age estimates of individuals aged 50 years and over (Ibid.). Not only is it now possible to calibrate the ages in publications based on the Suchey-Brooks method; in addition, future skeletal ages using the new methods promise to be much more accurate and precise in the old age categories. As the data used in this thesis are, however, based on more traditional approaches mortality is not further differentiated beyond age 60 years in the PCS.

3) The sex determination of sub-adult individuals, especially those well before puberty, is particularly difficult, and sex estimates for infants must be treated with caution (Lewis 2006). The skeletal traits which can be used by osteologists to differentiate between the sexes mostly develop after puberty. But a variety of metric and crude morphological methods have been developed for the differentiation of the two sexes in populations, assuming that the skeletal sample is more or less uniform. On a population basis, some indicators successfully identify sexual differences (Ahlbrecht 1997; De Vito and Saunders 1990; Duering 2014; Forschner 2001; Mittler et al. ; Wahl 1981); and aDNA approaches promise a solution to this problem whenever preservation conditions are favourable (Álvarez-Sandoval et al. 2014). Tendencies might give valuable insights into the treatment of children during their life and the burial ritual for children. Differential treatment of male and female infants might reveal valuable information about the social and ritual factors leading to the ‘missing infant’ phenomenon in the early medieval cemetery record, i.e. the low number of infant graves in most cemeteries (Crawford 2007; Kölbl 2004; Sayer 2014).

4) Below the problem of the ‘missing infants’ will be tackled and estimates provided of how many individuals are missing given certain assumptions. The possibility of utilising demographic models in order to study the *Kinderdefizit* (German term used for the ‘missing infant’ phenomenon) has been demonstrated brilliantly by Kölbl (2004). The mathematical complexity of the problem is just high enough that early medievalists and osteologists have not incorporated existing solutions to the problem in their research. For Neolithic populations the Juvenility Index is often used to overcome the problem of the deficit of infant burials in archaeological samples (see chapters 5.3.1

and 10.2.6). It relies on those age categories which are not affected by the deficit of the youngest individuals and which can be well aged and distinguished in a skeletal sample (Bocquet and Masset 1977; Séguy and Buchet 2013). PCS modelling will be employed to illustrate the difference between infant mortality and the number of infants in a cemetery sample, and provide a tool for analysing the phenomenon further.

5) The general challenges raised against the palaeodemography of the last decades, briefly described above are not without foundation. The dynamics of populations below the resolution of our blunt methods and few good datasets will ultimately stay beyond our grasp. However, exploring different probable scenarios and comparing these scenarios to contextual information, e.g. that derived through studies of the transformation of the landscape over time or the development of a settlement, in an inverse problem-solving routine represents a fruitful way forward.

The five points above apply less to archaeological demography in south Germany than to Anglo-Saxon archaeology. Different archaeological traditions in the Alamannic study regions have led to a more inclusive physical anthropology of both the old life tables and the new modelling approaches. Life tables are still calculated regularly for site reports and used more or less cautiously (Kokkotidis 1999; Wahl and Frey 1991; Wahl and Kokabi 1988; Wahl and Zink 2013). Kölbl's Monte Carlo simulations exploring the 'missing infant' phenomenon in the early medieval period (Kölbl 2004) inspired this thesis and show that archaeological demography has seen less discontinuity in southwest Germany than in England. Kölbl's models have, however, not been used in recent site studies as the software is unfortunately not available.

3.1.3 New hope for palaeodemography

From a palaeodemographer’s perspective, most of the demographic data published on prehistoric and early medieval skeletal populations so far are problematic. Both life tables and the osteological methods listed in the common standards of recording in the UK (McKinley and Roberts 1993; Roberts and Council for British Archaeology 2009) and the US (Buikstra and Ubelaker 1994) are seen as outdated (Séguy and Buchet 2013). The highly critical self-reflection of the last decades (Bocquet-Appel and Masset 1982; Bocquet-Appel and Masset 1996; Hoppa 2002) has caused a loss of interest in demographic research in archaeology. Anglo-Saxon and Alamannic cemeteries are still mostly studied using ‘traditional’ methods. From a methodological point of view, the data available in this thesis are ultimately unsatisfactory and results remain preliminary until enough new cemeteries are studied using more recent ageing methods.

Most Kentish and Alamannic populations have not yet been studied with the help of new Bayesian approaches, i.e. statistical methods which address problems related to the osteological methods of age-at-death determination (Hoppa and Vaupel 2002a; Konigsberg 2015; Milner and Boldsen 2012b; Séguy et al. 2013). The published mortality results for most of our populations are probably not representative of past living conditions, as they are biased by problems of the skeletal ageing methodology (Hoppa and Vaupel 2002a). The partly missing burials of children (Hedges 2011; Kölbl 2004), incomplete excavations (Hoppa 1996) and the complex relationships between burial community and living populations (Sayer 2014) further add to the problems. A general reassessment of the thousands of graves in the cemeteries published over the years with the help of new Bayesian methods of age estimation would require re-examination of the skeletal material (which has now partly been reburied). But re-examination of the skeletal populations is not the aim of this thesis. This would be a vast, but probably quite fruitful route for future research. Instead, I will try to apply the new PCS method using ‘traditional’ data in conjunction with demographic data from validation studies and other demographic methods to analyse what can still be learned from all the demographic results of the generations of researchers who have analysed Anglo-Saxon and Alamannic skeletal human remains. The information content of the data available is further discussed under more technical terms in the following methodological review.

A Modelling approaches are advantageous when the probability distribution of the ages at death of the target population has to be estimated a priori*.*

Firstly, the skeletal ageing problem raised in the Rostock Manifesto (Hoppa and Vaupel 2002b) is described as a bias introduced into the skeletal ageing methodology through a 'mimicry effect'. Ageing methods mimic the age pattern of the skeletal populations on which the ageing methods are based. For example, modern forensic known-age skeletal collections tend towards the male sex and the young to middle adult age group. Morphological skeletal ageing methods based on such collections emphasise male traits and the young to middle adult age category. Consequently, the actual populations studied will yield results that are a mix of the actual demographic age profile of the population and the young method's known-age population profile. Only by statistical calibration of the population's age profiles can researchers reconstruct real past demographic conditions (Hoppa and Vaupel 2002b). In the calibration process, counterintuitively (!), the age profile of the population studied – which represents exactly the entity the palaeodemographer sets out to find – has to be estimated beforehand and used in a Bayesian calculation process to improve the aggregate age results and in order to counter the mimicry effect (Konigsberg and Frankenberg 1994). I will not spend further time explaining these processes in detail. For further information on this topic I refer the reader to 'The Rostock Manifesto for palaeodemography' (Hoppa and Vaupel 2002b) and the transition analysis method (Milner and Boldsen 2012b).

Such mortality profile estimates can be based on ethnographic standards and historical data, but mostly represent a best guess of the demographics of the populations studied (Milner and Boldsen 2012b; Séguy et al. 2013; Wood et al. 2002). Séguy et al., for instance, employ an early modern demographic pattern for the calibration of their Iron Age, Roman and Merovingian cemeteries (Séguy et al. 2013). The effect of such a method is that age profiles of populations are mathematically 'early modernised' or at least equalised, whenever the same prior estimate is used, and that sometimes the first guess does not fit the demographic reality at all. The age profiles of skeletal assemblages and cemeteries are furthermore dependent on multiple parameters such as fertility, growth, migration, and selective effects (as will be described below). Breaking down the processes into these parameters is far superior whenever some of the sub-parameters can be better estimated than others that when combined, form the aggregate age curve of the cemetery population. A cemetery is not only affected by the ageing process and the probability of dying in a population, but also by growth rates, changes over time, migration and, importantly, reproduction rates, i.e. fertility. Demographic insights into the contextual parameters surrounding death are still often based on traditional ageing methods, and the wealth of data already produced before 2002 could theoretically greatly enhance estimation procedures. Hypothetical modelling approaches such as that proposed here can be used to explore and better understand the age-profile prior estimates required for Bayesian calibrations.

For the early medieval period, palaeodemographers have the problem that there is no known-age profile or demographic curve available for village populations which would have normally buried their dead in a typical Anglo-Saxon or Merovingian/Alamannic row cemetery. Kölbl (2004) employed standard demographic mortality patterns of different periods and ethnographic parallels which are not necessarily a good fit for early medieval populations (Wood et al. 2002). Furthermore, some of them are also based on life tables – the exact tool which is constantly criticised because it only works when populations are static. Demographic dynamics must be taken into account. Later medieval villages might not represent the same growth rates as during the sixth and seventh centuries and migration processes might have been different, such as fewer travelling workers and more short-range marriages than in late medieval and early modern rural areas that depended on a different economic system (Hajnal 1982). The mortality models proposed by Wood et al. (2002)

represent continuous curves independent of life tables (Gompertz and Siler models). They can be employed by the PCS but lack the detailed information contained in 5-years life table data. The mathematical curves consist of three added curves: exponential decay in the first years of life, simulating high infant mortality; then a relatively low constant linear level of mortality; and finally, the steady exponential increase of the risk of dying during old age. Two important aspects of medieval demography are masked in such curves: there are additional peaks of mortality around age 2 to 4 and young adulthood, which are very informative concerning past living conditions. The former is explicable in relation to the increased risk of weaned toddlers losing the immune protection and nutrients contained in the breastmilk of their mothers (Fuller et al. 2006a; Fuller et al. 2003; Grupe et al. 2005; Grupe et al. 2013; Lewis 2006; Tietze and Lincoln 1987), while the latter increase in risk is sex-specific: females are often described to show a mortality peak due to the perils of childbirth (Duering 2014; Sayer and Dickinson 2013; Wahl 2007), although the increased mortality is not visible in the historical profiles (Séguy and Buchet 2013), and young adult males often also have increased risk of dying comparable to that of the females. This peak might have to do with a more perilous lifestyle for young adult men, e.g. leading a violent lifestyle as a warrior or being less cautious and experienced while doing dangerous work (Chamberlain 2006; Duering 2014). These peaks (although probably misplaced due to skeletal ageing errors on the absolute age axis) can be seen in life table mortality models and contain data, which are lost in continuous mathematical curves.

B Agent-based models utilise individual multi-method age estimates and do not require aggregate mortality profiles.

Secondly, there are two ways of estimating the mortality pattern of a population based on human skeletal remains: the individual vs. the aggregate approach. In the individual ageing approach, a single individual is studied with all the applicable methods known by the osteoarchaeologist, limited by the state of preservation, by research traditions and the age of the individual, as different ages are studied using different sets of methods. The osteologist then establishes the age estimate based on a combination of observed age indicators. This equals the process of forensic investigation or even virtual autopsy in modern contexts. In addition, almost all archaeological skeletal populations have been studied using this approach, which is easily discernible whenever individual ages estimated are given per buried individual. Individual grave goods can thereby be grouped according to individual ages and a focus can be placed on single graves in addition to the average over all buried individuals. Whenever a life table is calculated, the individual ages are pooled and transformed into an average age profile of the population studied. The advantage is that the different methods used have been developed based on different known-age skeletal collections and thereby produce a mixed 'mimicry effect' (see above), i.e. general differences between chronological age and biological age might differ from method to method and ideally cancel each other out (but probably also reinforce errors). Additionally, contextual information can be employed in order to check and improve age estimates. Information about social rank and differential living conditions contained in the archaeological record can be used to both inform and complicate the individual age estimate (Mays 2015). For instance, the female individual found near West Hanney, Oxfordshire, was buried with a high-status brooch. An initial osteological study probably under-aged the individual, who had not suffered from severe periods of stress and showed no signs of hard work compared with an average Anglo-Saxon female. The female consequently hypothetically 'looked younger' in terms of biological age versus chronological age (Hamerow et al. 2015). The reverse was observed for the individuals buried at Bärenthal in SW Germany. Biological age indicators not related to degeneration during the ageing of the individuals suggest higher ages in a number of adult males and females than those skeletal elements which are used for ageing, because they change due to skeletal degeneration. These individuals at Bärenthal had worked very hard and had related lesions indicating osteoarthritis and arthropathies in the spine (Duering 2014; Waldron 2009). Offsets between individual ageing methods sometimes contain valuable information about the life style of individuals (Duering 2014). Pooling the individual information of contextually interpreted autopsies can then be used in studies of complete skeletal populations. If differences between subpopulations exist within a site, the subpopulations can be studied separately. This individual-based approach further focuses on the experience of the osteologists studying the human remains (Mays 2015). Training with skeletal populations in collections can enhance the accuracy of age estimates, as more experienced observers usually do much better in blind tests than inexperienced people. For instance, Truesdell, who had examined c. ten times more individuals than her test observers had, did better against the known-age sample in our recent study than her test observers although all produced the same general trends (Truesdell and Duering forthcoming). Intuition and the building up of a ‘feeling’ for a specific population is often discounted as unscientific in modern palaeodemographic research. But we must not forget that morphognostic ageing methods are not neutral machine methods; they require human observers with their own human individualities.

The aggregate ageing approach does not age single individuals in a comparative approach. The observed skeletal changes of one specific morphological method are pooled and mortality of the complete population is directly estimated from that, including the calibration routines tackling the mimicry effect (Hoppa and Vaupel 2002b; Konigsberg 2015). The aggregate approach is favoured by researchers engaged in statistical palaeodemographic analysis, which is largely independent of context information or individual considerations although they take growth and fertility into account (Hoppa and Vaupel 2002a; Séguy and Buchet 2013). The skeletal population is studied as an aggregate. Single ageing methods must be improved within themselves to achieve scientifically precise and accurate age estimates. Multiple overlying mimicry effects (see above) might cloud method errors and should be avoided. Séguy et al. (2013), for instance, use cranial suture closure as the only skeletal method informing the statistical routine employed. Information contained in other skeletal regions is not included in Séguy et al.’s case study. The disadvantages of focussing on single bone regions are as follows:

a) Every single individual is treated as if it were subject to the same risk of death, discounting differences within populations (Wood et al. 1992),

b) The bone region alone might be only loosely correlated with chronological age. For example, cranial sutures are affected by many other biological factors and are therefore not a reliable stand-alone age indicator (Konigsberg 2015).

c) Whenever the specific bone region is not preserved, the individual has to be excluded from the ageing process.

In a recent validation study, Milner and Boldsen (2012b) used both single-method aggregate approaches and experience-based multi-method estimates and demonstrate, interestingly, that at this stage, the aggregate ageing methodology employing Bayesian calibration methods produces inferior results compared with the traditional experience-based approach where Milner aged each individual using a variety of methods and personal experience. They conclude that

a) although prior estimates chosen to calibrate against the mimicry effect had some influence, the effect was "dwarfed by the inaccuracy and imprecision of the ageing methods" (*ibid.*, 98), and

b) that "Transition Analysis estimates do not perform as well as experience-based assessments" (*ibid.,* 98).

So, in conclusion, how reliable are the skeletal ageing methods employed for most of the cemetery sites studied in this thesis? Milner and Boldsen cannot reach better precisions and accuracies of the age estimates using the new transition analysis method in practice. The theoretical scenario that only one specific age estimation method is employed (Konigsberg 2015) is rarely found in osteoarchaeological practice, where different ageing methods are employed and compared whenever skeletal elements necessary for employing specific methods are missing. The insights gained in the last decades are methodological in nature and do not necessarily discredit the individual-based ageing method employed in the vast majority of cemetery reports. But the more rigorous approaches have future potential, for instance, Milner and Boldsen currently focus on a multitude of smaller changes in the skeleton, informative in an individual-based ageing approach. Traditional points of view and new stats trends are converging. More openness towards neighbouring approaches, updating standards, allowing for hypothetical explorative modelling and shedding the constraints of the entrenched times are all on the future agenda.

3.1.4 Summary of the developments in palaeodemography

The palaeodemographic literature from the past decades provides methodological insights into the process of estimating the ages of skeletal populations as well as their transformation into demographic parameters such as mortality, longevity and life expectancy. Few subfields in archaeology and anthropology have seen more formal mathematical in-depth analysis; excepting archaeological chronology, materials and stable isotope approaches (Kristiansen 2014). Although palaeodemography has developed into a specialised subfield focussing more and more on biological ageing, a review holds considerable potential for collaborative research with archaeologists and historians.

A) The problem of estimating demographic parameters based on cemetery data was the starting-point of the debates. The traditional life table approach was shown to be inferior to hazard models that take fertility and growth into account. At this point in the development, a specialist subfield of palaeodemography emerged within osteoarchaeology and physical anthropology. Modelling routines were developed (e.g. Howell’s AMBUSH (Howell and Lehotay 1978)) and palaeodemographers moved on to study B (see below). Most archaeologists and historical demographers were lost at this stage. Despite the problems described, life tables are still often calculated (as they are also the standard tool in historical demography).

B) The focus was on inaccuracies of the ageing methods developed for adult skeletal human remains, which led to a biological and statistical specialist sub-field. The problem of the mimicry effect was tackled and single ageing methods were the target of re-examination and critique. The osteological ageing community was split into a group focussing on ageing individual human skeletal remains using many methods, and a small group of palaeodemographers interested in statistical calibration of ageing methods using single bone regions. This resulted in the publication of the 'Rostock Manifesto', including the Transition Analysis method, employing Bayesian statistics (Hoppa and Vaupel 2002a). Adult ageing methods were, however, not changed in practical osteoarchaeological work as the statistical toolkits are not useful in paractical osteoarchaeological work and have not really produced demonstrably better age estimates. The methodological insights gained are unquestionably immense, but matter little in osteoarchaeology beyond the specialist sub-field. The hot debates have led to general distrust of age estimate data based on skeletal populations. Recently, researchers have started to explore methods which seek to reconcile the individual ageing and transition analysis methods (Milner and Boldsen 2012b).

C) In parallel, the problem of the static concept of 'population' was approached. Wood et al. (1992) showed that heterogeneity between individuals within a population studied can cause complex problems. They also linked demographic dynamics and explored the difference of pathological frequencies between cemeteries and their living populations. Awareness was raised that demographic dynamics strongly influence the rates gathered in cemetery analyses. Disease frequencies cannot be understood without demographic analysis and vice versa, as diseased individuals have a selective higher mortality rate compare to the healthy individuals in the population. I will argue in this thesis that the problems identified in the 'Osteological Paradox' are also relevant when artefacts and grave goods are analysed.

The PCS will not be useful for the ageing problems outlined in (B). The results obtained using the PCS are only as good as the ages estimated in the skeletal samples studied. The PCS is focussed on picking up the loose ends of (A) and (C). The PCS is designed to help estimating demographic dynamics in a modelling approach which is simplified yet powerful enough to be useful and understandable by archaeologists, osteologists and historians. By providing a tool which can shed light on the internal processes of populations and cemeteries and allows for modelling sub-populations, nuclear families and even individuals with specific diseases and grave goods, complex mathematical insights gained in palaeodemographic analysis can be translated into a language archaeologists understand.

3.2 Agent-based modelling in archaeological demography

3.2.1 Agent-based modelling - beginnings and principles

Agent-based modelling is a specific way of constructing a model, distinct from mathematical equations. The first agent-based models were coded in the 1970s and 1980s, including Schelling's segregation model (Schelling 1971). From its beginnings, the field of agent-based modelling was concerned with social behaviour and tried to model aspects of life which are not normally expressed numerically. The core methodology of agent-based modelling was developed during the 1990s, and in the following years NetLogo became the primary programming language for agent-based modelling in academic research (although many other specialist agent-based modelling tools exist) (Epstein 1999; Epstein 2006; Wilensky 1999; Wilensky and Rand 2015). Applications of agent-based models in archaeology have become more and more common, especially since appearance of key publications describing an ecological model of the development of settlement of the Anasazi in Long House Valley (Axtell et al. 2002; Dean et al. 2000). Agent-based modelling has become an emergent field in archaeology, promising to contribute to a scientific revolution in a field which is described as resistant to computer technology because of labyrinthine theoretical debates (Ammerman 1992; Crema et al. 2014; Dyke 1981; Van Der Leeuw 2004; Verhagen and Whitley 2012). One disadvantage of agent-based models is that they require prior knowledge in programming to be used. Kenneth Kahn has tackled the problem of exclusivity, which often disadvantages researchers who do not have programming experience. The Behaviour Composer is an open-source web tool which helps users to learn and visualise modelling procedures in an easily understood way (Kahn and Noble 2010). He heads the Modelling4All project at Oxford with which the PCS is linked. I have coded the PCS using the Behaviour Composer, to simplify teaching agent-based modelling and provide archaeologists lacking modelling experience with software that is ready to be used and understood.

Agent-based modelling is so far completely distinct from palaeodemography. In the subfield of palaeodemography, researchers prefer continuous mathematical modelling, e.g. Markov Chains, which are even more exclusive than the agent-based models available on the NetLogo website. In the PCS I use highly effective and powerful agent-based technology, bridge the gaps to palaeodemography and historical demography, and design a demographic basis for research into artefacts, diseases, migrations etc. that has to be founded on a solid biological human population model.

Agent-based modelling utilises the power of computers in order to calculate probabilities influencing the behaviour of agents in a virtual environment which develops over time. The mathematical term for such models is ‘stochastic model’. Stochastic models are distinct from continuous mathematical models that are equation-based and work with average parameter values instead of producing a virtual representation of every single virtual individual modelled in the system. In a continuous model, one cannot zoom in to ask the age, sex, etc. of each single individual existing at a specific point in time; a continuous model will only produce the average per parameter. The advantage of continuous models is that the equations can be solved and direct mathematical relationships understood between parameters in the system. Stochastic models need repetition and multiple testing to tell researchers about general behaviours and relationships between parameters. However, for an archaeologist, modelling with agent-based models means that the small scale appears and individuals in the models can be different from the average – can be given personal ‘agency’ in the system. For instance, individuals of different social ranks can be modelled within the same system, interacting yet distinct from the lower ranks. This bottom-up element makes agent-based modelling especially important in the social and ecological sciences (Ammerman 1992; Axtell et al. 2002; Brewis et al. 1990; Bryson et al. 2007; Cioffi-Revilla et al. 2011; Courgeau et al. 2016; Crabtree and Kohler 2012; Dean et al. 2000; Doran 1970; Epstein 2006; Epstein 2008; Gaines and Gaines 1997; Griffith et al. 2010; Kahn and Noble 2010; Kohler et al. 2012; Kohler and Gumerman 2000; Macy and Willer 2002; Rubio Campillo et al. 2012; Van Der Leeuw 2004; Verhagen and Whitley 2012; Whitehouse et al. 2012; Young 2002). The focus of these models is either on ecological factors influencing human populations or on hunter-gatherer populations, studying the small-scale behaviour of hominids and primates. Historical populations and early medieval populations have not been modelled to date (with a few emerging examples which show the strength of the method (Crema et al. 2014)), which is surprising because of the wealth of data available for such populations compared to the very theoretical concepts on which models of the behaviour of ancient primates are based. More theoretical models are still better accepted in their research communities. The main job of agent-based models in archaeology and anthropology is to be used for checking theories against defined mathematical frameworks. Whenever more detailed data of the past are available, more traditional aggregate approaches are employed, such as those prevalent in historical demography (De Moor and Van Zanden 2010; Engelen and Puschmann 2011; Guo et al. 2015; Hatcher and Bailey 2001). As will be demonstrated below, the PCS is a tool for both, purely theoretical modelling and data-based research.

3.2.2 Inspirations for the PCS

The Population & Cemetery Simulator (PCS) has a number of stochastic predecessors which were developed with similar research aims, e.g. providing researchers with a demographic model for analysing processes in human micro-populations. However, the full potential of agent-based routines has not been tapped with regard to demographic archaeological modelling.

Although there have been some modelling approaches in anthropology and archaeology in previous years (Doran 1970; Dyke 1981), Howell's AMBUSH of the late 70s represents "A Computer Program for Stochastic Microsimulation of Small Human Populations" (Howell and Lehotay 1978) and is thereby the first attempt at modelling the demographics of archaeological and anthropological micro-populations. It utilises life table data in a very similar way to the PCS and results in a detailed analysis of the demography of the Libben Site (1327 skeletons buried between AD 800 and 1100 near Lake Erie in Ohio) (Howell 1982), suggesting methodological problems with life tables used as static tools because of the unnaturally 'young' population sample. Howell, having modelled living populations based on cemeteries, understood that such a population produced an extreme number of orphans and cautioned that a population consisting of mostly children (50% of the individuals living at the same time being under age 15) would be socially unstable. By closely examining the average numbers of individuals of different ages present at any point in time, she analysed the micro-level of the population. Contextual information gained by modelling the small-scale was shown to be very informative at two levels, firstly at the level of past demographics contained in the data analysed and, secondly, the reliability of the data gathered on a methodological level. Howell also understood that fertility could be studied as a direct result of the mortality at a site, and that changes in fertility had an extremely strong effect on the populations (Howell 1986; Wood et al. 1992). That fertility reacts much more directly to changes in living conditions was observed in parallel by historical demographers (Hajnal 1965; Hajnal 1982; Kelly and Ó Gráda 2012; Lesthaeghe 1971; Marini and Hodsdon 1981; Schofield 1985a; Schofield 1985b; Wrigley and Schofield 1983).

Modelling had been instrumental in understanding the methods and data of archaeological demography from the start. Howell's models, however, do not go beyond demographic questions. She does not further contextualise the demographic results as relevant for archaeological interpretations.

Howell's importance for the development of palaeodemography is at odds with the first theoretical reactions to modelling in anthropology and archaeology, which were also published very early (Dyke 1981). Howell's insights gained by modelling and her decisive influence on the development of palaeodemography at a methodological level is in stark contrast with Dyke's claim that modelling has limited potential in anthropological research. But while Howell's insights into population dynamics and methods employed are still the starting point for archaeological demographic research (Hoppa 2002), her modelling approach, AMBUSH, has not really been used by many researchers and has, unfortunately, not really been developed further. The palaeodemographers focussed instead on the ageing problems described above, and modelling of micro-populations led a shadowy existence in archaeology and anthropology. The focus was placed on continuous population models (Hoppa 2002; Hoppa and Vaupel 2002a; Wood et al. 1992), i.e. the problems raised by Howell at the level of single nuclear families and households were replaced by a focus on 'populations'. These 'populations' were equated with the complete skeletal sample analysed, and still remain the basis for the majority of modelling approaches studying demographics of the past (including parts of this thesis). Dynamics within populations and complex formation processes, e.g. those responsible for the missing infants in many early medieval cemeteries are often overlooked or even avoided. Séguy et al. (2013), for instance, only calculate the longevity of the adult population, excluding the subadults from the start as they are probably underrepresented in their samples. Palaeodemography has little interest in studies beyond mere demographics, i.e. getting exact measures of mortality, fertility etc. As an archaeologist, I am further interested in the implications of these findings within a more general context. In a way, the demographic data are the starting-point, the substratum for more complex models of cemetery populations and their artefacts and diseases.

Kölbl's (2004) research has already been mentioned above. She uses the Monte Carlo method for probabilistic modelling, i.e. stochastic modelling, of subadults in early medieval populations. Her question is archaeological: are there really infants missing in early medieval cemeteries, and which factors have to be taken into account in order to find out how many individuals are missing? And the interpretation of her results does not stop at the point where demographic numbers have been put to paper. Instead of focussing on actual demographic data from early medieval cemeteries and being aware of the recent developments in palaeodemography, she utilises demographic standard models (Kölbl 2004; Wood et al. 2002). Had she utilised the published life tables in the literature while being aware that they have intrinsic problems, she might have reached a wider audience within the community of early medieval archaeologists. However, recent discussions of the 'missing infant' phenomenon (Crawford 2007; Hamerow et al. 2011; Sayer 2014) do not take Kölbl's results into account, e.g. identifiable in the pervasive confusion of infant mortality and the number of buried (or estimated) infants in cemeteries. As the PCS owes a great deal to Kölbl's research, I will demonstrate again with the PCS what Kölbl has found out. The more inclusive open-source approach used in the software presented here, coupled with the inclusive use of data from Alamannic and Anglo-Saxon cemetery sites will hopefully lead to further applications of modelling in early medieval archaeology.

3.2.3 Towards virtual experiments in archaeology

I will now try to answer why archaeology has long been reluctant to include modelling and virtual experimentation in their methodologies. Theoretical debates on the advantages and disadvantages of modelling approaches in archaeology are nothing new, and constituted a part of the debates between processualists and postprocessualists. The clash of archaeological theories in the 1970s and 1980s resulted in the production of a “labyrinth” of theoretical literature (Verhagen and Whitley 2012, 65) which made it very hard to employ modelling approaches in archaeology compared to other social sciences that produced very successful and influential models (Van Der Leeuw 2004; Verhagen and Whitley 2012). One of the major arguments raised is that a ‘Middle Range Theory’, e.g. via ethnographic observation or experimental archaeology, is necessary for translating between the silent static archaeological record and past dynamics (Binford 1981; Johnson 2010; Raab and Goodyear 1984). The New Archaeology had already put the focus on model validation. But the list of possible goals of modelling in the social sciences (Epstein 2008) shows that this is a very limited point of view, probably perpetuated because of a building resistance towards technology in the phase following the New Archaeology. As soon as model building and modelling alternatives become part of the interpretative process, the models themselves represent tools which can bridge the ‘middle range’ between archaeological data and the past (Epstein 2006; Epstein 2008; Van Der Leeuw 2004; Verhagen and Whitley 2012). Furthermore, and probably most importantly, the technological limits of computers in the 1970s and 1980s are in no way comparable to modern computational power and developed tools. Much more data can be processed in short periods of time, which leads to a much higher number of testable scenarios.

Computer models provide the interface to which the data produced by different fields can be linked. Trying to find out how one set of data might influence another dataset and formulating these relationships in an explicit way leads to a new sphere of analytical interpretation of bioarchaeological and archaeological data. Models are helpers and triggers of communication and interdisciplinary interaction. They function, inter alia, as a visualisation tool that makes research at interfaces easier. Whenever archaeologists envisage a community of the past, a burial ritual or a social dynamic, they have to make predictions about the population involved. Age, sex, gender, rank, health etc. are demographic parameters which are hard to disentangle from the archaeological material. The agent-based model PCS is able to link the demographic, biological and social spheres of archaeology.

But how strong are the arguments based on such models? Modern computational power allows thousands of repetitions to test aspects of stochasticity and contingency and, therefore, the plausibility of archaeological hypotheses. Positive results are hard to verify because of the equifinality problem in archaeology. A good fit of a set of variables might just be a plausible virtual version of reality. The actual past reality might have been different, either because it was a manifestation of something rather improbable or because some variables that might change the results are unknown to us (Epstein 2008).

Negative results from such models are much harder to question and provide very useful insights. By ruling out implausible interpretational models or wrong data, the models can emancipate themselves from being purely powerful visualisation and communication tools. Such models must be positioned at the point in the research methodologies after which data have been produced by other means, such as stable isotope research, skeletal age and sex estimation and artefact studies, and before general interpretations are construed. Archaeology becomes more and more science-based at both levels: data production and data interpretation (Kristiansen 2014). Interpretational simulation was always present but is now seeing a resurgence. In that realm, all theories are temporary until they become falsified and replaced.

But are we not forgetting the human individuals behind all the mathematics and biological data? Agent-based models, i.e. models which have the power to code individual decision making and thereby transform virtual individuals into ‘agents’, are very powerful tools that have the ability to intertwine positivistic biological data and postprocessual concepts of human actions. Kristian Kristiansen (2014, 14) observes that:

> *"…we have witnessed the silent collapse of the dominant post-processual framework, as it did not account for the kinds of evidence we have seen emerge during the last ten years. And neither did the processual framework. In short: we are in a period of theoretical and methodological experimentation and reorientations, where everything that was 'forbidden' research 10-15 years ago are now among the hottest themes: mobility, migration, warfare, comparative analysis, evolution, and the return of grand narratives."*

There is no reason why, for instance, a specific life history of an artefact found in a cemetery could not be simulated in a mathematical contextual framework including the demographic situation of the individual in its grave. Specific points of time within the life of individuals can be linked to certain rites of passage marked by the acquisition of the artefact and tested against the final excavated artefact record defined by the dead population. The prevalent 'death-histories' would thereby become virtual life-histories. By applying computer models along the lines of other social sciences, archaeologists will realise that modelling is not a processualist scientistic endeavour but instead brings together the various coexisting theoretical camps (Johnson 2010; Kristiansen 2014; Van Der Leeuw 2004; Verhagen and Whitley 2012; Whitehouse et al. 2012).

METHOD

4 The Population & Cemetery Simulator (PCS)

4.1 Description

In the following, I will describe the agent-based computer model called Population & Cemetery Simulator (PCS), which I have developed for this doctoral project, specifically for the simulation of archaeological populations and their cemeteries. The computer model tackles the issue of how to link data from different sources, i.e. skeletal analyses (age and sex), cemetery context (grave goods, phases), e.g. the settlement, landscape, settlement/population size and frequency and historical sources (e.g. parish registers, Domesday Book).

4.1.1 Modelling a living population and its cemetery - central functions of the software

The model simulates a living population of females and males over a specific period of time, represented as agents in the programme. Each agent has specific individual ‘behaviours’, e.g. reproduction, and general ‘environmental’ properties active for the whole number of agents (e.g. reoccurring catastrophic events). Each year (equal to one tick of the simulation run), randomised events occur to each agent within the model according to their properties. Females might reproduce and individuals of both sexes might die, with specific risks of dying for each age group. A dead individual leaves the living group and is ‘interred’ in the cemetery, counting as a member of the dead population from that point onwards. In principle, all demographic and archaeological parameters can be sorted into three categories (Fig. 2):

(1) Parameters of the first category describe the life of individuals in the living population – for example, the rate of reproduction but also the size of the starter population, the sex ratio and the age distribution of the living population. The living population category is dynamic.

(2) The second category of parameters describes the cemetery population – for instance, the average age at death or the number of individuals who died at the same age etc. The cemetery category is static and mostly represents end results and final states controlled by (1) and (3).

(3) The third group of parameters controls the transitions between categories (1) and (2), such as mortality, which controls when living individual will cease to belong to category (1) and be added to category (2). Parameters of category (3) control category (2), but mostly affect the living (1) instead of the dead (2) directly.

Childhood mortality also belongs to category (3) as it controls which child will transition between (1) and (2). This parameter is often wrongly equalised with the ratio of buried children to buried adult individuals (Kölbl 2004), a parameter which belongs to (2) and represents the final result rather than the transition. To clarify the importance of understanding the three categories, it should be noted that the ratio of child burials in a cemetery (2) does not only depend on childhood mortality (3) but also on the actual number of children present and born in the population (1) and thus on a combination of transitional parameters and parameters describing the living population.

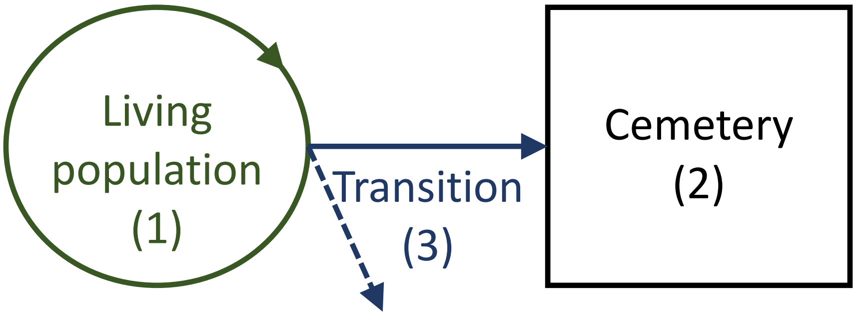


Fig. 2 The three categories of parameters: the living population, the cemetery and the transition category.

The static structure of the three categories was transformed into a dynamic process, which changes in annual intervals in the PCS once the initial population has been created. Annual checks against individual (e.g. age-dependent mortality) and global parameter values (e.g. presence/absence of additional catastrophic events) are conducted for each individual. For instance, the programme checks whether an individual will transition from the living group to the cemetery based on the specific age-dependent mortality in a randomised procedure, the limits of which are controlled by data. The programme calculates a random number between 0 and 1 and compares the result with the mortality rate chosen by the user, which is also a number between 0 and 1. If the overall mortality for the individual in this year is, for instance, 0.5 and the computer has calculated the random number of 0.8, the individual has survived, ages one year and still belongs to the living group. If the computer calculates 0.1, the individual dies and transitions to the cemetery, and is therefore removed from the living population of the following years. Based on this randomised procedure and applying a mortality rate of 0.5, the computer will kill approximately 50% of a large number of individuals and 50% will survive. Thus, behaviour at the level of the individual thus randomised but at the same time limited by parameter input are aggregated into behaviour at population level. Fig. 3 represents a strongly simplified flow diagram of the general PCS operations. The additional functions of the software, such as catastrophic events and artefact modelling, are excluded in this diagram. Interface 2 represents a mind-map-like structure of the complete operations of the PCS (see below). The development and dynamics of the living and the dead population are tracked and visualised in plots. Each simulation run creates an individual pattern due to the mathematical effects of chance, i.e. stochastic effects, inherent to the code and, hopefully, also to human demography more generally. By repeating simulations it is possible to address questions of probability and contingency.

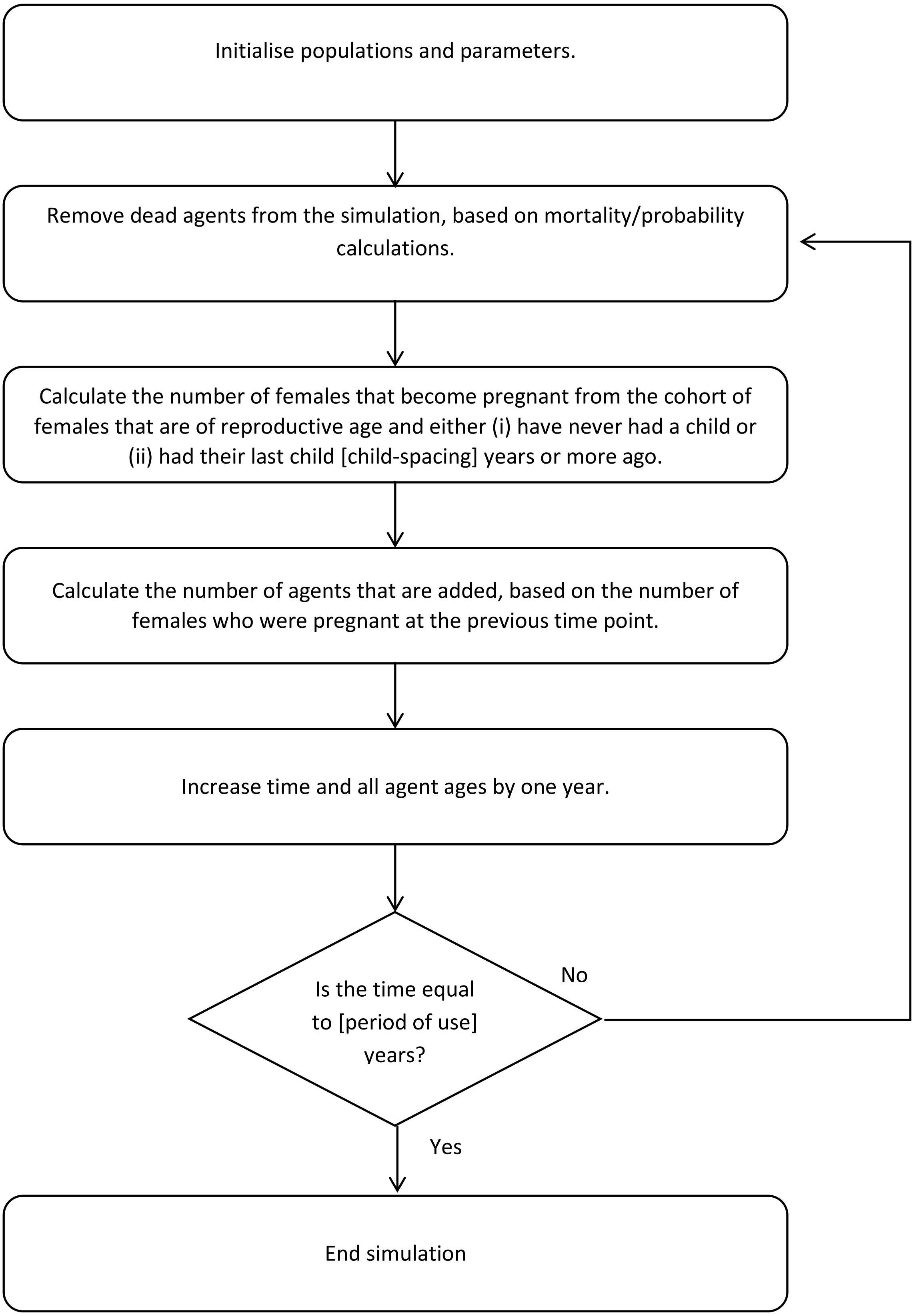


Fig. 3 Flow diagram of the PCS operations.

The general model using the PCS works with five basic categories of parameters:

4.1.1.1 Time/period of use of a site in years

The first parameter is simply the period of time that the cemetery was in use. It utilises the absolute chronology established by archaeological methods or scientific dating. One step in time, i.e. one tick of the virtual clock, equals one year in the PCS. It can be controlled by starting and stopping a simulation run at specific values, or be automatically controlled in NetLogo by setting a time limit, e.g. in the *BehaviourSpace* (see below, Fig. 19). The simulation will produce data for each year between the start and the end-date of the site, and record all the demographic changes of the living population and the virtual burial place.

4.1.1.2 Starter generation

The second set of parameters comprises the initial size and composition of the living population in year one before the modelling routine is launched. These data are hypothetical and usually comprise a random group of individuals of different randomised ages. The PCS allows the number of initial females and males to be controlled as well as their upper and lower ages. The model then sets up the number of individuals per sex given, and calculates a random age for each individual between the lower and upper boundary (Fig. 4). Usually, the mean number of living individuals of a static population or of the first phase in a cemetery is used. To calculate the average number of living individuals, one can apply the general formula developed by Acsádi and Nemeskéri (Acsádi and Nemeskéri 1970), which is commonly used in archaeological site studies (Donat and Ullrich 1971; Hamerow 1993). In this version of the model, the starter group is uniformly distributed between the given age boundaries – which is normally not the case in human demographics. More realistic would be a starter population in the shape of a regular population pyramid. This is a change which can be affected in future versions of the model. For this version, it was decided to treat the actual starter generation as an emergent entity to limit the number of input parameters necessary. Currently, realistic age structures emerge after a few generations of 'burn-in' time. It is also possible to 'find' the average population size of a possible initial population in an inverse modelling process using the PCS, by experimenting with different sizes until the initial population size and composition are found that produce a number of burials comparable or equal to the excavated data.

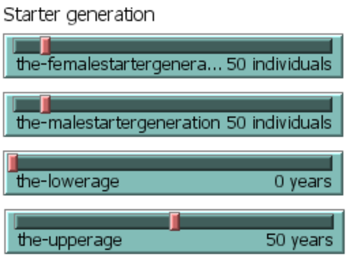


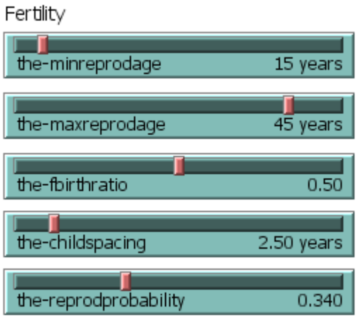
Fig. 4 The four sliders that control the size and age composition of the initial population.

4.1.1.3 Reproduction and fertility

The third set of parameters consist of the female reproduction cycle. Fertility is controlled by specifying the reproductive period of women, the distribution of male versus female babies born, the delay between each birth (known as 'child-spacing') and the probability of actually producing offspring when the period of delay is over. These parameters and how they are obtained will be described in more detail in chapter 5. The PCS does not contain a model of the male role in the reproduction process other than a check if there are still males left at any one point in time who are aged between 16 and 50. All the often totally unknown social influences on female reproduction are comprised in the general 'probability of reproduction' parameter. For instance, female fertility is dependent on age, i.e. it varies over the age of a female (Chamberlain 2006). The PCS' current fertility routines can be improved by introducing a parameter for age-dependent fertility in future versions when data are available for specific archaeological phases or estimated based on general observations of human demographics.

In the PCS, fertility is controlled by five parameter sliders (Fig. 5) and the following section of the code shows how female reproduction is modelled. If females have reached ages beyond the upper age limit (menopause, the-maxreprodage), the whole behaviour of ‘female reproduction’ is deleted in the list of behaviours of the relevant female.

```
to -FEMALE-REPRODUCTION-190
  when task [ time > 0 ]
     task [ when task [ my-age >= the-minreprodage ]
            task [ if ( ( count ( all-of-kind "males" ) with [ my-age >= 16 and my-age <= 50 ] ) > 0 )
                  [ do-after ( random-integer-between 0 the-childspacing )
                         task [ do-every ( the-childspacing )
                                   task [ if random-float 1.0 <= ( the-reprodprobability )
                                         [ if-else ( random-number-between 0 1 <= the-fbirthratio )
                                               [ -CHANGE-NUMBER-OF-CHILDREN-F-3
                                                 -CREATE-FEMALE-OFFSPRING-70 ]
                                               [ -CHANGE-NUMBER-OF-CHILDREN-M-3
                                                 -CREATE-MALE-OFFSPRING-195 ]
                                                                 ; Notes <br>; <br>; <br>; <br>;
] ] ] ] ] ]
end
```



the-minreprodage 15 years

the-maxreprodage 45 years

the-fbirthratio 0.50

the-childspacing 2.50 years

the-reprodprobability 0.340

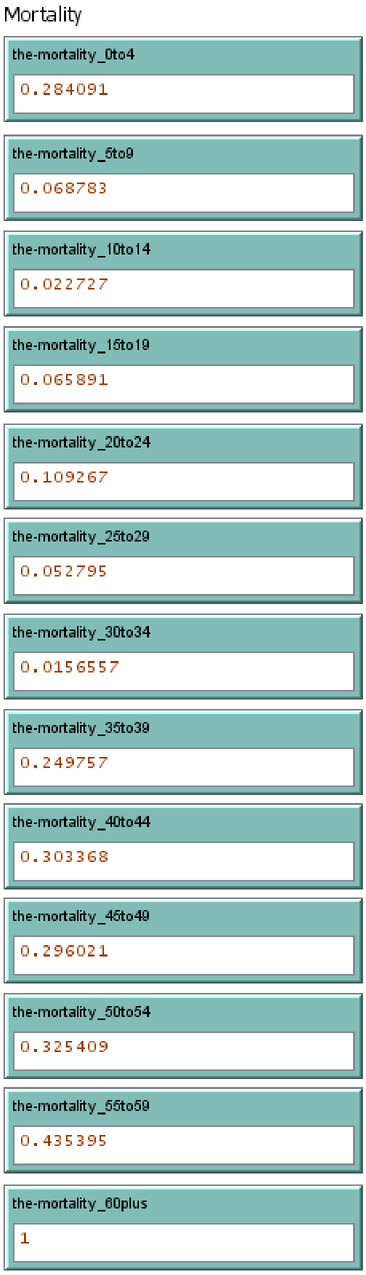
Fig. 5 The five parameters which control female reproduction in the PCS.

4.1.1.4 Mortality

The fourth set of parameters consist of the age-dependent probabilities of dying for each year of the simulation. The overall mortality pattern is calculated based on the distribution of the ages at death of the individuals buried in the cemetery, using estimated or demographic standards. The age dependent mortality pattern can be modelled in two different ways which can be chosen in the Behaviour Composer interface. The Siler Curve model creates a continuous mortality pattern based on an equation. This is useful as some of the anthropological mortality patterns obtainable in the literature have been presented in that form (Kölbl 2004; Wood et al. 2002). The life table form allows researchers to fill in a table of age-dependent mortality rates from life tables that were calculated for age increments of five years (Chamberlain 2006; Grupe et al. 2005). The latter form is used in most of the site reports of Alamannic and Anglo-Saxon populations. The PCS uses the data in the q(x) column of a life table. Fig. 6 shows the mortality data entry of the Life table form in the PCS, and the following section of the code explains how the age-dependent risk of death per male and female in the system is computed. x is equal to the specific age in years of the agent modelled. In all the following models, males and females have the same mortality pattern, usually the average pattern calculated. Differences between male and female mortality exist and can be studied in future applications of the PCS. The 'the-mortmult' parameter is used to change the individual risks of death of specific males and females modelled in more complex simulations, such as experiments on differences within populations and selective effects of mortality caused by diseases or access to wealth, symbolised by burial with rich furnishings.

```
to-report probability-death [ x ]
  if x >= 0 and x <= 4
    [ report ( ( 1 - ( 1 - the-mortality_0to4 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 9
    [ report ( ( 1 - ( 1 - the-mortality_5to9 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
```

```
  if x <= 14
    [ report ( ( 1 - ( 1 - the-mortality_10to14 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 19
    [ report ( ( 1 - ( 1 - the-mortality_15to19 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 24
    [ report ( ( 1 - ( 1 - the-mortality_20to24 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 29
    [ report ( ( 1 - ( 1 - the-mortality_25to29 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 34
    [ report ( ( 1 - ( 1 - the-mortality_30to34 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 39
    [ report ( ( 1 - ( 1 - the-mortality_35to39 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 44
    [ report ( ( 1 - ( 1 - the-mortality_40to44 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 49
    [ report ( ( 1 - ( 1 - the-mortality_45to49 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 54
    [ report ( ( 1 - ( 1 - the-mortality_50to54 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  ifelse x <= 59
    [ report ( ( 1 - ( 1 - the-mortality_55to59 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
    [ report ( 1 - ( 1 - the-mortality_60plus ) ^ ( 1 / 5 ) ) ]
end
```



Mortality

the-mortality_0to4
0.284091

the-mortality_5to9
0.068783

the-mortality_10to14
0.022727

the-mortality_15to19
0.065891

the-mortality_20to24
0.109267

the-mortality_25to29
0.052795

the-mortality_30to34
0.0156557

the-mortality_35to39
0.249757

the-mortality_40to44
0.303368

the-mortality_45to49
0.296021

the-mortality_50to54
0.325409

the-mortality_55to59
0.435395

the-mortality_60plus
1

Fig. 6 The input boxes for age-dependent mortality (qx).

4.1.1.5 Population dynamics, growth and decline

Growth and decline of a population are not modelled as separate parameters in the PCS, but represent a consequence of the balance between births and deaths in the modelled population. In static populations the death rate is equal to the birth rate. Growth and decline can be modelled by changing either the reproduction or the mortality parameters of a population. Both methods are used in demographic research (Séguy and Buchet 2013). However, in archaeological research the mortality pattern is often known, whereas fertility is unknown and can only be reconstructed, e.g indirectly based on the assumption of a static population. It therefore seems prudent to model growth and decline by changing fertility parameters instead of mortality in this thesis. Furthermore, female fertility is much more dynamic than the mortality of a population. In research on late medieval and early modern fertility and marriage patterns, historical demographers have demonstrated that the reproduction behaviour of a population reacts more directly to economic growth and decline than population mortality does; the latter is more dependent on long-term trends – with the exception of extreme short-term epidemics or natural disasters (Bumpass 1969; Cain 1983; Engelen and Puschmann 2011; Frier 1994; Hajnal 1965; Hajnal 1982; Paine and Harpending 1998).

4.1.1.6 Overview of output

1	Time (in yearly steps)	Living population
2	Starter population (in year one)	
3	Fertility/reproduction	
4	Mortality (age dependant probability of dying)	
5	Population dynamics (stagnation, growth & decline)	

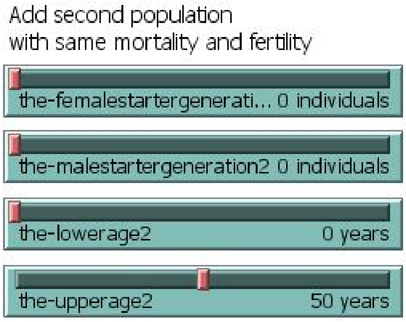
Fig. 7 Parameters of a basic virtual population in the PCS.

This set of parameters (Fig. 7) suffices for conducting simple demographic experiments. Plots of the living and dead population sizes are continuously updated with each tick of the simulation. The age patterns of the living and dead populations at each point in time can be followed in histograms. Within the NetLogo toolkit, the model can also produce Excel spreadsheets and tables of all temporal stages of each simulation run. Most models in the case studies below use only a sub-set of the possible behaviours programmed to govern the agents in the system. Tools to model more complex archaeological situations beyond the simple demographics have been implemented as well. It is however important to keep the simulations as simple as possible for analysis; using all the following functions at the same time produces complex interdependent effects.

4.1.2 Additional functions of the software

4.1.2.1 Multiple populations

More than one population can be modelled in parallel, and sex-specific rates of immigration and emigration can be selected to assess different ratios of interaction between the populations. In the current version of the model, only the starter generation of one additional population can be created in parallel to the first, and the initial size per sex and general composition per age changed using a second starter generation creator (Fig. 8). The mortality and fertility entry data for the second population are therefore exactly the same for Population One and Population Two.

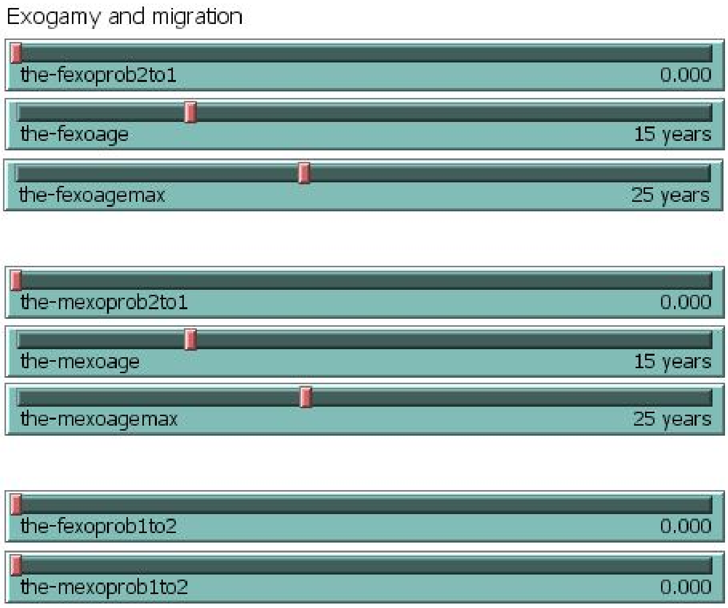


Add second population
with same mortality and fertility

the-femalestartergenerati... 0 individuals
the-malestartergeneration2 0 individuals
the-lowerage2 0 years
the-upperage2 50 years

Fig. 8 Here a second population can be modelled in parallel to the first.

The interaction between the two populations can be controlled by a number of parameters. The annual rate of migration from Population One to Population Two and vice versa can be modelled, controlled by the sex and age of the individuals. Consequently, migration populations can be modelled with different age structures from those of sedentary populations. Very low rates of patrilocal and matrilocal intermarriage/exogamy can be modelled in the form of low sex-specific ratios of transitioning from Population One to Population Two and vice versa (Fig. 9). Mathematically, the rate of migration is modelled as a ratio of migrants per year (the-f/mexoprob2to1/1to2), who transition between the populations dependent on age (upper and lower age limit) and sex. The model further tracks the origins of the individuals who have transitioned between populations, so that differences in frequencies of immigrants between the living and the cemetery populations over time can be plotted in graphs.



Exogamy and migration

the-fexoprob2to1 0.000

the-fexoage 15 years

the-fexoagemax 25 years

the-mexoprob2to1 0.000

the-mexoage 15 years

the-mexoagemax 25 years

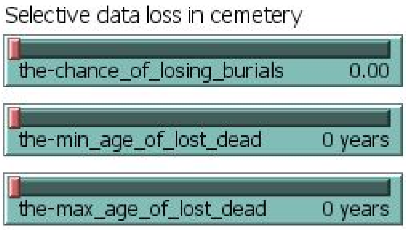
the-fexoprob1to2 0.000

the-mexoprob1to2 0.000

Fig. 9 Females and males can transition from one population to the other based on the parameters controlled by these sliders.

4.1.2.2 Selective data loss

Data loss between living and cemetery populations is a common problem in archaeology due to taphonomy, recovery and other factors (Hoppa 1996). In order to model data loss, the PCS can randomly destroy the information of a proportion of deceased individuals before they are buried in the virtual cemetery. As data are often lost in specific age groups, e.g. the ‘missing infant’ phenomenon (Crawford 2007; Kölbl 2004; Séguy and Buchet 2013), parameters to control data loss were chosen to include a general chance of loss as well as a lower and upper age limit for targeted individuals (Fig. 10).



Selective data loss in cemetery

the-chance_of_losing_burials 0.00

the-min_age_of_lost_dead 0 years

the-max_age_of_lost_dead 0 years

Fig. 10 The parameters sliders for controlling data loss.

4.1.2.3 Modelling catastrophic events

Reoccurring or single catastrophes can be modelled by activating the ‘catastrophe generator’ (The default is ‘off’). The events can be delayed by a number of years and during the catastrophic year, the mortality of the whole population is temporarily raised by a factor controlled by a slider (Fig. 11). The following section of code explains what the parameter performs that multiplies the standard mortality. In any catastrophic year, ‘the-mortmult’ can be raised temporarily beyond 1 and therefore raises the risk of death per individual:

```
to-report probability-death [ x ]
  if x >= 0 and x <= 4
```

```
    [ report ( ( 1 - ( 1 - the-mortality_0to4 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 9
    [ report ( ( 1 - ( 1 - the-mortality_5to9 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
(…)
```

Catastrophes

the-disaster_generator

the-years_between_catastrophes 10 years

the-mortality_multiplier 1.0

Fig. 11 The catastrophe generator can be turned on and off, and the time interval and the mortality impact of the event can be controlled with sliders.

This way of modelling years in which a catastrophe occurs has disadvantages, as a multiplication leads to stronger increases of mortality in age groups that are already strongly affected. This happens in famine situations and in the case of diseases, which have a much stronger effect on the fragile, weak young and old than on healthy and middle-aged adult individuals. In order to model indiscriminate plague events such as the Black Death (Gowland and Chamberlain 2005; Séguy and Buchet 2013), 'the-mortmult' would have to be added (+) instead of multiplied in order to reflect the age dependent risks of death. An additive factor will be included in a future version of the model.

4.1.2.4 Modelling artefact frequencies and disease rates: The artefact and disease distribution tool

Age and sex-specific burials with traits such as acquired diseases or artefacts can be simulated in the following way: the artefact and disease distribution tool allows for the creation of a disease or artefact, which is then carried by 'infected' living individuals during their lifetime. When these individuals die, they retain the artefact/disease trait when they are added to the virtual cemetery. It is therefore possible to crudely model the difference between artefact and disease frequencies in both the living and the cemetery populations.

Age at ‘infection’ strongly affects the frequencies. This is why the PCS lets users control the initial age of receipt and the percentage of individuals in that age group affected per year (Fig. 12). This can be seen as a rite of passage or ‘infection event’. By distributing artefacts and diseases at specific ages and tracking the ‘infected’ individuals, the PCS can model aspects of the furnished burial rite and palaeopathological prevalence rates (Waldron 2007) in both the living and the cemetery populations.

To be further able to model the impact of the artefact/disease on the survival probabilities of the individuals, the ‘the-m/ftrait_mortchange’ is multiplied with the ‘the-mortmult’ parameter (see above) and can have either a beneficial or an adverse effect on the person’s survival rate. This is the concept for modelling the selective mortality aspect of Wood et al.’s Osteological Paradox (Wood et al. 1992), an observation which will be explained below (chapter 5).

Artefacts and diseases

the-mtrait_age 30 years

the-mtrait_probability 0.20

the-mtrait_mortchange 1.00

the-ftrait_age 50 years

the-ftrait_probability 0.50

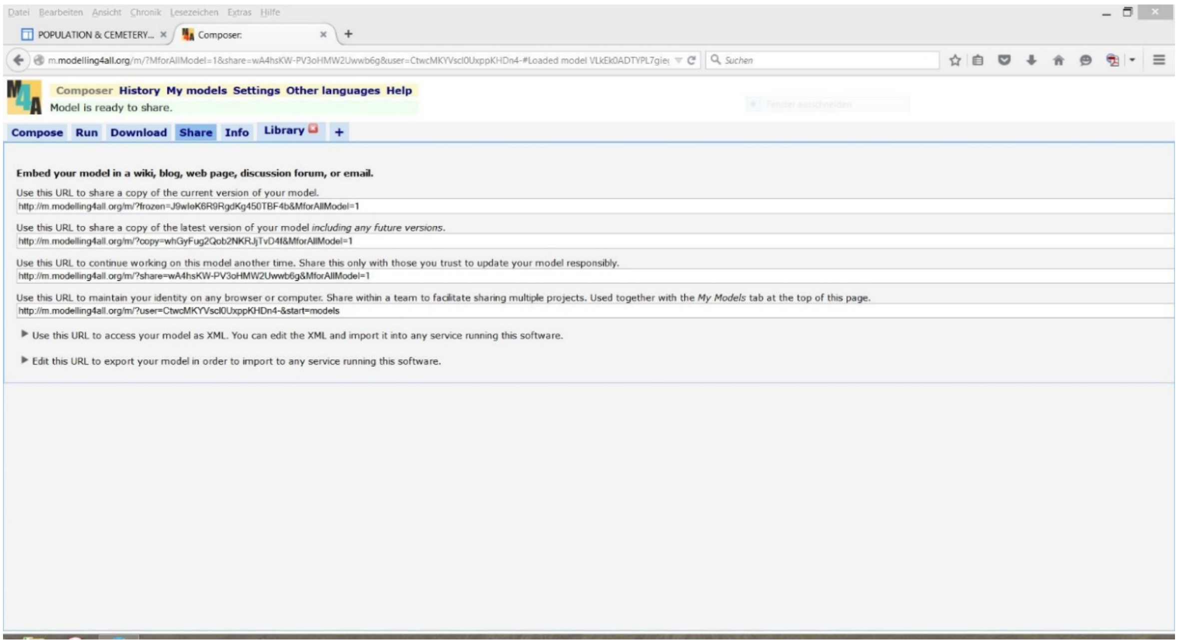
the-ftrait_mortchange 1.00

Fig. 12 The artefact/disease distribution tool. Age of receipt and percentage of individuals receiving the artefact/disease at this point in time can be controlled, as well as the impact of the artefact/disease on the individual mortality.

4.2 The PCS as an open-access tool in archaeology

The idea of the Web 2.0 is that information, programmess and specific pieces of code can be shared freely and constantly updated. Fig. 13 shows an example of the links which are used to share PCS models on the web. The Oxford-based Modelling4All Project (www.modelling4all.org) provides users with a solution to coding simulations that is easily understandable by people who have not received extensive training in programming languages. With the help of the Behaviour Composer, parts of code can be assembled by simply dragging and dropping buttons from a library of behaviours (Kahn and Noble 2010). The default behaviours can then be altered and enhanced in a comparatively simple manner. For example, sub-programmes developed in ecology which model the death of animals can be used for modelling death in the PCS. This way of programming ensures the comparability and accuracy of the sub-programmes.

Modelling4all is based on the NetLogo software made available as open-source material by Northwestern University, which is particularly powerful and widely used for agent-based modelling by an active interdisciplinary community (Wilensky 1999; Wilensky and Rand 2015). A preliminary version of the Population and Cemetery Simulator is available on the Modelling4All webpage for downloading, and I have also attached a brief manual and description (Duering 2015). Based on the intrinsic logic of the Modelling4All project, it has two interfaces.



Model is ready to share.

Embed your model in a wiki, blog, web page, discussion forum, or email.

Use this URL to share a copy of the current version of your model.

http://m.modelling4all.org/m/?frozen=J9wleK6R9RgdKg450TBF4b&MforAllModel=1

Use this URL to share a copy of the latest version of your model *including any future versions*.

http://m.modelling4all.org/m/?copy=whGyFug2Qob2NKRJjTvD4f&MforAllModel=1

Use this URL to continue working on this model another time. Share this only with those you trust to update your model responsibly.

http://m.modelling4all.org/m/?share=wA4hsKW-PV3oHMW2Uwwb6g&MforAllModel=1

Use this URL to maintain your identity on any browser or computer. Share within a team to facilitate sharing multiple projects. Used together with the *My Models* tab at the top of this page.

http://m.modelling4all.org/m/?user=CtwcMKYVscl0UxppKHDn4-&start=models

▶ Use this URL to access your model as XML. You can edit the XML and import it into any service running this software.

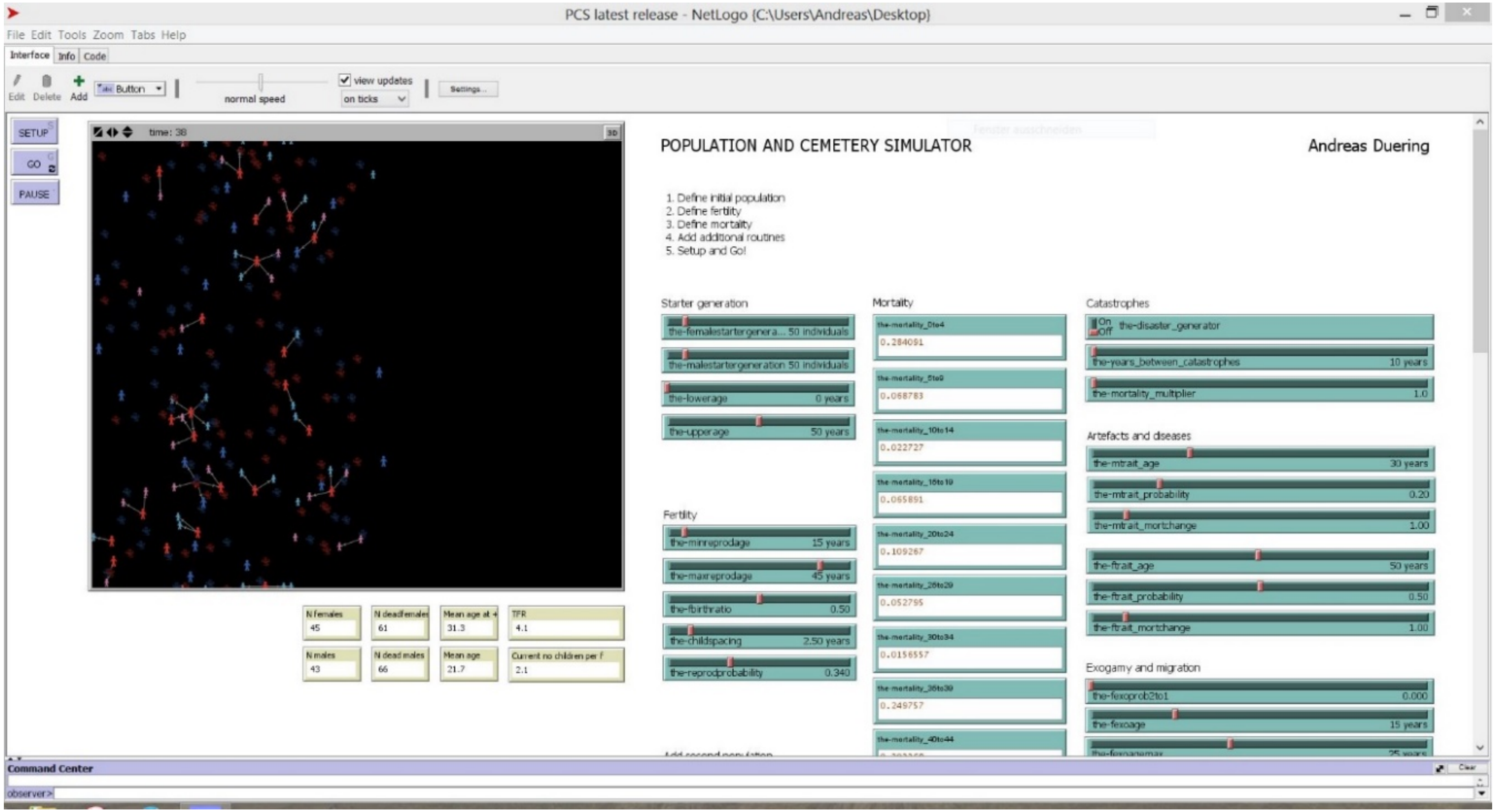
▶ Edit this URL to export your model in order to import to any service running this software.

Fig. 13 PCS models can be shared over the internet by sending URLs using the Behaviour Composer of the modelling4all project.

4.2.1 Interface 1

The first interface (Fig. 14 and 15), alternatively run in the web browser or in NetLogo, has input boxes and sliders for simple entry of demographic data from cemetery sites. The setup of a population with specific parameters and the running of the population for a period of time chosen by the user can be achieved by a simple click on the relevant buttons. The modelled population visualised as red females and blue males in the ‘world’, i.e. a black space which offers the possibility of being filled by a map or abstract environment in future applications of the model.

The data output of demographic parameters directly measured in real time for each modelled year of the population such as TFR and the ratio of orphans is achieved using monitors for numbers, graphs and plots. The use of this interface requires no prior knowledge of a programming language or the internal mathematical logics. It is designed for practical use in archaeological analyses of cemeteries.



POPULATION AND CEMETERY SIMULATOR

Andreas Duering

1. Define initial population
2. Define fertility
3. Define mortality
4. Add additional routines
5. Setup and Go!

Starter generation

the-femalestartergenera... 50 individuals
the-malestartergeneration 50 individuals
the-lowerage 0 years
the-upperage 50 years

Fertility

the-minreprodage 15 years
the-maxreprodage 45 years
the-fbirthratio 0.50
the-childspacing 2.50 years
the-reprodprobability 0.340

Mortality

the-mortality_0to4 0.284091
the-mortality_5to9 0.068783
the-mortality_10to14 0.022727
the-mortality_15to19 0.065891
the-mortality_20to24 0.109267
the-mortality_25to29 0.052795
the-mortality_30to34 0.0156557
the-mortality_35to39 0.249757
the-mortality_40to44

Catastrophes

On Off the-disaster_generator
the-years_between_catastrophes 10 years
the-mortality_multiplier 1.0

Artefacts and diseases

the-mtrait_age 30 years
the-mtrait_probability 0.20
the-mtrait_mortchange 1.00
the-ftrait_age 50 years
the-ftrait_probability 0.50
the-ftrait_mortchange 1.00

Exogamy and migration

the-fexoprob2to1 0.000
the-fexoage 15 years

N females 45
N deadfemales 61
Mean age at + 31.3
TFR 4.1
N males 43
N dead males 66
Mean age 21.7
Current no children per f 2.1

Fig. 14 First interface of the Population & Cemetery Simulator (PCS). Parameters sliders and input boxes can be seen on the right. The ‘world’ and the modelled agents are on the left.

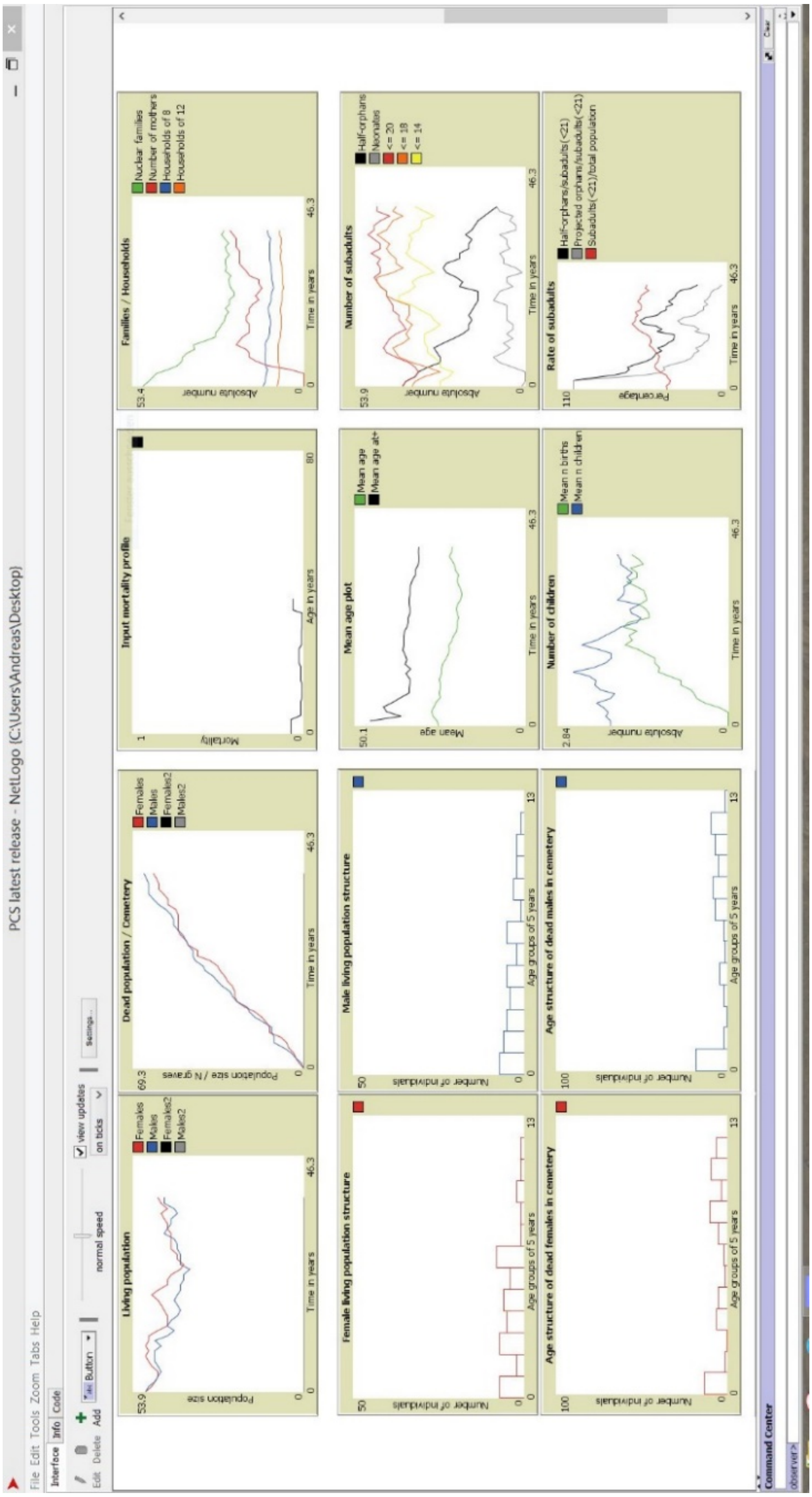
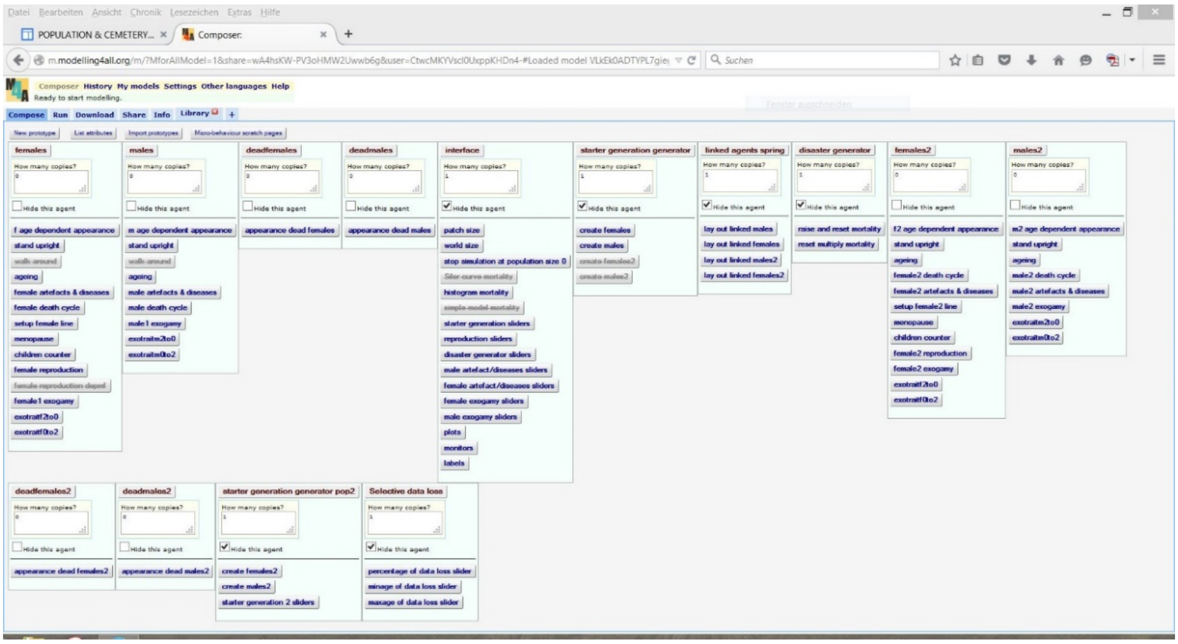


Fig. 15 Data output. Graphs record parameters such as ages at death or the frequency of immigrants for both the living and the cemetery population for each modelled year.

4.2.2 Interface 2

The second interface uses the open-source Behaviour Composer of the modelling4all project (Kahn and Noble 2010). The primary logics and behaviours of the agents in the simulation are ordered in a mind-map-like structure, as buttons that can be clicked on to open deeper layers of the programme (Fig. 16). Alterations of all basic principles of the PCS and the addition of further functions are possible in this interface. The structure and visualisation is superior to many pages of code created by the Behaviour Composer in the background. The inner workings of the PCS become apparent after a short period of engagement with the programme, so that the Behaviour Composer is consequently very effective way of teaching archaeological demography. The second interface works at two levels. Firstly, it is the basis of the computer software and the first interface. Secondly, it is a platform for considering archaeological demography and the biology of cemetery populations in a structured way.



females
How many copies? 0
☐ Hide this agent

males
How many copies? 0
☐ Hide this agent

deadfemales
How many copies? 0
☐ Hide this agent

deadmales
How many copies? 0
☐ Hide this agent

interface
How many copies? 1
☑ Hide this agent

starter generation generator
How many copies? 1
☑ Hide this agent

linked agents spring
How many copies? 1
☑ Hide this agent

disaster generator
How many copies? 1
☑ Hide this agent

females2
How many copies? 0
☐ Hide this agent

males2
How many copies? 0
☐ Hide this agent

deadfemales2
How many copies? 0
☐ Hide this agent

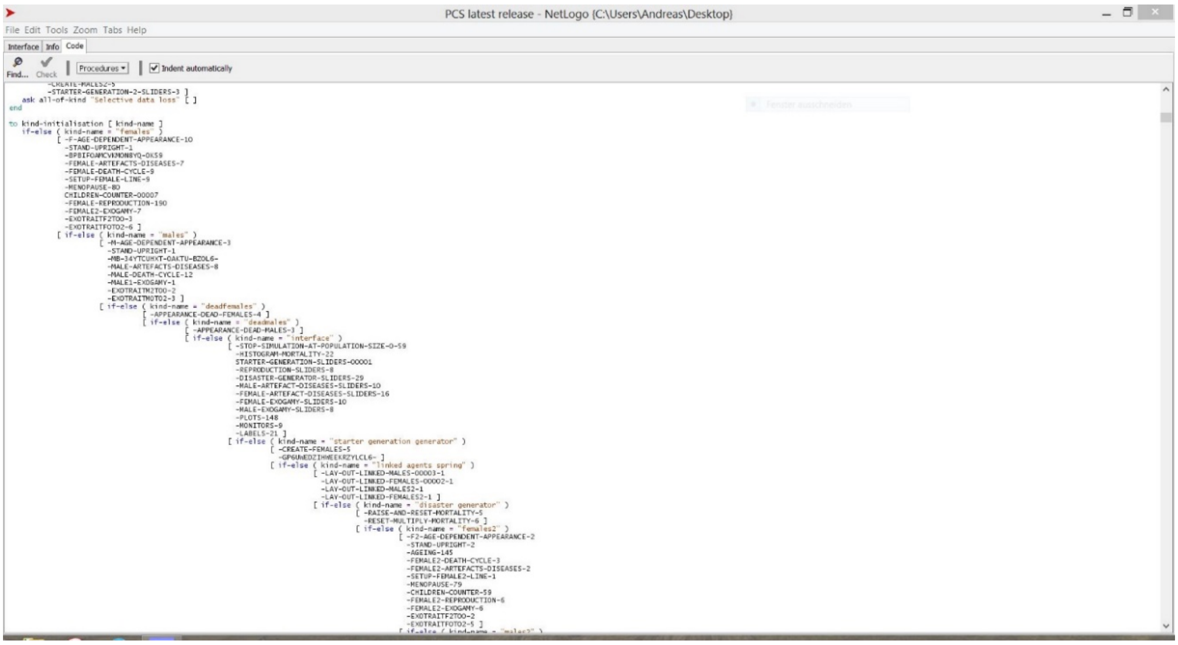
deadmales2
How many copies? 0
☐ Hide this agent

starter generation generator pop2
How many copies? 1
☑ Hide this agent

Selective data loss
How many copies? 1
☑ Hide this agent

Fig. 16 The second interface of the PCS. The agents in the system are represented as boxes with lists of their behaviours in the model.

The actual code (Fig. 17, see Appendix) can always be looked at and changed, but remains invisible for those who do not wish to engage with it directly. It is therefore possible for archaeologists and bioarchaeologists to share simulations of specific sites, and are no longer degraded to users of a black-box software. They can share different versions of the model, alter procedures and behaviours, and use the tool itself to communicate the sometimes very complex problems which arise when conducting such simulations.



```
       -CREATE-MALES2-5
       -STARTER-GENERATION-2-SLIDERS-3 ]
  ask all-of-kind "Selective data loss" [ ]
end

to kind-initialisation [ kind-name ]
  if-else ( kind-name = "females" )
          [ -F-AGE-DEPENDENT-APPEARANCE-10
            -STAND-UPRIGHT-1
            -BPBIFOAMCVKMON8YQ-0K59
            -FEMALE-ARTEFACTS-DISEASES-7
            -FEMALE-DEATH-CYCLE-9
            -SETUP-FEMALE-LINE-9
            -MENOPAUSE-80
            CHILDREN-COUNTER-00007
            -FEMALE-REPRODUCTION-190
            -FEMALE2-EXOGAMY-7
            -EXOTRAITF2TOO-3
            -EXOTRAITFOTO2-6 ]
          [ if-else ( kind-name = "males" )
                    [ -M-AGE-DEPENDENT-APPEARANCE-3
                      -STAND-UPRIGHT-1
                      -MB-34YTCUHXT-OAKTU-BZOL6-
                      -MALE-ARTEFACTS-DISEASES-8
                      -MALE-DEATH-CYCLE-12
                      -MALE1-EXOGAMY-1
                      -EXOTRAITM2TOO-2
                      -EXOTRAITMOTO2-3 ]
                    [ if-else ( kind-name = "deadfemales" )
                              [ -APPEARANCE-DEAD-FEMALES-4 ]
                              [ if-else ( kind-name = "deadmales" )
                                        [ -APPEARANCE-DEAD-MALES-3 ]
                                        [ if-else ( kind-name = "interface" )
                                                  [ -STOP-SIMULATION-AT-POPULATION-SIZE-0-59
                                                    -HISTOGRAM-MORTALITY-22
                                                    STARTER-GENERATION-SLIDERS-00001
                                                    -REPRODUCTION-SLIDERS-8
                                                    -DISASTER-GENERATOR-SLIDERS-29
                                                    -MALE-ARTEFACT-DISEASES-SLIDERS-10
                                                    -FEMALE-ARTEFACT-DISEASES-SLIDERS-16
                                                    -FEMALE-EXOGAMY-SLIDERS-10
                                                    -MALE-EXOGAMY-SLIDERS-8
                                                    -PLOTS-148
                                                    -MONITORS-9
                                                    -LABELS-21 ]
                                                  [ if-else ( kind-name = "starter generation generator" )
                                                            [ -CREATE-FEMALES-5
                                                              -GP6UWEDZIHWEEKRZYLCL6- ]
                                                            [ if-else ( kind-name = "linked agents spring" )
                                                                      [ -LAY-OUT-LINKED-MALES-00003-1
                                                                        -LAY-OUT-LINKED-FEMALES-00002-1
                                                                        -LAY-OUT-LINKED-MALES2-1
                                                                        -LAY-OUT-LINKED-FEMALES2-1 ]
                                                                      [ if-else ( kind-name = "disaster generator" )
                                                                                [ -RAISE-AND-RESET-MORTALITY-5
                                                                                  -RESET-MULTIPLY-MORTALITY-6 ]
                                                                                [ if-else ( kind-name = "females2" )
                                                                                          [ -F2-AGE-DEPENDENT-APPEARANCE-2
                                                                                            -STAND-UPRIGHT-2
                                                                                            -AGEING-145
                                                                                            -FEMALE2-DEATH-CYCLE-3
                                                                                            -FEMALE2-ARTEFACTS-DISEASES-2
                                                                                            -SETUP-FEMALE2-LINE-1
                                                                                            -MENOPAUSE-79
                                                                                            -CHILDREN-COUNTER-59
                                                                                            -FEMALE2-REPRODUCTION-6
                                                                                            -FEMALE2-EXOGAMY-6
                                                                                            -EXOTRAITF2TOO-2
                                                                                            -EXOTRAITFOTO2-5 ]
                                                                                          [ if-else ( kind-name = "males2" )
```

Fig. 17 Section of PCS code in NetLogo.

4.3 Data input

The following is a list of the demographic parameters used in the PCS and the models of this thesis, with a short description (Tab. 2). Chapter 5 contains more information about the actual demographic properties of the parameters and their sensitivities. The names of the parameters in the PCS do not adhere to the common palaeodemographic nomenclature to improve readability, e.g. the meaning of c or q(x) is less obvious than a word such as ‘the-childspacing’. But there are also NetLogo-specific limitations on nomenclature. Most of the parameters controlled by sliders or input boxes must be named ‘the-NAME’, such as ‘the-mortality_0to4’. The use of ‘the-‘ as a suffix of the parameters is required by the logic of the NetLogo programming language.

The abbreviations in brackets behind the parameter names only refers to the PCS Data Sheet for each virtual experiment presented in the thesis, e.g. ‘the-years_between_catastrophes’ (Delay).

Setup / Go / Pause	These buttons control the model. The model will stop automatically whenever the total population of the living is 0.
Number of Repetitions	The number of repetitions of one virtual experiment with equal parameters
Time / Duration of Run	1 step in time, 1 tick in the PCS, equals 1 year
Initial Population / Starter Generation	
the-femalestartergeneration (Nf)	Number of female individuals at time step 0
the-malestartergeneration (Nm)	Number of male individuals at time step 0
the-lowerage (Lage)	Minimum age of the individuals of the initial population
the-upperage (Uage)	Maximum age of the individuals of the initial population
Reproduction / Fertility	
the-minreprodage (Minrage)	Minimum age of reproduction for females, menarche
the-maxreprodage (Maxrage)	Maximum age of reproduction for females, menopause
the-fbirthratio (Fbratio)	Ratio of female versus male new-borns
the-childspacing (Childsp)	Temporal delay between births, in years
the-reprodprobability (Reproprob)	Probability of reproduction at a point in time defined by age and child-spacing
Mortality	
the-mortality_0to4 (…) to the-mortality_60plus	Age-dependent risk of dying; each input box controls a 5-year age group from age 0 to age

	60+. 100 percent mortality equals 1 in the input format.
Selective Data Loss in Cemetery	
the-chance_of_losing_burials (Chance)	Probability that a death in the living population is not recorded in the cemetery population
the-min_age_of_lost_dead (Min Age)	Minimum age of individuals considered for the data loss routine
the-max_age_of_lost_dead (Max Age)	Maximum age of individuals considered for the data loss routine
Catastrophes	
the-disaster_generator (On/Off)	The disaster generator can be enabled and disabled. The default is disabled. Will disable at every Setup.
the-years_between_catastrophes (Delay)	Time delay between catastrophes when the disaster generator is enabled
the-mortality_multiplier (X Mort)	This number is multiplied by the age-dependent mortality per individual in the living population. The X Mort will most affect those that already have high mortality rates.
Artefacts / Diseases	
Males:	
the-mtrait_age (Iniage)	The initial age for individuals in the living population for receiving the object / getting infected
the-mtrait_probability (Prob)	The probability of receiving the object / getting infected when being the right age
the-mtrait_mortchange (X Mort)	The adjustment (multiplier) of the individual’s mortality when in possession of the object / infected
Females:	
the-ftrait_age (Iniage)	The initial age for individuals in the living population for receiving the object / getting infected

the-ftrait_probability (Prob)	The probability of receiving the object / getting infected when being the right age
the-ftrait_mortchange (X Mort)	The adjustment (multiplier) of the individual's mortality when in possession of the object / infected
Exogamy / Migration	
Emigration	
Females:	
the-fexoprob2to1 (Probabilities, Female, P2 to P1)	The probability of migrating from Population 2 to Population 1
the-fexoage (Migrant Age, Female, Min)	The minimum age of migrants
the-fexoagemax (Migrant Age, Female, Max)	The maximum age of migrants
Males:	
the-mexoprob2to1 (Probabilities, Male, P2 to P1)	The probability of migrating from Population 2 to Population 1
the-mexoage (Migrant Age, Male, Min)	The minimum age of migrants
the-mexoagemax (Migrant Age, Male, Max)	The maximum age of migrants
Immigration	
The same age parameters are applied as for emigration (s. above).	
the-fexoprob1to2 (Probabilities, Female, P2 to P1)	The probability of migrating from Population 1 to Population 2
the-mexoprob1to2 (Probabilities, Male, P2 to P1)	The probability of migrating from Population 1 to Population 2

Tab. 2 Overview of PCS input parameters.

4.4 Data output

This section lists the output data produced by the PCS in real time during the runs (Tab. 3). The following refers to the graphs and monitors which are immediately produced in the interface when the model is running. Virtual experiments in NetLogo allow many more parameters and output data to be observed and collected in xml format tables and spreadsheets (under: Tools, BehaviourSpace).

Monitors	
Time	Number of modelled years
N females	Total number of living females at this point in time
N males	Total number of living males at this point in time
N dead females	Accumulated dead females in the cemetery up to this point
N dead males	Accumulated dead males in the cemetery up to this point
Mean age at +	Mean age at death of all individuals buried in the cemetery up to this point
Mean age	Mean age of all living individuals at this point in time
TFR	Total Fertility Rate. The average number of children which are produced by the average female in the living population with the current reproduction settings assuming the women survives until menopause (the-maxreprodage).
Current no children per f	The average number of living children per living reproductive female in the current modelled year. While the TFR is a hypothetical value, this number reflects the real current state for nuclear families.

Graphs	
Modelling space	The black window shows the living and the dead populations modelled in the PCS. Symbols represent age, sex, living individuals and deceased, and the links between living individuals represent the female biological line.
Living population	Plots the size of the female population at each point in time in red, and that of the male population in blue. Other populations beyond the first are added in different colours.
Dead population / Cemetery	Records the total number of the accumulating dead females and males in the cemetery
Female / Male living population structure	Plots the number of individuals for population 1 in each age category at each point in time, divided by sex. The 13 age categories each have lengths of 5 years.
Age structure of dead females / dead males in cemetery	Plots the accumulating number of individuals who die in certain age categories divided by sex. This equals the data obtained from a cemetery excavation.
Input mortality profile	This is the overall risk of dying over age, showing the mortality data input.
Mean age plot	Plots the mean age at death, i.e. the development of the average age at death of the cemetery population (in black) and the mean age of each living individual over time (in green)
Number of children	This plots the actual TFR per step in time (usually only appearing after c. one generation length) and two different ways of recording the mean number of living children and births per reproductive female. The mean number of births is calculated on the basis of the number of direct links established between the females and their offspring. The mean number of

	children is calculated as the ratio of subadults (males and females below age 20) to reproductive females.
Families / Households	Plot of the number of coexisting nuclear families per step in time, the number of living females with children and the number of coexisting households based on household sizes of 8 and 12 individuals
Number of subadults	Plots the absolute number of coexisting subadult males and females between the ages of 0 and 1 (newborn), below the ages of 14, 18 and 20 and the number of living children who have lost their mothers per step in time
Rate of subadults	Plot of the rate of individuals below the age of 21 (subadult) and the proportion of subadult individuals who have lost their mothers (half-orphans) and the projected rate of those who have lost both parents (orphans)
% of artefact / disease in subgroup	Compares the living population incidence rates of artefact bearers / diseased individuals in the relevant age group with the prevalence rate, i.e. the accumulating rate of artefact bearers / diseased individuals in the cemetery who died in the relevant age group, provided that all individuals are buried with the object / disease they carried in life.
% of artefact / disease in total population	Compares the living population incidence rates of artefact bearers / diseased individuals in the total population with the prevalence rate, i.e. the accumulating rate of artefact bearers / diseased individuals in the complete cemetery population, provided that all individuals are buried with the object / disease they carried in life.

Exogamy / Migration	Plots the rate of immigrants, i.e. of individuals that have been born in a different population, in the living and in the cemetery populations
Three coexisting generations	Plot of the number of females which have more than one incoming and more than one outgoing family link. This records the number of living grandmothers that are coexisting with their daughters' living offspring.

Tab. 3 Overview of immediate PCS output parameters and graphs in the interface 1.

4.5 Experimental setup and repeating experiments

To compare cemeteries and their living populations, it is necessary to reconstruct a plausible scenario of how a cemetery might have been formed. The following describes how this is achieved using the PCS in five steps ((1) to (5) below). Fig. 18 shows the work-flow of conducting such experiments.

(1) To calculate the average mortality pattern of each age group of the population, a mortality or life table – a standard tool in demography (see chapter 3) – is needed (Acsádi and Nemeskéri 1970; Chamberlain 2006). Alternatively, standard models or standard life tables for preindustrial populations can be used (Kölbl 2004; Séguy and Buchet 2013; Séguy et al. 2013; Wood et al. 2002). Most simulations with the PCS start with the calculation of a life table, as it transforms the distribution of aged individuals in a cemetery into an estimate of the population's mortality profile (for all the various problems and biases of this technique, see chapter 3). Mortality tables assume that every individual in a population belongs to the same cohort and that by comparing the proportion of dead and the survivors according to their individual ages at death, one can calculate the overall probability of dying for each age (Acsádi and Nemeskéri 1970; Howell 1982; Moore et al. 1975; Williams 1992). Palaeodemographers usually work with age categories of 5 years (see

above); i.e. individuals aged 0 to 4, 5 to 9, 10 to 14, 15 to 19 etc. are grouped together up to a general category for the few individuals who lived for 60 years and over. Some life tables even go up to 80. In the mortality table procedure, the age-at-death pattern of a cemetery population is transformed into a mortality profile giving the probability of death in age categories of 5 years. This step is not automated in the PCS; the production of a suitable mortality pattern for a population needs to be made with caution because of the problems described in chapter 3. Examples of life table calculations can be found in the case studies below, and the absolute variation between the various mortality profiles employed in more theoretical and more realistic scenarios can be observed in chapter 5.1.

(2) The other parameters above are then chosen to reflect a stationary population for the period of use of the cemetery as a starting-point. In order to achieve a stationary population, the fertility parameters are chosen to balance out the mortality of the population: birth rate = death rate. This can be done manually in interface 1, but can also be automated in NetLogo.

(3) The simulations with the Population & Cemetery Simulator are now conducted and repeated several times. The simulations will thereby repeatedly create virtual living and virtual cemetery populations and collect data such as the yearly age profile, demographic structure, mean ages at death, and mean number of children.

(4) The results of the first runs of the model are checked for several aspects in the next step, to test how realistic the simulations are and how closely they reflect the primary archaeological input. Step (4) is simply a general test for plausibility, which consists of two parts:

(4a) Stationary populations: have the average population sizes stayed stationary, or does a majority of the runs tend towards growth or decline? In this case, the fertility routine should be adjusted until a stationary state can be seen, because observations should ideally always start from the stationary state.

(4b) Exclude unrealistic aberrations: if the population stayed relatively stationary, other parameters can be compared to check how realistic the simulations are:
Does the virtual cemetery produce the same number of graves as in the excavated site, and does the living population reproduce the original estimate? One must, however, be aware that the PCS cannot exactly reproduce the values, as the effects of chance in a stochastic model lead to a factor of uncertainty which depends on the overall size of the population. Small populations will therefore show a stronger variation than larger populations modelled with the PCS. Exploring the strength of these effects can itself be a valuable research objective, as the same variation affected the actual archaeological population in the past.

How realistic is the age structure of the virtual living population? The average age at death and the average age of the living group can be an indicator of how realistic a population is. Populations with an average age of 16 hardly form a sustainable social system, although demographic aberrations with median ages of 16 exist in modern Africa. These populations, however, are fast-growing and not stationary (United Nations Population Division 2012; United Nations Statistics Division 2013).
Does the simulation reproduce the mean age at death of the cemetery site? This parameter does not normally fluctuate strongly after a few initial years of the simulation have passed, and represents a good immediate way to check the models internal consistency.

(5) If the simulations have passed the first general plausibility checks in step (4a) and (4b), the average age-at-death profile of all the simulated populations is compared with the initial age-at-death profile of the excavated site. If the virtual cemetery, i.e. the age-at-death profile of all deceased individuals, closely resembles the excavated site, one mathematically plausible scenario for the demographic development of the population has been discovered. This also means that the

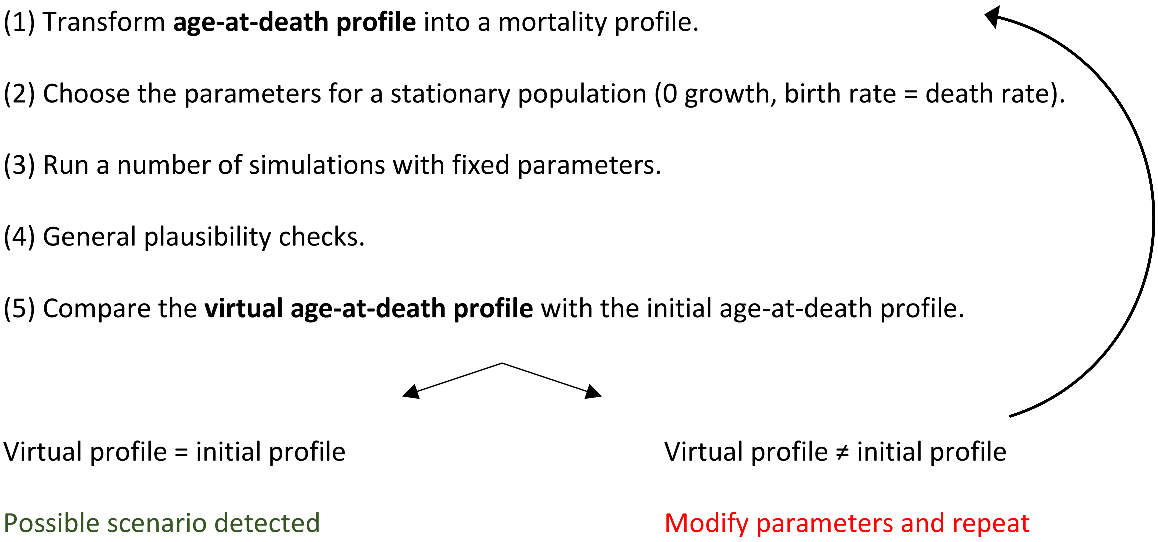
specific combination of all the initial parameters reveals a lot of secondary information, e.g. the size of the living group, the structure of the families, the number of children and the average age of the living group. Contextual studies of these secondary parameters can further test the quality and plausibility of the detected scenario. This can be the starting-point for more detailed experiments.

If, however, the age-at-death profiles of the simulated populations and the actual sample do not match, the search for better parameters can begin. Following the initial run, gradual alterations of parameters, such as fertility (and thereby population growth) or the real number of children in the population (and thereby infant mortality) etc., can be attempted by repeating steps (1) to (5) until a better fit has been found.

However, it should be noted that modelled populations and their mortality patterns are not automatically correct merely because the model shows that the data are generally mathematically consistent according to the described steps. For instance, unnaturally low childhood mortality in some archaeological cemetery sites can lead to low fertility requirements, which seem plausible at first. But such populations often also have extremely high adult mortality rates, which would immediately lead to declining populations under normal demographic conditions, i.e. if more natural childhood mortality rates were modelled. All in all, this routine is able to exclude a variety of inconsistent patterns, but does not necessarily test per se whether data are demographically realistic.

The steps (1) to (5), their re-evaluation and again repetition create a hermeneutic circle of data interpretation embedded in a virtual environment in which parameters depend on other parameters. This highlights the network and mutual dependency of the single parts of the system.

An important function of the PCS is the repetition of the same experiments with the same parameters for multiple times or with continuously changing parameter values. The NetLogo *BehaviourSpace* (Fig. 19) allows for automated parameter repetitions and the recording of parameters and results in spreadsheets and tables which can then be used for analysis in Excel, R or data analysis software such as SPSS.



(1) Transform **age-at-death profile** into a mortality profile.

(2) Choose the parameters for a stationary population (0 growth, birth rate = death rate).

(3) Run a number of simulations with fixed parameters.

(4) General plausibility checks.

(5) Compare the **virtual age-at-death profile** with the initial age-at-death profile.

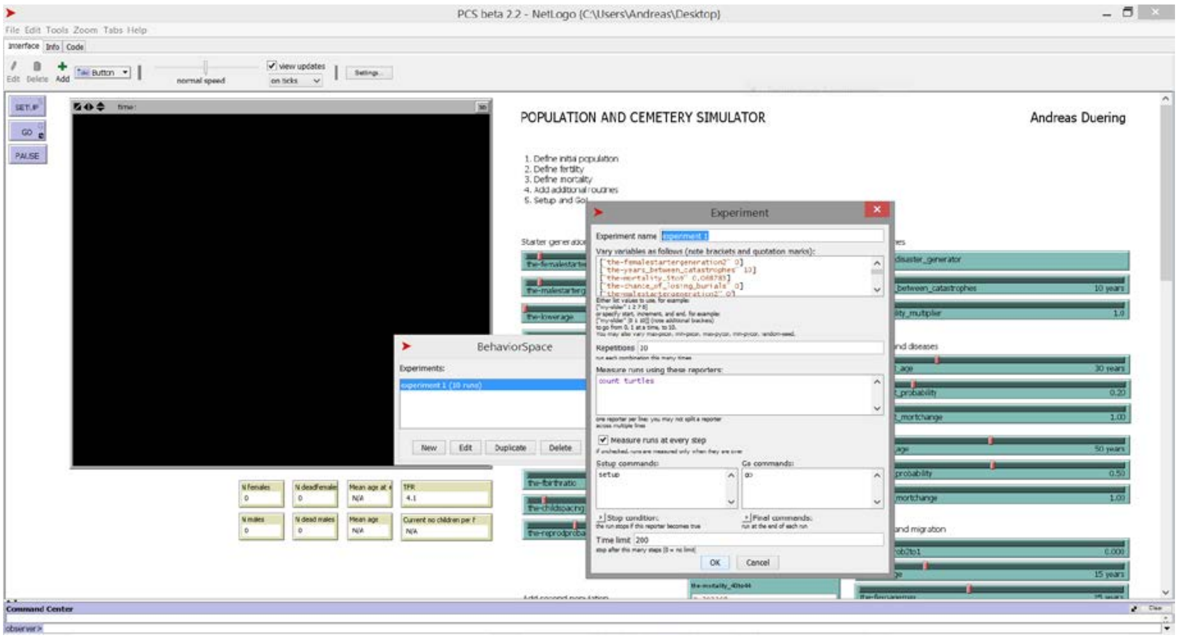
Virtual profile = initial profile

Possible scenario detected

Virtual profile ≠ initial profile

Modify parameters and repeat

Fig. 18 The five steps of the initial experiments.



1. Define initial population
2. Define fertility
3. Define mortality
4. Add additional routines
5. Setup and Go!

Experiments: experiment 1 (10 runs)

Experiment name: experiment 1

Vary variables as follows (note brackets and quotation marks):

```
["the-femalestartergeneration2" 0]
["the-years_between_catastrophes" 10]
["the-mortality_5to9" 0.048783]
["the-chance_of_losing_burials" 0]
```

Repetitions: 10

Measure runs using these reporters: `count turtles`

☑ Measure runs at every step

Setup commands: `setup`

Go commands: `go`

Time limit: 200

Fig. 19 BehaviourSpace allows for many automated repetitions of the experiments.

4.6 Model validation

In this chapter the model is validated against standard demographic data to demonstrate that the agent-based stochastic model can reproduce standard models in demography as well as historically documented demographic data. This provides evidence that the inner workings and mathematics of the model are correct. The model is also validated by comparison with a mathematical deterministic model in chapter 6.

The aim of the following experiment is to reproduce published values of mortality, fertility and population growth. For this purpose, the PCS employs mortality data from the model life table “West”, number 1, females (Coale and Demeny 1983, 42) and the fertility rate, GRR=3.16 (c. TFR=6.32) which levels out mortality in this life table in the stationary population case according to Coale and Demeny (1983, 55). When such data are modelled we expect that the populations will neither grow nor decline, i.e. r=0. As the PCS is a stochastic model, the same experiment needs to be repeated multiple times to allow for an average picture of the modelled populations’ reactions. In order to validate the model, the average behaviour of the populations modelled must equal the population prediction based on the deterministic model life table, i.e. if 100 individuals are modelled at year 1 the population must also be of the size of 100 individuals at time 100, or x. All input data of the following experiment are presented in Tab. 4.

The PCS is validated by modelling populations 100 times, each of the size of 100 individuals with the West 1 demographic data for stationary populations and zero population growth. Repeating the experiment more than 100 times could improve the curve fit but seems not necessary in the light of the good results after 100 repetitions. The results after having conducted the model present an average size of the modelled populations over all modelled years of 100.5, and an average size of the modelled populations at year 100 of 101.1. The demographic standard predicts 100 individuals at year 0 and 100 at year 100. The minor difference of 0.5 and 1.1 individuals can be attributed to the small size of the populations modelled and the relatively few repetitions. Fig. 20 shows 20 of the 100 modelled populations (showing all runs obscures the graph) as well as the overall average population sizes per year, and demonstrates that the demographic standard models predictions for mortality and fertility can be reconstructed with the PCS. The erratic effect in the first 30 years modelled can be explained by the randomised age distribution of the initial populations (see chapter 5.5), an effect which is levelled out relatively quickly after one to two generations.

The PCS does not differentiate between mortality rates after the age of 60; this is different from the demographic standard which includes mortality values up to age 85/90. This could have caused the very small offset described above. As the demographic projection can be reproduced well using the PCS it becomes clear that mortality patterns beyond age 60 can be neglected in such a case. A further variable which can be compared regarding this point is the average age at death in the modelled populations (modelled: age 19.3) and the standard projection (expected: age 20) (Coale and Demeny 1983, 55). The choice to stop modelling mortality at age 60 in the PCS leads to a lower age at death by an overall average of 0.7 years than in the standard projection that includes data for ages beyond 60. If, in the future, osteological methods reveal ages in the old adult ranges, the model can be extended to model beyond age 60 years. But the error is acceptable at this stage.

The PCS will further be validated against historical English data, more precisely the age structure of well-documented early modern populations. Using published life table data and fertility data based on baptisms, burials and marriages recorded in 404 Anglican parish registers dating to the period 1541 to 1871 (Wrigley and Schofield 1983; Wrigley and Schofield 1989), 100 populations will be modelled artificially using the PCS, using the approximate age structure recorded by historians. As it is not the intention to reconstruct complex population developments over time, the experiment was limited to the 150-year period from 1541 to 1691; in addition, the PCS does not break down mortality and fertility into annually changing parameters, but instead uses constant values over the complete period. As the total fertility rate and marital fertility ratio varied very little over the period according to Wrigley and Schofield (1983, 168 & 176) and, furthermore, the historian’s life table results also depend on the assumption of constancy, i.e. that “the peculiarities in the age structure of English death rates in the mid nineteenth century were also present in earlier periods" (Wrigley and Schofield 1989, 708), it seems reasonable to model an age structure which remains constant for a few generations.

The fertility and life table data used in the PCS model (Tab. 5) were taken directly from Wrigley and Schofield's research, e.g. the fertility modelled represents TFR=4.3, (Wrigley and Schofield 1983; Wrigley and Schofield 1989), and the age structure against which the PCS results are compared represent the data generated using back-projection methods employed by the historians (Wrigley and Schofield 1989, 216 Fig. 7.4).

In this second validation experiment, the crude age structure of the early modern English population can be reproduced using published fertility and mortality values. Fig. 21 shows the population's average age structure modelled using the PCS in four age groups (black signal) against the average numbers published (red signal). The PCS results are the average of 100 repetitions of populations with the same parameter setup. The period of time modelled is 150 years. Both the modelled and expected adolescent and juvenile age groups are of equal sizes. The initial aberrations before year 50 are caused by the randomised starter generation and the slight difference in the group aged 25 to 59 years can be explained as an effect of the termination of life at age 60 years and over in the PCS.

In conclusion, both model validation experiments show that general demographic dynamics can be reproduced with the PCS, and the modelled populations' internal age structures are similar to age structures projected using different methods based on historical data.

PCS DATA SHEET VIRTUAL EXPERIMENT NO Model validation 1

Research Question	Observed Parameters	Number of Repetitions
Validation of model. Reconstruction of a stationary population using standard demographic data.	Living population size, average age at death.	100
		Time / Duration of Run
		100

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
50	50	0	40				

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
15	45	0.5	2	0.422

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Mortality (qx)	
0-4	0.53
5-9	0.07318
10-14	0.05722
15-19	0.074
20-24	0.074
25-29	0.10262
30-34	0.11561
35-39	0.12588
40-44	0.13336
45-49	0.14078
50-54	0.17886
55-59	0.22187
60+	1

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
-	-	-	-	-	-

Mortality based on:
West 1 Females (Coale and Demeny, 1983, 42)

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 4 Data sheet for model validation against demographic standard life table West 1 Females.

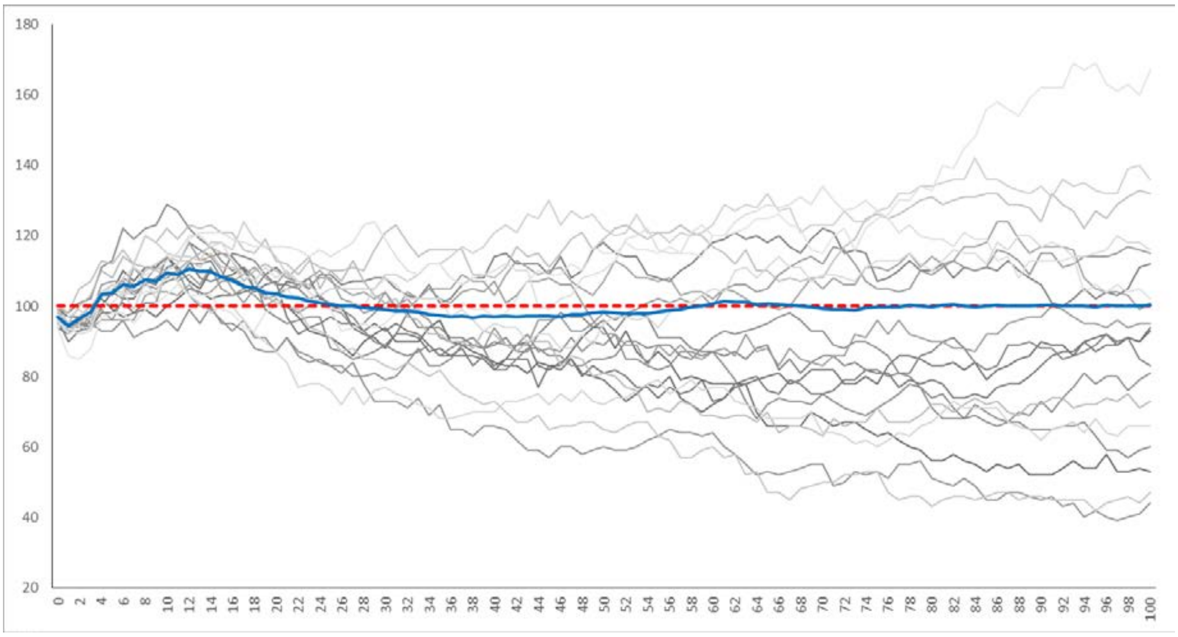


Fig. 20 Validation experiment 1, input: Mortality: West 1, Females (Coale and Demeny 1983), TFR: 6.32, Expectation: r=0. 100 populations of 100 individuals modelled for 100 years. X-axis: years modelled, y-axis: number of individuals, blue: Average living population size per year of 100 repeated modelling runs. Red: Population size 100. Grey: Random 20 out of 100 modelling runs.

PCS DATA SHEET VIRTUAL EXPERIMENT NO Model validation 2

Research Question	Observed Parameters	Number of Repetitions
Validation of model. Reconstruction of population age structure using historical demographic data.	Number of living individuals by age.	100
		Time / Duration of Run
		150

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
50	50	0	40				

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
25	40	0.5	1	0.284

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Mortality (qx)	
0-4	0.2629
5-9	0.0466
10-14	0.0255
15-19	0.0319
20-24	0.0433
25-29	0.0478
30-34	0.0526
35-39	0.0584
40-44	0.0662
45-49	0.0662
50-54	0.0943
55-59	0.1233
60+	1

Artefacts / Diseases						**Mortality based on:**
Male			**Female**			Early modern English life table, level 10 (Wrigley and Schofield, 1989, 714, Tab. A14.5)
Iniage	Prob	X Mort	Iniage	Prob	X Mort	
-	-	-	-	-	-	

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 5 Data sheet for model validation against age structure of early modern English population.

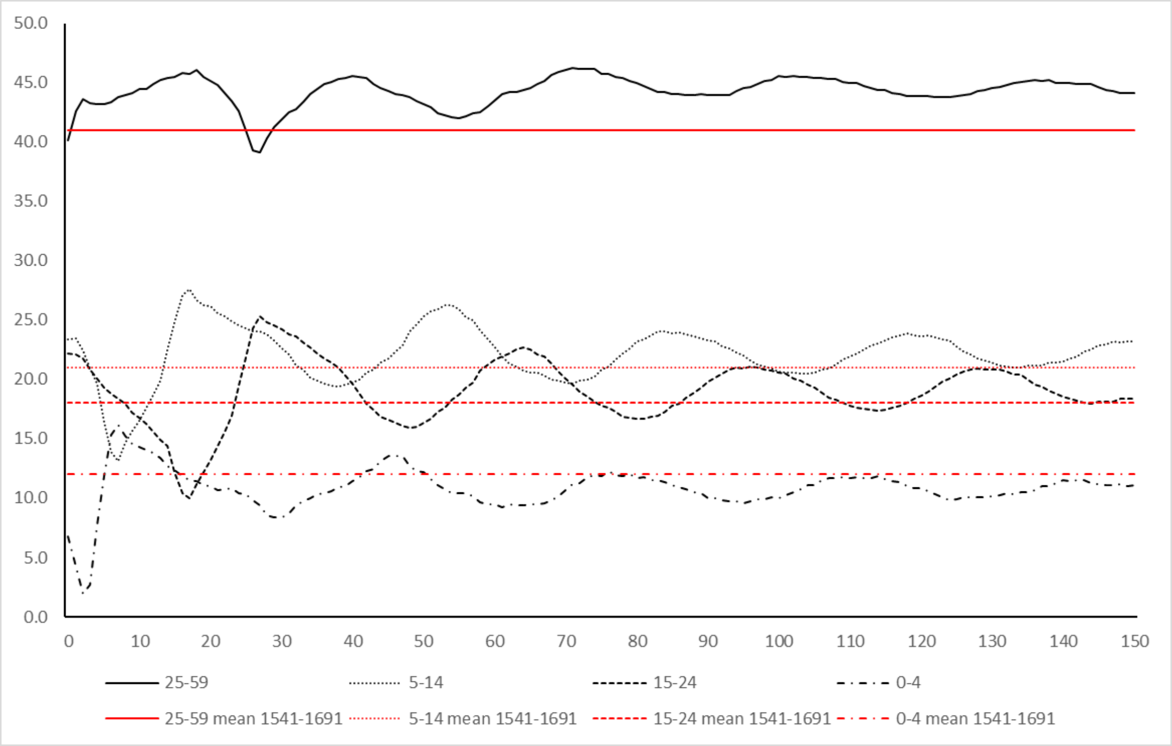


Fig. 21 Validation experiment 2, average age structure of 100 populations modelled for 150 years using early modern English historical data. X-axis: years modelled, y-axis: number of individuals, PCS results (black) for the following age groups: age 25-59 years, age 5-14 years, age 15-24 years and age 0-4 years compared with the average recorded for each age group by Wrigley and Schofield (1989, 216, Fig. 7.4).

5 Parameters and data

This chapter explores the archaeological, demographic and historical data available for PCS models of early medieval populations and their cemeteries. The chapter is closely linked with chapter 3, which focuses on the methodological developments in palaeodemography and the various groups of thought. The emphasis of the following is, however, placed on the actual data instead of the way in which they were produced. This chapter also includes some general models to show the interaction and sensitivities of the parameters.

5.1 Finding a medieval mortality profile

The most basic data needed for the following case studies are the mortality of the modelled populations. As demonstrated in chapter 3, the demographic debate is unresolved, and therefore, mortality data available for PCS models always fall into at least two distinct categories. I distinguish between site-specific mortality models (5.1.1) and the controversial 'realistic' mortality profiles (5.1.2) of medieval populations. I will also separate the chapter into a section on childhood mortality and one on adult mortality. It is further necessary to describe the difference between attritional (general) mortality and catastrophic mortality.

5.1.1 Site-specific mortality profiles

Independent of the recent palaeodemographic debate set out in chapter 3, theoretical (re)assessments of published interpretations based on specific cemetery sites can be based on the published demographic profiles of these archaeological sites, i.e. skeletal or artefact-based age and sex information per individual buried, as the interpretations of these sites are similarly based on the same data. However, demographic data from archaeological cemetery sites rarely correspond to realistic demographic profiles because of general problems in skeletal ageing (see chapter 3). Models of populations based on single sites are more useful for checking site-specific interpretations and their mathematical consistency. When the mortality profiles of two cemeteries are compared, e.g. differences in childhood mortality or higher rates of deaths in an age category attributed to a site-specific event such as a famine recorded in historical sources, we often cannot distinguish between real differences and unknown effects affecting the numbers of excavated individuals.

Site-specific demographics vary a great deal. In Fig. 22 a selection of different mortality profiles used in this thesis are compared in order to illustrate the enormous differences encountered in the literature. Although the generally expected U-shape of human mortality is formed in most cases (Acsádi and Nemeskéri 1970; Chamberlain 2009), extreme variation in mortality per age can be observed between the archaeological sites. Overrepresentation of young adults is common for some of the sites and might be associated with inaccurate ageing methods (see also chapter 3). The small Anglo-Saxon sites of Stretton-on-Fosse (Duering and Tompkins in preparation; Ford 2003; Gardner et al. 1980) and Blacknall Field (Annable and Eagles 2010) show high variability and relatively low childhood mortality. Missing infant burials (Crawford 2007; Lohrke 2004; Sayer 2014), exceptional mortality circumstances in border regions and the erratic behaviour caused by small sample sizes (see numbers for n in Fig. 22) could be responsible for the unrealistic mortality behaviour (Duering and Tompkins in preparation). That the high adult mortality rates of some of the sites are not representative of natural demographic profiles can be explained using a comparison with the Neolithic massacre site of Talheim, Kreis Heilbronn, (Alt et al. 1995; Duering and Wahl 2014a; Duering and Wahl 2014b; Wahl and König 1987; Wahl and Strien 2007; Wahl and Trautmann 2012): Talheim represents an absolute maximum mortality model, as the individuals buried in the mass grave did not die according to their natural mortality pattern but were all killed violently at one point before all of them would have died of natural causes. Adult mortality beyond the massacre site mortality is therefore unlikely to have been caused by natural demographics of populations which buried their dead in a cemetery over time (Duering and Wahl 2014b). The late Alamannic site of Bärenthal was included here to show the mortality pattern of a population where a realistic number of subadults was excavated and adult mortality was raised beyond the norm due to severe living conditions in a challenging landscape – a valley in a mountain region in the north of the upper Danube (Duering 2011a; Duering 2014; Duering and Wahl 2010; Duering and Wahl 2015).

All in all, although methodological differences, problems of ageing skeletal human remains, sample biases, and the effects of small numbers of burials cause enormous differences between mortality patterns, they can be used in PCS models in order to test site-specific interpretations.

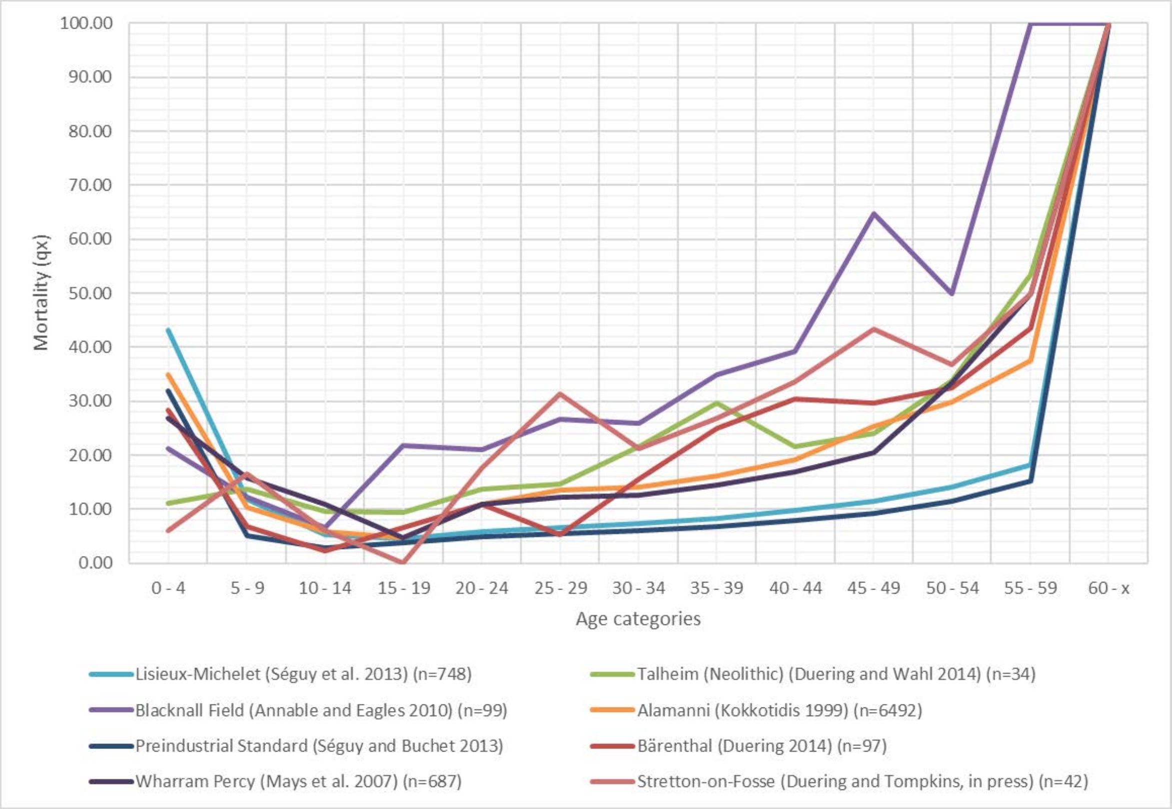


Fig. 22 Site-specific and aggregate mortality in percent per age category. For modelling purposes, all survivors die in the final 60+ age category.

5.1.2 'Realistic' mortality profiles

PCS models based on more realistic demographic data require information about the reliability of the site-specific mortality profiles and comparisons between population profiles of different sizes, periods, regions etc., as well as comparisons with modern demographic models and data. The reliability or representativeness of a site-specific mortality curve cannot be easily assessed. As long as it is not completely impossible to produce a surviving population using the data (e.g. the mortality would be so high that fertility beyond the human biological capacity would be required to stabilise the population) and unless they are not lower than modern demographic profiles (as we believe that pre-modern populations had much higher mortality than modern populations with access to modern medicine etc.), only comparative research holds information about their proximity to the actual demographics of a population (Séguy and Buchet 2013).

Valuable comparative information is contained in analyses of the methods employed, and the ageing methodology has a huge influence on the resulting numbers (Caldwell et al. 1987; Hoppa and Vaupel 2002a; Séguy and Buchet 2013). Comparisons with ethnographic and pre-industrial European mortality profiles from historical registers and anthropological research can further be used to assess the realistic nature of archaeological mortality data under the condition of biological and chronological uniformity (Bocquet-Appel 2008a; Séguy and Buchet 2013). If chronological age and biological age were correlated in a different way in (pre)history, e.g. if hard labour caused a much faster degeneration of the bone surfaces often used for adult ageing (Duering 2014), palaeodemographers would fail to establish correct mortality profiles but would still be able to conduct relative comparisons between populations of the same temporal and regional horizon (Bocquet-Appel and Masset 1982; Bocquet-Appel and Masset 1996; Séguy and Buchet 2013). Again, the palaeodemographer is unable to study the 'absolute' ages at death of a specific population in the archaeological record. As all skeletal ageing methods (as well as the sex determination methods) are based on comparative collections with known information from the 18th and 19th century (i.e. anatomical collections and excavation of individuals for which historical information is still available, e.g. in parish registers or as inscriptions on grave stones), it was soon pointed out that archaeological and anthropological mortality profiles based on skeletal data must stand up to comparisons with historical preindustrial mortality curves and standard life tables calculated by generations of modern and historical demographers (Bocquet-Appel and Masset 1982; Bocquet-Appel and Masset 1996; Bocquet and Masset 1977). Unfortunately, the differences observed between preindustrial standard tables and the skeletal mortality curves were enormous (see also Fig. 21), which initially led to two very different reactions which are the routes of the palaeodemographic camps still present today. Most American anthropologists believed that the demography of prehistoric populations was different from that of more modern populations and that the skeletal ageing techniques were more or less reliable (Howell 1982; Lovejoy et al. 1977). A few French demographers believed the exact opposite: that the actual mortality of the populations must have been different from the initial results based on skeletal ageing methods, and that the palaeodemographic techniques were riddled with method errors (see chapter 3 for an analysis of the development of the methodology). Consequently, they developed calibration methods which adjust the skeletal ages such that they closely resemble preindustrial standards (Bocquet-Appel and Masset 1982; Bocquet-Appel and Masset 1996; Hoppa 2002; Séguy and Buchet 2013). When the ‘Rostock Manifesto’ (Hoppa and Vaupel 2002b) was finally published, the camp using the calibration methods developed in France seemed to be proved correct, supporting conclusions underpinning the uniformity of historical and prehistoric mortality profiles (Séguy and Buchet 2013). As can be observed in the proximity of the mortality profiles of the preindustrial standard and the archaeological population of Lisieux (Fig. 22), the archaeological mortality patterns are pushed towards preindustrial standards whenever calibration methods are employed. Site-specific differences are completely lost in this way. As it is unlikely that all medieval mortality profiles exactly follow the standard curve, the current calibration methods are still not definite.

In summary, the main problems are the following:

A) the often underrepresented infants, leading to divergent opinions on the extent of childhood mortality in the past;

B) the general observation that historical and modern ethnographic populations have much lower adult mortality rates than populations studied using osteological methods. The latter place many more deaths in the young and middle adult age categories.

These two problems are addressed in the following sections.

5.1.3 Childhood mortality

Childhood mortality is generally relatively high in pre-industrial populations (c. 40% to c. 60%), as complications at birth and infectious diseases cause a high percentage of newborn children and infants to die in their first years of life. This is consistent with all populations before the introduction of modern medicines, most importantly the antibiotics which became available to human populations from the turn of the 19th to 20th century (Duering 2014; Duering and Wahl 2015; Gowland and Chamberlain 2002; Kölbl 2004; Mays et al. 2007; Séguy and Buchet 2013). It is a well-known dilemma that some archaeological populations do not have enough burials of infants and children compared with the expectations based on modern demographic data and data provided by historical demography. The 'missing infant' phenomenon is especially pronounced in pre-Christian Anglo-Saxon and Alamannic cemeteries (Crawford 2007; Lohrke 2004; Sayer 2014). Osteological ageing methods are relatively exact in the case of subadult individuals, provided that enough skeletal material in preserved. For instance, dental development and the length of long bones enable particularly precise and accurate age estimates to be made (Lewis 2006; Lewis and Gowland 2007).

5.1.3.1 Calibration methods

To account for the ‘missing’ infants, crude calibration methods (Acsádi and Nemeskéri 1970; Kokkotidis 1999; Kölbl 2004), indices which avoid the problematic age groups (Bocquet-Appel 2008a; Bocquet and Masset 1977) and sophisticated models (Kölbl 2004; Paine and Boldsen 2002; Séguy and Buchet 2013) have been employed in osteoarchaeology and demography:

The crude calibration routine is generally employed by physical anthropologists who studied Alamannic cemeteries. They simply add subadults (either defined as individuals aged 0 to 14 or 0 to 20, with variation between authors as shown by Kölbl (2004) of up to 45% or even 60% compared with the complete population (including adults) to the cemeteries before calculating the life table based on the ‘corrected’ age profile. Kokkotidis, for instance, simply adds 1987 infants aged 0 to 4 years and 98 children aged 5 to 9 years to his overall Alamannic population to account for presumed missing infants and subadults on the assumption that the missing individuals were buried elsewhere or were not interred at all.

5.1.3.2 Analysis of the uncalibrated rates

Other archaeologists and osteologists have started to question this approach (Kölbl 2004). According to them, childhood mortality cannot be the same in all periods and regions. Czarnetzki (1995) even proposes that Alamannic populations might have had much better living conditions than ethnographic populations used as parallels in pristine and rural south Germany and that the c. 23% of subadults excavated (between 13.5% at Munzingen and 33.7% at Kösingen) (Wahl et al. 1998, 338) could be the result of a realistic demographic situation. Similarly, Sayer (2014) argues for a much lower infant mortality rate in Anglo-Saxon populations. He believes that whenever child burials are missing in specific sites, the children might have been buried in larger ancestral burial grounds according to ritual practices which place emphasis on the female family lineage. Under specific circumstances, children might therefore be buried in their mother's ancestral cemetery instead of that used by their father's family. This, he argues, leads to an emphasis of subadult burial in "cemeteries central to tribal identities" linked with the "mother's identity" (Sayer 2014, 78). As the average ratio of subadults in Anglo-Saxon sites equals not more than 23.5% of individuals aged 12 years and over in cemeteries of 100 individuals and over and 14.7% in cemeteries with fewer than 100 individuals (Sayer 2014, Tables 1 and 2), this observation also supports the view that infant mortality is generally overestimated. But most importantly, Sayer demonstrates that infants in early medieval cemeteries must not be analysed as pure demographic numbers "in isolation: they are part of community networks and kinship groups which extend beyond the boundaries of one cemetery and one community" (Sayer 2014, 78). If calibrations crudely equalise different archaeological sites, information can be lost.

5.1.3.3 Natural medieval childhood mortality and parameter confusion

However, palaeodemographers do not believe that childhood mortality was generally low in the early medieval period. They base their point of view on the fact that no ethnographically and historically attested demographic profile exists which shows low childhood mortality rates before the modern demographic transitions following the Industrial Revolution and medical inventions of the last 150 years (Acsádi and Nemeskéri 1970; Andorka 1994; Bocquet-Appel 2008a; Bumpass 1969; Chamberlain 2006; Dalla-Zuanna et al. 2012; De Moor and Van Zanden 2010; Engelen and Puschmann 2011; Grupe et al. 2005; Hajnal 1965; Hajnal 1982; Hollingsworth 1957; Paine and Boldsen 2002; Séguy and Buchet 2013; Shahar 1991; Zhang 2000). It would therefore be surprising to find low childhood mortality rates in the early medieval period as an exception to the rule, which is why Sayer starts his article on Anglo-Saxon childhood mortality thus: "Children and infants are underrepresented in archaeological discovery and it would be unwise to believe otherwise." (Sayer 2014, 78.) A multitude of reasons for the underrepresentation of subadults have been presented and debated (Bello et al. 2006; Crawford 2007; Hoppa 1996; Jackes 2011; Kölbl 2004; Lohrke 2004; Paine and Harpending 1998). This thesis will not enter the debate of weighing the factors mentioned. But an interesting and recurring theme is the influence of Christianity. The change from pre-Christian 'field cemeteries' to Christian churchyards is accompanied by a strong increase in child burials in the archaeological record in both regions, Anglo-Saxon England (e.g. Wharram Percy, Yorkshire) (Lewis and Gowland 2007; Mays et al. 2007; Sayer 2013; Sayer 2014) and the Alamannic territory (e.g. Bärenthal and Berslingen) (Duering 2014; Duering and Wahl 2015; Kaufmann 2000; Lohrke 2004). Sayer (Sayer 2013) noted that 21% to 37% of subadults were found in churchyard burials, whereas only 5% to 17% of subadults were present in contemporary field cemeteries. The demographically representative excavations at Berslingen (Kaufmann 2000) and Bärenthal, both Alamannic churchyard sites where burials and church features were excavated, contained just over 40% of individuals aged 0 to 19 years. This equals 36% of individuals aged 0 to 14 (i.e. 0 to 14.99) years at Bärenthal (Duering 2014).

But what can be considered a realistic level of early medieval childhood mortality based on this complex evidence and is there really any disagreement in the data? A crucial element in assessing comparisons of childhood mortality is to understand that, apart from the different age spans used by authors to describe 'infants' or 'subadults', researchers are confusing two different kinds of demographic parameters. The 'infant mortality' palaeodemographers are talking about refers to something mathematically different from the 'infant mortality rates' Sayer (and most other archaeologists) are using. Kölbl (2004) mentions this important point in her modelling approach. Using the three categories model I propose in Fig. 2 (Chapter 4.1.1) the error can be identified: while the ratio of the numbers of infants in the total buried population (demographically: d_x / $d_{0\text{-}19}$) belongs to the second cemetery category, describing the buried population, 'infant mortality' in demography means the probability of dying in the subadult age categories (demographically: q_x / $q_{0\text{-}19}$) and thereby belongs to the third category of parameters comprised of transitions between the living population and the cemetery. This represents one of the major examples of category error in burial archaeology.

The difference between childhood mortality and the ratio of children’s burials is far from trivial. In a scenario in which the probability of subadults of dying (and their transition from the living population to the cemetery) remains stable, the ratio of subadult individuals in the cemetery can still change as mortality is not the only parameter which affects it. For example, Kölbl (2004) provides detailed information on the effects of population growth, fertility and the size and composition of the starter population, i.e. the population in the first year of the modelled scenario, on the number of children in cemeteries compared with burials of adult individuals.

Her results can be reproduced using the PCS: In the two following virtual experiments, the identical mortality profile (medieval Bärenthal, see Fig. 22) was used over all age groups (Duering 2014), with a mortality rate for individuals aged 0 to 4 years (meaning 0 to 4.99 years) of $q_{0\text{-}4}$=0.284 (28.4%):

In the first experiment (Fig. 23), a population of 100 individuals (50 females and 50 males) was modelled with a Total Fertility Rate (TFR) of 4.1 children per female for 100 years, resulting in a relatively stable population of between c. 70 and 120 individuals in the living group. At the same time, the growing cemetery was recorded over the duration of 100 years. The age structure for females and males can be observed in the bottom two graphs in Fig. 23. In this simulation run, 36 females aged 0 to 4 years and 39 males aged 0 to 4 years were buried in the virtual cemetery (first bars in the two bottom graphs in Fig. 23).

In the second experiment (Fig. 24), a population of the same 100 individuals as in the previous experiment was modelled with an altered Total Fertility Rate (TFR) of 5.1 children per female for 100 years, resulting in a growing population (to 169 individuals after 100 years). Although the exact same childhood mortality rate was employed in both models, the change in TFR results in a strong increase in infants in the cemetery. The ratio of infants aged 0 to 4 years increased to 66 females and 46 males (first bars in the two bottom graphs in Fig. 24).

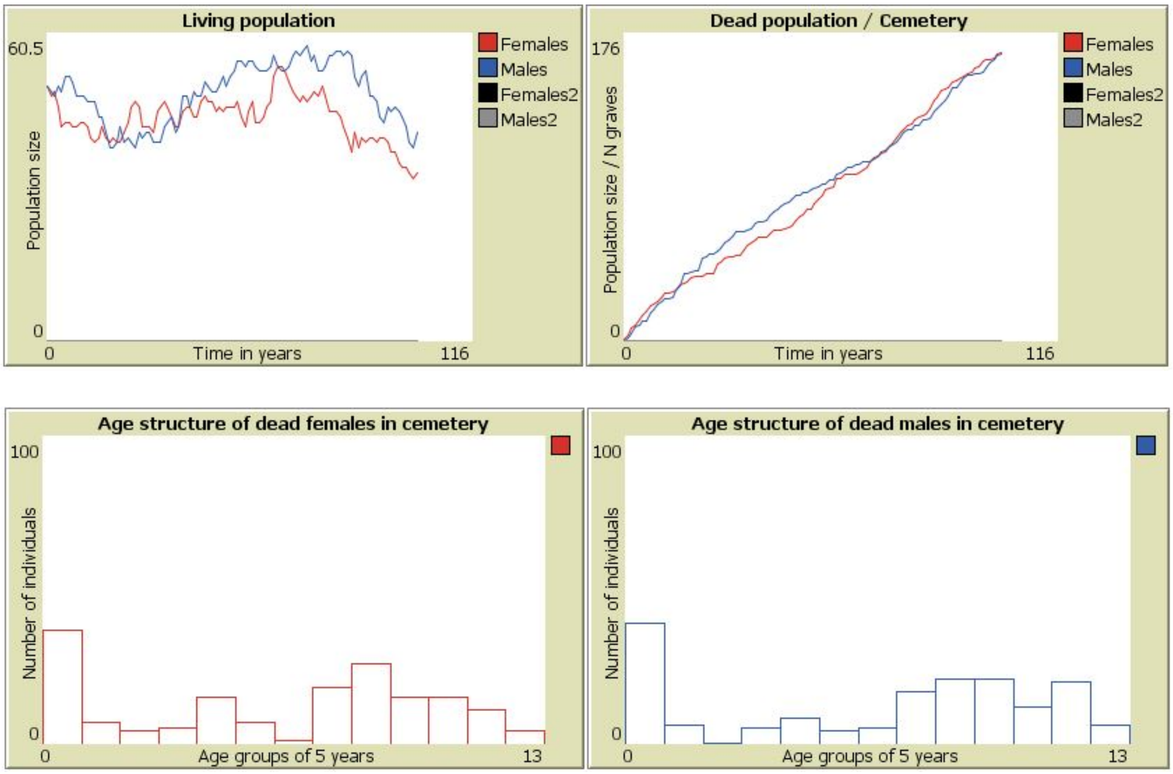


Fig. 23 The influence of fertility on the number of children in the cemetery, experiment one: relatively stable total population of 50 females and 50 males, fluctuating between c. 120 and 70 individuals with a Total Fertility rate (TFR) of 4.1 children per female. 36 females aged 0 to 4 years and 39 males aged 0 to 4 years were buried in the virtual cemetery in year 100.

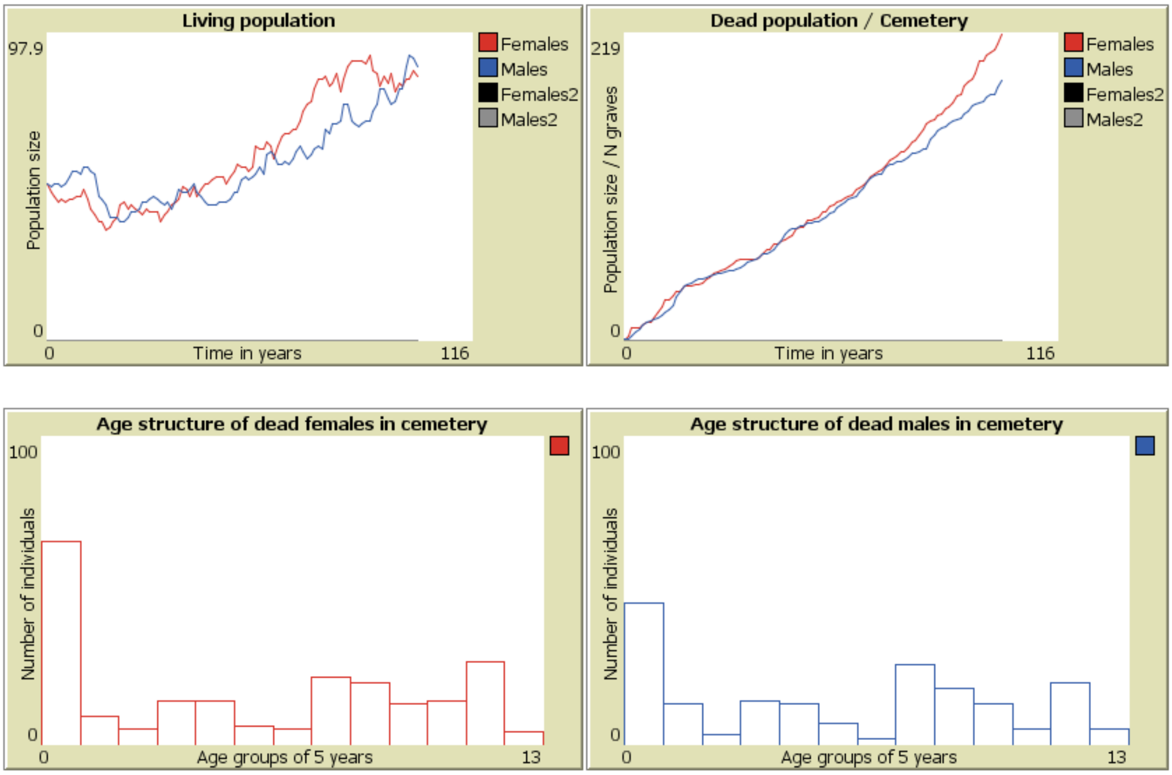


Fig. 24 The influence of fertility on the number of children in the cemetery, experiment two: Growing population, from 50 females and 50 males in year 0 to 82 females and 87 males in year 100, with a Total Fertility rate (TFR) of 5.1 children per female. 66 females aged 0 to 4 years and 46 males aged 0 to 4 years were buried in the virtual cemetery in year 100.

The examples illustrate that childhood mortality is distinct from the resulting ratio of children in a cemetery, as the number of buried infants changed, although the probability of dying (q_{0-4}=28.4%) remained exactly the same. In this case, a slight increase in female fertility (TFR) leads to a considerable increase in children in the living population which, consequently, leads to an increased number of children affected by death. Whenever archaeologists write about ‘childhood mortality’, they need to be careful which of the two parameters they mean. For instance, Sayer (2014), like so many archaeologists, should not have used the term ‘childhood mortality’, as he is talking about the proportion of subadult burials in cemeteries. The crude addition of infants and children described above, practised regularly by physical anthropologists in the Alamannic region (and elsewhere) (Groove 2001; Kokkotidis 1999) since 1970 (Acsádi and Nemeskéri 1970), is based on the same category error. The practice of artificially increasing the ratio of subadults to equal 40% or 60% of the total population likely leads to false results (Kölbl 2004).

The influence of fertility (and growth) on the number and proportion of subadults in the cemetery is not the only, but the strongest (most sensitive) parameter in this context to have been demonstrated in published analyses (Kölbl 2004; Paine and Harpending 1998; Séguy and Buchet 2013). Any parameter which describes the living population (category 1, Fig. 3), e.g. the number of children and fertility rates, as well as the transitional parameters (category 3, Fig. 3), e.g. childhood mortality and data loss, can influence the ratios in the cemetery (category 2, Fig. 3). The parameters influencing the ratio of children in cemeteries studied by (Kölbl 2004) are listed in Tab. 6.

Fertility (limited to varying rates of child-spacing in Kölbl)	The more children are born, the more children are buried in the cemetery.
Average life-expectancy (e_0) of total population	This influences the length of the reproductive phase of females. Low average life expectancy decreases the overall number of children through early deaths of mothers. Kölbl states that this effect can theoretically be stronger than infant mortality in her tests of parameter sensitivity. But this depends on the mortality data used.
Subadult/infant mortality	Ratio of individuals who transition from the living population to the cemetery per year.
Length of stabilisation phase, i.e. the first years/decades of the use of a cemetery	The time interval starting from the initial burial at a site needed for a population to produce stable percentage values. Sites used for short periods of time are more strongly governed by chance than by their average parameter values.
Starter generation: initial population size and composition	The higher the average age of the initial population, the lower the ratio of children buried in the cemetery.

Tab. 6 Parameters which influence the ratio of children in cemeteries, based on Kölbl 2004.

Furthermore, childhood mortality (qx) is itself a highly variable parameter and the values in the standard life tables represent an average over the effects of changing living conditions over time. The theoretically possible variation for the probability of dying between the ages of 0 and 5 in the preindustrial standard have been modelled to a minimum value of 12.8% and a maximum value of 60.7% (mean: 31.69%) (Séguy and Buchet 2013, especially Tab. 9.4). Childhood mortality values beyond these limits are improbable. But the overall variation illustrates that the whole debates over how 'realistic' a certain infant mortality ratio is and whether the living conditions and burial practices of a site are well represented remain probabilistic, albeit not entirely random as Kölbl (2004) suggests. The low ratios of infant burials uncovered in some medieval cemetery sites, therefore, do not suffice to justify dismissing the demographic standards (Séguy and Buchet 2013) and mean values recorded in populations with known age profiles.

In conclusion, for the models used in the following, approach one (1) is simply to utilise the actually published rates of infants and children per site and transform them into a crude childhood mortality rate. Such models will most likely fail to represent the actual demographic circumstances of the studied population and are ultimately only useful for checks of mathematical consistency in a single-site approach.

A second (2) route would be the use of average childhood mortality rates (qx) from the preindustrial standard – if we believe in the relative uniformity of preindustrial and medieval living conditions and, at the same time, entirely devalue site-specific archaeological input. The infant mortality rates are high, with $q_{0\text{-}14}$=43.1% and $q_{0\text{-}19}$=46.9% (Séguy and Buchet 2013, 147, Tab. 9.1), but not at all excessive compared with values calculated for the churchyard sites below. Furthermore, chapter 9 includes a model of the range of possible infant mortality rates and infant burials in a population.

The most promising route (3), which neither ignores the differences between sites nor the realism check against standard demographic information, is to work with skeletally recorded rates of infants and children which are close to demographically probable values. These can be observed in churchyards in both regions from approximately the 8th century, e.g. Bärenthal with $q_{0\text{-}19}$=49.4% and Wharram Percy with $q_{0\text{-}19}$=58.1% (Duering 2014; Duering and Wahl 2015; Mays et al. 2007; Sayer 2013; Sayer 2014). These cemetery populations probably include all (or most) of the children that died over the period the sites were used. Lewis and Gowland state that "of the four sites under study, Wharram Percy in Yorkshire showed the most convincing 'natural' infant mortality profile, suggesting the inclusion of all births at the site (i.e., stillbirths and unbaptised infants)" (Lewis and Gowland 2007, 117). All the previously described problems apply in the case of these sites as well (e.g. Lewis and Gowland also use the term 'infant mortality' in the typically confusing way); however, some of the churchyards provide an intriguing contrast to the earlier pre-Christian cemeteries and field cemeteries.

5.1.4 Adult mortality

Contrary to the problem of childhood mortality (age 0 to 19 years) – where children can be accurately aged using skeletal methods but are missing in archaeological discovery – the issue in the osteoarchaeological study of adult mortality (age 20 to 60+ years) is that all ageing methods are unreliable, although 'natural' numbers of adults are present in cemeteries (Angel 1947; Bocquet-Appel and Masset 1982; Bocquet-Appel and Masset 1996; Hoppa 2002; Hoppa and Vaupel 2002a; Kemkes-Grottenthaler 2002; Konigsberg and Frankenberg 1992; Meindl and Russell 1998; Milner and Boldsen 2012b; Moore et al. 1975). The immense methodological differences are presented above (chapters 3 and 5.1.1/5.1.2) and cause the actual data used in the following case studies to be far from homogenous (Fig. 22). The preindustrial standard published in the most recent handbook of palaeodemography by Séguy and Buchet (2013) shows relatively high infant mortality and much lower adult mortality values than the mortality profiles based on skeletal data (mostly traditional life tables with the exception of Lisieux-Michelet, a profile based on a new 'post-Rostock' demographic method (Hoppa and Vaupel 2002a; Séguy et al. 2013)). The preindustrial standard is based on a sample of 292 traditional historical and ethnographic life tables of "farming populations, (with) little urbanisation, no modern medical care" (Ledermann 1969; Séguy and Buchet 2013, 117-118) and index estimator methods (Bocquet-Appel 2008a; Bocquet and Masset 1977), and was also compared with a modern African standard (Brass 1975; Séguy and Buchet 2013, 114-162). The large skeletal samples of Wharram Percy (N=687) (Mays et al. 2007) and the Alamannic population sample, an aggregate of 6,492 Alamannic inhumations (Kokkotidis 1999), are very similar, but show generally higher adult mortality rates than the preindustrial standard. This general offset is caused by the methodological differences described in chapter 3: the French mortality profile was calibrated against the known-age standards, whereas Wharram Percy and the Kokkotidis data are based on traditional life tables using individual skeletal age estimates. In this thesis, both the traditional individual skeletal age estimates entered in life tables and the new calibrated aggregate population mortality curves are employed and compared.

5.1.5 Attritional versus catastrophic mortality

The interest in Black Death cemeteries dating to the later medieval period has led to the analysis of a further kind of mortality: catastrophic mortality (DeWitte 2014). In contrast to the natural 'attritional' mortality (Chamberlain 2006; Margerison 1997; Margerison and Knüsel 2002; Waldron 2001), which includes all possible causes of death in the daily lives of people, e.g. represented in standard mortality curves (see above), the term 'catastrophic mortality' refers to peaks of the probability of dying at specific single points in time or reoccurring irregular intervals. Some cemetery sites and mass burials include the victims of such events or a mixture of individuals deceased of 'attritional' causes and epidemics, war or natural disasters. Historical documents often provide the information necessary to identify the special character of such sites. In the absence of historical accounts, or to test and corroborate historical analysis, genetic analyses of pathogen DNA in bone samples can reveal epidemic events (Bos et al. 2011; Margerison and Knüsel 2002; Raoult and Drancourt 2002; Roberts and Buikstra 2003; Roberts and Council for British Archaeology 2009; Roberts and Manchester 2005; Twigg 2003).

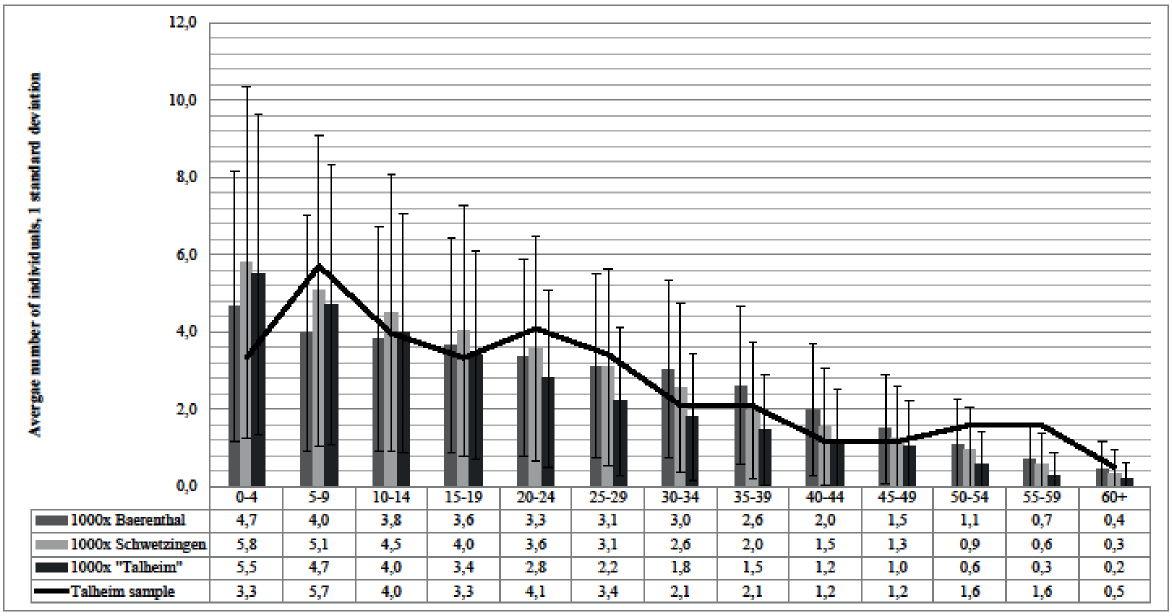
Additional information about catastrophic events is further contained in the age and sex profiles of the buried individuals. Mass graves which contain soldiers follow a simple osteological signal representing mostly males roughly aged 16 to 40 years (Knüsel and Boylston 2000; Loe et al. 2014; Wahl 2012).

Massacres sites of families and communities, on the other hand, often include all sexes and ages. Their age profile, however, does not follow the usual U-shaped mortality curve, with high infant and high old adult probabilities of dying. Instead, they exactly conserve the pyramid-shaped living population structure when all the individuals present at one point in time are violently killed (Alt et al. 1995; Meyer et al. 2015; Wahl 2012; Wahl and König 1987; Wahl and Strien 2007; Wahl and Trautmann 2012).

Epidemics, such as those caused by the Bubonic Plague and the more virulent Pneumonic Plague lead to indiscriminate death in a large part of the population (Aufderheide and Rodríguez-Martin 1998). However, as a considerable number of individuals also survive these events (generally more than 50% of the population), the age profile in mass burial sites and cemeteries does not reflect exactly the population profile of a living community (Margerison and Knüsel 2002). Instead, such sites form an age at death profile lying somewhere between the living population structure and the ‘attritional’ natural demographic mortality pattern of the population. The main characteristic of these epidemic profiles are an increase in overall mortality coupled with a proportionally stronger increase in adolescent, young adult and middle adult age categories if the disease strikes irrespective of age (Margerison 1997; Margerison and Knüsel 2002). However, many epidemic diseases hit the weakest parts of the population, the children and the elderly, more severely than they do men and women in their prime (Aufderheide and Rodríguez-Martin 1998; Ortner 2003; Roberts and Buikstra 2003; Roberts and Cox 2003; Roberts and Manchester 2005; Waldron 2009). It is therefore theoretically possible to detect pathogen-specific epidemiological and demographic signals in the age-at-death and mortality profiles of archaeological burial sites.

The concept of attritional mortality has recently received criticism, as the dynamics of hundreds of years of small and large epidemics, wars, disasters and famines have all contributed their specific alterations to the overall mortality profiles in most archaeological cemetery sites (Atkin in preparation). It is almost impossible to distinguish the causes of death in the case of most individual burials and, therefore, the overall age at death profiles in most cemeteries can only be analysed according to attritional versus catastrophic mortality if additional information is available, e.g. trough pathogen DNA studies or palaeopathological research, or if the age structures found are exceptionally characteristic of one or the other.

The PCS can be used to analyse different kinds of catastrophic mortality as possible scenarios for specific sites. An example for this is the model of the Talheim massacre which was virtually repeated 250,000 times using the PCS and the average massacres containing complete Neolithic living communities could be shown to exactly reproduce the excavated age at death profile. Thus, cases of pure catastrophic mortality do exist in the archaeological record (Fig. 25) (Alt et al. 1995; Duering and Wahl 2014a; Duering and Wahl 2014b). Such cases, however, are rare and it is possible that some (or all) of the early medieval cemeteries analysed in this thesis contain an unknown mixture of (different kinds of) natural and catastrophic signals. It is therefore reasonable to define the mortality patterns encountered in these sites as the aggregate of all causes of death, including single and reoccurring plagues, famines, raids, epidemics etc.



	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60+
■ 1000x Baerenthal	4,7	4,0	3,8	3,6	3,3	3,1	3,0	2,6	2,0	1,5	1,1	0,7	0,4
■ 1000x Schwetzingen	5,8	5,1	4,5	4,0	3,6	3,1	2,6	2,0	1,5	1,3	0,9	0,6	0,3
■ 1000x "Talheim"	5,5	4,7	4,0	3,4	2,8	2,2	1,8	1,5	1,2	1,0	0,6	0,3	0,2
— Talheim sample	3,3	5,7	4,0	3,3	4,1	3,4	2,1	2,1	1,2	1,2	1,6	1,6	0,5

Fig. 25 The ‘pure’ catastrophic age at death profile of the massacre of Talheim and 250,000 modelled massacres of complete living populations, from Duering and Wahl (2014b, Fig. 9).

5.2 Fertility and marriage patterns

In this section presents social and biological fertility parameters from historical and archaeological populations. Firstly, an overview of modern and historically attested data will be given. Based on these data, I will describe various fertility estimation methods in human osteology and bioarchaeology. My choice of fertility parameters (also in the PCS) is selective as I only focus on those which can be either directly assessed or indirectly estimated in archaeological populations.

The PCS uses only four parameters to control female fertility (see chapter 4.1.1.3): the age in years at which a female theoretically starts to bear children (menarche), the age at which she stops giving birth to children (menopause), the delay time in years between each birth (child-spacing) and the general aggregate remaining probability of each female to giving birth at any possible point in time during the modelling runs. The initial and final ages depend on natural human biology and can best be estimated using the historical and modern demographic literature as well as indirect modelling with the PCS. The child-spacing value can be estimated using bioarchaeological methods which will be described below, and the residual probability mainly represents an indirect value taken from models which balance mortality and fertility. All these parameters contain biological and social elements.

The role of males in a population's fertility is limited. Trends in fertility over time have changed alongside the social and economic transitions of the lives of women (Engelen and Puschmann 2011; Hajnal 1965; Hajnal 1982). The PCS therefore models reproduction based on female parameters and only checks whether males of a reproductive age are generally present in the living population. This reduces parameter numbers and the complexity of the system without impairing the reliability of the PCS results.

At this stage, the model does not include an age-dependent fertility profile for females. Female fertility is relatively low just after menarche (age 12 years onwards) and peaks at c. age 25 years, after which the probability of reproducing declines again until menopause between ages 40 and 50 years (Fig. 26) (Frier 1994; Grupe et al. 2005; Hoem et al. 1981). That the probability of reproducing is evenly distributed over the complete fertile period of females in the PCS might be a weakness, but as we cannot estimate this fertility parameter in the early medieval archaeological record and to simplify the modelling, it was excluded here. Interesting future updates of the PCS could be based on the inclusion of this parameter, e.g. in order to test the uniformity of female fertility over large time spans in human prehistory.

5.2.1 Fertility in historical demography

Parish registers, lists of baptisms, the records of the upper classes and comparisons with contemporary demographic transitions, e.g. in Africa, Arabia, India and China, allow historical assessment to be made of reproduction rates in past populations, especially through the method known as ‘family reconstitution’ which combines data available for each individual in the historical record to establish numbers for birth, death, age etc. Most of the information is relatively reliable in the late medieval and early modern periods, although the historical data are biased towards urban populations, males are usually better represented in the data and some social strata of the populations as well as unbaptised children and other individuals on the social periphery, are among the excluded (Ackerman 1976; Andorka 1994; Bumpass 1969; Cain 1983; Coale 1992; Dalla-Zuanna et al. 2012; De Moor and Van Zanden 2010; Dyer 2001; Engelen and Puschmann 2011; Frier 1994; Gies 1987; Gilchrist 2014; Hajnal 1965; Hajnal 1982; Hollingsworth 1957; Kelly 1975; Kelly and Ó Gráda 2012; Laslett 1971; Lelis 2003; Lesthaeghe 1971; Nath et al. 1993; Reynolds 1994; Rheubottom 2000; Richard 2004; Schofield 1985a; Schofield 1985b; Shahar 1991; Sprague 1987; Westoff 1992; Wrigley 1997; Wrigley and Schofield 1983). The historical demographic information relevant for early medieval England, such as the information recorded in the Domesday Book cannot be used to reconstruct fertility because of the focus on male-dominated legal statuses, such as heads of households and taxpayers. Data on women and children do not appear in historical documents in a form which is useful for the purpose of fertility estimation until the late medieval and the early modern period (Gilchrist 2012; Hinton 2013; Shahar 1991; Woods 2007).

As fertility estimates are based on data about females and children, even some historical estimates are problematic. For instance, it is often unclear whether the complete population has actually been recorded, a problem which is accentuated in dynamic communities with high rates of migrants. Additionally, documents might have been partially been lost or are hard to transcribe, and the age information given can be dubious because of high rates of illiteracy and innumeracy in such populations (Schofield 1985b; Wrigley 1997). Ages in historical demography can be unreliable, and as this thesis requires comparisons with rural agricultural communities, the uncertainty regarding some of the data is even stronger. Studies of modern pre-industrial populations in Europe, as well as research in areas of contemporary populations which currently make the transition from the preindustrial state to a more industrialised modern state, reveal extreme rates of innumeracy. Historical demographers have identified a problem called ‘age-heaping’, a tendency to round up and round down ages in written documents whenever the actual age is unknown. Ages ending in zeros and fives are listed in unnaturally high quantities compared to other numbers, which allows for a mathematical test of ‘age-heaping’ (A'Hearn et al. 2009; Baten et al. 2010; Földvári et al. 2012; Kaiser and Engel 1993; Pardeshi 2010).

Of further interest is the discussion of whether prehistoric and modern populations practised some measures of birth control and whether they are visible in the demographics of the populations. Again, two opposing positions exist: Riddle sees a multitude of evidences for contraception (Riddle 1991; Riddle 1992), whereas Frier (1994) argues that family planning (in legitimate family relations) was not practised to any great extent in pre-industrial populations as the demographic curve of the Roman Egyptian population he analyses shows no sign of shortened fertile periods for women, i.e. a decision to stop bearing children when a woman had already raised ‘enough’ which would result in a drop in fertility much earlier in women’s lives than at the age of menopause. Instead, Frier (1994) argues that the studied population exactly represents a natural fertility pattern in which females give birth to children throughout the complete fertile period between the ages of 12 and 50 years (Fig. 26). Consequently, even if a certain amount of contraception was practiced, especially controlling illegitimate births, birth control was not so common that it left any demographic signal. Fertility in populations dating to before the demographic transitions (for instance early medieval Anglo-Saxon and Alamannic populations) shows a standard natural pattern (Frier 1994; Gilchrist 2012).

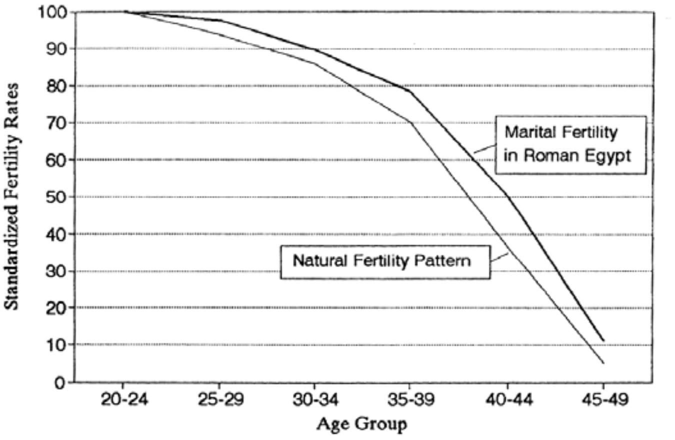


Fig. 26 Marital fertility rate in Roman Egypt compared with the natural fertility pattern, from Frier (1994).

In that case, how did premodern populations, at least unconsciously, control the birth rate? The age at which females marry and start to give birth to children is a fertility parameter with considerable impact as it constricts the most fertile years of a female's life-span (Engelen and Puschmann 2011; Gilchrist 2012). The historical demographer, John Hajnal, first discovered that there were two different demographic fertility regimes in European populations based on two different household formation systems: agricultural patrilocal households with early marriage, and (urbanised) post-transitional household systems with later ages at first marriage for females. He called the second system the 'European marriage pattern'. (De Moor and Van Zanden 2010; Hajnal 1965; Hajnal 1982). Chapter 6 uses both the PCS and a mathematical deterministic model to examine whether early medieval populations in the archaeological record indeed fall into the first category.

The most convincing model of fertility for the early medieval period is unlikely to have deviated much from the general fertility pattern described for agricultural populations in the historical demographic literature (De Moor and Van Zanden 2010; Hajnal 1965; Hajnal 1982; Kelly and Ó Gráda 2012). The fertility pattern can be found in pre-transitional populations all around the world, and there have not been many exceptions to the norm (Engelen and Puschmann 2011). It is therefore reasonable to model early medieval populations using general fertility from such studies in the demographic literature. In the following graphs, pre-transitional and transitional population data are presented, firstly, on the TFR (total fertility rate) and, secondly, on the age at which females marry and start their reproductive phase (Fig. 27 and 28). While these data from the Arab world are surely different from the early medieval situation, they provide the basis for a crude reality check of modelled results. Data of European fertility during the transitions in the 19th and 20th centuries was analysed by Lesthaeghe (1971). The transitions are all relatively similar all over the world (Engelen and Puschmann 2011), and even urban southern European medieval and renaissance populations (Dalla-Zuanna et al. 2012) which do not follow Hajnal's 'North European Marriage Pattern' (Hajnal 1965; Hajnal 1982) are very similar to the pre-transitional situations.

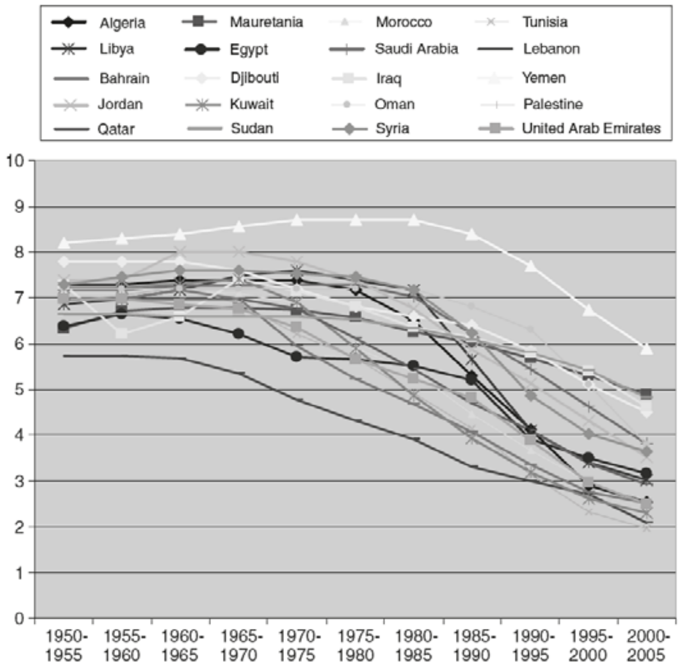


Fig. 27 The development of the Total Fertility Rate (TFR) in the Arab world, from Engelen and Puschmann (2011, Fig. 2).

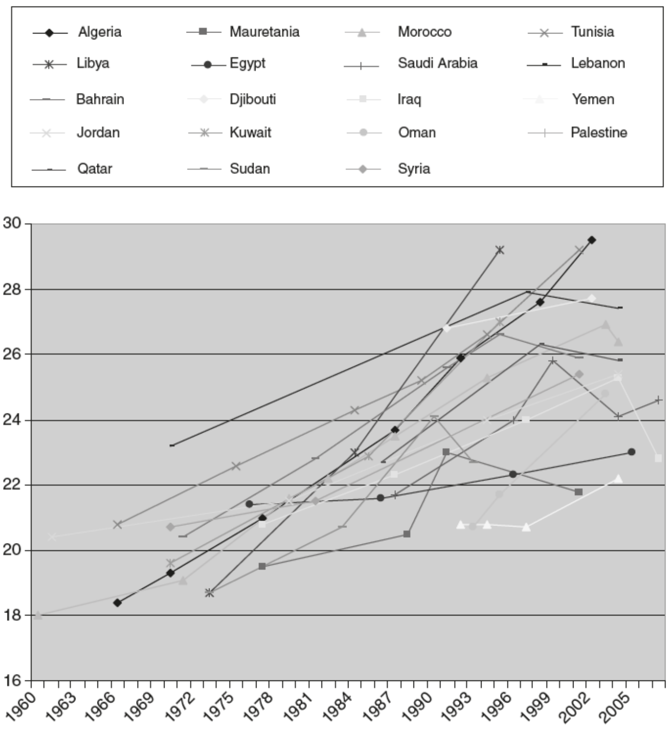


Fig. 28 The singulate mean age at marriage of women in the Arab world, from Engelen and Puschmann (2011, Fig. 3).

5.2.2 Fertility in bioarchaeology

Fertility is usually modelled indirectly using formula approaches in bioarchaeology, but osteological changes in the pelvis were also used to calculate the number of births per female individual – a highly problematic procedure. Linear enamel hypoplasia, a signal of stress experienced by the human organism, is employed to assess breastfeeding and weaning habits which are directly related to the child-spacing parameter. This was also criticised by subsequent research (Smith 2013). Weaning age is further estimated using stable isotopes.

5.2.2.1 Indirect fertility estimates based on mortality

Sayer and Dickinson (2013) employ female mortality curves to assess whether the initial, most dangerous, births took place as early as in females' mid-teens or later. They base their argument on the mortuary profile of 374 female individuals from 46 cemeteries published by Stoodley (1999). As over 38% of females in the sample fall into the age category of 20 to 30 years, Sayer and Dickinson (2013, 293) argue that this shows that females were exposed to higher risks during that period in their lives because of maternal mortality. This allows them to place the most risky initial births of females living in the Anglo-Saxon period in the age category 20 to 30 years. Consequently, they argue for a late marriage and onset of female reproduction in Anglo-Saxon populations. I will comment on this finding in detail in chapter 6. At this point, the question must be raised of which problems arise when fertility estimates, a Category 1 parameter describing the living population (see chapter 4.1.1, Fig. 2) are based on mortality, a Category 2 parameter describing the cemetery; especially, as the overall numbers of children per female are also estimated in such a way in archaeological research.

In the seminal osteological analysis of the human remains of the cemetery of Wharram Percy, Mays et al. (2007), for instance, calculated the average number of deceased children per deceased female and thus estimated the average fertility rate of the population at eight children per female. This value cannot be reproduced using the PCS, which produces stationary populations at a TFR of only 5.1 (see chapter 6). As fertility rates by country collected by the World Health Organisation (2013) only exceed TFR=7 in extreme cases, i.e. in developing countries with extreme growth rates, it is dubious that eight children per female represents a realistic fertility regime in the case of relatively static Wharram Percy. In the late Alamannic site of Munzingen, Stadt Freiburg, the average number of children was also estimated as eight (Burger-Heinrich 2001, 365) using a method developed by Drenhaus (1976) based on traditional calibration to account for missing infants (for the problems involved in the traditional method used to account for missing infants, see chapter 5.1.3). Burger-Heinrich concludes that if eight children were born per female in total, an average of four to five children survived using a value of 45% of childhood mortality (Burger-Heinrich 2001, 365). Another formula for estimating fertility is published in Henneberg (1976). The average number of children per female in the Roman cemetery of Stettfeld was calculated for the four phases of the site. The number of children declines from c. 4 to 2.5 between the temporal phases 1 to 4 based on this estimation method (Wahl and Kokabi 1988, 143). In the late Alamannic churchyard of Bärenthal Henneberg's formula resulted in c. four children per female, which, interestingly, was consistent with the output of the PCS (Duering 2014, 444-448). A variety of more recent estimator methods also exist (Brass 1975; Paine and Harpending 1998; Robbins 2011).

All these indirect ways of estimating fertility based on the age-at-death patterns of archaeological populations share the same shortcomings, e.g. sample bias, the quality of the mortality data available or the requirement for static populations (Brass 1975; Paine and Harpending 1998; Robbins 2011). Some of the problems also apply when using the PCS to straightforwardly measure the number of children needed to balance the death rate of a population with a known mortality profile. However, the possibility offered by the PCS of testing a variety of static scenarios and change parameters according to additional information makes the programme a more powerful tool for estimating fertility indirectly than the traditional static formulas which are always limited to standard scenarios (Brass 1975; Drenhaus 1976; Henneberg 1976; Paine and Harpending 1998; Robbins 2011).

5.2.2.2 Morphological methods

A method that is more a curiosity than an actually working method is sometimes applied by physical anthropologists to estimate the number of new-borns which passed through the birth canal in the female pelvis. Scars which are reported to form at the back of the pubic bone during parturition (the separation of the cartilage of the pubis symphysis, which softens in the later phase of pregnancy) are recorded and sometimes counted (Bergfelder and Herrmann 1980; Bertino and Bertino 2015, 451; Cox and Scott 1992). The number of parturition scars has even been employed in palaeodemographic fertility analysis as a way to count the number of births experienced by female skeletonised individuals. However, the aetiology of the scars is unknown and a recent study demonstrates what has long been suspected by bioarchaeologists (Cox and Scott 1992): “[that] the term ‘parturition scarring’ should be revised to reflect its non-connection with parity status and that future investigations should examine musculoskeletal interactions based on body and pelvic size variation that affect the presence of such scarring in males” (Decrausaz 2014, iv). Parturition scars should not be employed in skeletal demographic analysis to estimate human fertility.

A more widely accepted method is the assessment of dental linear enamel hypoplasias connected with the age of weaning. The position of the stress marker on an individual’s tooth is retained later in life and can be used to estimate the age at which the line was formed in comparison with standard growth charts (Goodman and Rose 1990; Hillson 1996; Suckling 1989). Weaning is reported to represent a stress period for a child’s organism (nutrition, immune system, infections), and the enamel formation of a child is disrupted because of these unspecific factors (Lewis 2006). While breastfeeding acts as a natural contraceptive, it is not an absolutely secure method of birth control, but instead leads to a statistically significant reduction in the probability of conception (Tietze and Lincoln 1987). Breastfeeding and weaning have a strong effect on the time interval between births and in addition to the c. nine months of pregnancy, bioarchaeologists have estimated the child-spacing interval using liner enamel hypoplasia. There is a lot of uncertainty in the method because different kinds of systemic stress might have been responsible for the formation of the stress line, because of the individual uncertainty involved in measuring the age using tooth formation charts, and because of the lack of close connection between stress line, age of weaning and the contraceptive effect of breastfeeding (Boldsen 2007; Boldsen and Schaumburg 1990; Suckling 1989). An overview of the problems associated with using enamel hypoplasia to assess weaning age can be found in Lewis (2006, 104-107). However, it seems a promising route for further research to assess whether stable isotope nitrogen values used as indicators of weaning age (see below) and enamel hypoplasia stress merely coincide between ages 2 and 4 years in most human remains or whether they contain any demographic information. For such studies, the relevant data should still be collected when human remains are studied.

5.2.2.3 Stable isotopes and weaning age

The stable isotopes used to study the age of weaning include nitrogen, oxygen, strontium, calcium and zinc (Britton et al. 2015; Fuller et al. 2006a; Fuller et al. 2006b; Grupe et al. 2005; Grupe et al. 2013; Hedges 2011; Lewis 2006; Mays et al. 2007). It shall suffice to describe the most widely used trophic level shift appearing when young adult female and infant nitrogen stable isotope ratios are compared. As long as an infant is being breastfed, its trophic level shifts to one level above that of its mother as it consumes the tissue of the mother in the form of breastmilk. This shift can be detected and compared with the sub-adult ages estimated osteologically, enabling the average weaning age of a population to be worked out. The method has been employed successfully in many archaeological populations, e.g. the Yorkshire population of Wharram Percy (Fuller et al. 2003; Mays et al. 2007) and the early medieval town population of Schleswig in north Germany (Grupe et al. 2013). The weaning age estimated using stable isotope studies can be used as a proxy for the child-spacing parameter in the PCS although it should be noted that weaning is a process rather than a single event. Most of the European medieval data indicate that weaning took place roughly between the ages of 1.5 and 3 years. Weaning ages beyond 3 which are sometimes recorded in anthropological and prehistoric populations have not yet been reported in the case of medieval populations (Fuller et al. 2003; Grupe et al. 2013; Lewis 2006; Mays et al. 2007). New methods of sequential sampling of teeth promise more information about the weaning habits of archaeological population on an individual level and seen as a process rather than a single event (Eerkens et al. 2011; Henderson et al. 2014; Tsutaya and Yoneda 2013).

5.3 Stability, growth and dynamics

Historical demography has long focussed on large-scale models studying the interaction of wages, economic developments and population numbers. In these first models, human population size is mainly characterised by population limits defined by the economic regime and crises whenever populations exceeded these maxima (Hatcher and Bailey 2001). But mortality is not the only parameter which defines population size and dynamics. Late medieval and early modern (1540-1800) demographics seem to be closely linked with developments in wages and prices, both at aggregate and parish level. Kelly and Ó Gráda (2012), for instance, have combined the iconic opuses of Mathus (the preventive check) (Malthus 1992 (based on 1803)) and Hajnal (the European marriage pattern) (Hajnal 1965; Hajnal 1982), and tested the link between birth rates and economic developments in 404 English parishes. They demonstrate statistically that a preventive check exists, “defined as a short-run response of marriage and births to variations in living standards” (Kelly and Ó Gráda 2012, 1015). Fertility can change quickly due to circumstances and seems even more dynamic than aggregate mortality in human populations. Short-term peaks in mortality due to catastrophic events should not be underestimated in altering age at death distributions, but fertility has a stronger impact on population sizes and age-at-death structures in cemeteries than mortality because it has constant and lingering effects compared to single famines, attacks, natural disasters etc. (Cain 1983; De Moor and Van Zanden 2010; Kelly and Ó Gráda 2012; Lesthaeghe 1971; Wood et al. 2002; Wood et al. 1992). However, it should also be noted that the two parameters are linked, as marital mortality affects fertility by shortening the reproductive phase of females (Kölbl 2004). This strengthens the case for modelling demographics using complex models such as the PCS, where the interactions between parameters do not have to be estimated beforehand but can instead be tested. In the chapter “Should Population Dynamics be Modelled by Fertility or by Mortality”, Séguy and Buchet (2013, 111-112) argue that the observation that fertility is dynamic does not imply that palaeodemographers should assume severe mortality crises and high infant mortality rates could not outweigh fertility, especially as “the old demographic regime did not enable populations to achieve very high growth rates over the long term”. Although Séguy and Buchet (2013) offer age-at-death distributions for their preindustrial standard mortality curve for growth rates between -3% to +3% by 0.25% increments, they state that that “demographic situations affecting preindustrial populations was much narrower” (119-120). Benedictow (1996, 181-182) estimates the annual growth rate of Scandinavian medieval populations between A.D. 750 and 1300 at 0.2%, which results in a population three times larger in 1300 compared to the population in 750. Hedges (2011, 81) estimates that annual growth rates of c. 1% could account for the population growth in the first centuries in England after the collapse of the Roman Empire. The relatively low overall growth rates in human prehistory and history up to the development of urban centres and the high growth rates induced by the Industrial Revolution are well-known and long established facts (Acsádi and Nemeskéri 1970; Bocquet-Appel 2008a).

It is, however, different when single small agricultural communities are concerned. While the overall aggregate probably remained stationary in premodern demographics, the strength of dynamics at the small scale are an unknown. Disasters, changes in living conditions and crises in geographic corridors affected by war and economic instability, etc. might have had a strong effect on populations of the size studied in archaeological discovery (Duering and Tompkins in preparation). For example, although the statistical mean of parishes reacted to changes in living standards in Kelly and Ó Gráda (2012), some parishes did not adhere to the majority trajectory. Some populations even profited from crises in adjacent parishes and followed inverse trends. These small-scale effects are on the level of the archaeological sites discovered in the early medieval period, and wisdom established on aggregate population behaviour probably does not apply in most of our samples. In dispersed small populations of sizes of one or two households, often well below the average size of Mucking with roughly 100 individuals (Hamerow 1993; Hamerow 2002; Hamerow 2010; Hamerow 2011; Hamerow 2012; Härke 1997; Herlihy 1985; Hirst and Clark 2009; Zimmermann et al. 2009), the effect of chance and local events can lead to short-term growth and collapse well beyond the viscous aggregate population reactions of complete countries, and even well beyond the rates observed in developing countries today (Lopez et al. 1999; World Health Organisation 2013); e.g. the 100% population collapse in Neolithic Talheim (Duering and Wahl 2014b) has nothing to do with the overall growth rate of LBK populations in south Germany during that period, and although the single archaeological signal documents disaster, the overall populations might have grown. This is the typical difference between macro-models and micro-models (Hatcher and Bailey 2001), and due to the tendency of archaeological information to fall into the latter category, the nature of site-specific and community-specific demographics needs to be modelled using individual-based finely grained systems. In chapter 7, historical data on the development of the population size in the parishes of South Oxfordshire are utilised in a PCS model to assess whether internal population growth and decline can account for the changes observed between c. A.D. 1000 and 1800.

5.3.1 Detecting growth using palaeodemographic information

Researchers using traditional osteoarchaeological approaches have tried to detect growth in age-at-death distributions by calculating the living population pyramid (Acsádi and Nemeskéri 1970). The results have then been compared with modern demographic information, presented as growing pyramidal structures with many infants and children versus stagnating onion-shaped populations with an excess of adults and elderly people – graphs we all know from projections of the over-ageing modern Western population (Kokkotidis 1999; Wahl and Kokabi 1988). Unfortunately, the ratio of subadults and young adults compared with old adults and the elderly in a population is also used in life table calculations to project mortality, based on the assumption that the population remains static (neither growth nor decline, nor migration) over the whole period of its use (Moore et al. 1975; Williams 1992). Similarly, the preindustrial standards only work under the assumption of stable growth rates (Séguy and Buchet 2013). Consequently, it is impossible to decide whether the high numbers of deceased transitioned from the living population (Category 1) to the cemetery (Category 2) = because of an excess of young individuals in the living population or because of an increase in mortality of the same age category in the population (Cox et al. 2011; Johansson and Horowitz 1986; Pinhasi 2007). Additional information is required to decide which of the two effects is responsible for the age-at-death structure in a cemetery. Shifts in the numbers of graves per phase can give some hints, as well as more general indicators of growth.

Indirectly, the number of graves per period or phase in a cemetery is typically used to assess population development. Although a majority of unfurnished graves cannot be dated and might well bias the numbers uncovered in phased graves, and although the uncertainty of the absolute dating methods is well-established, artefact and radiocarbon dating are employed in order to assess demographic change (Ade et al. 2008; Alt et al. 2014; Annable and Eagles 2010; Bayliss et al. 2013; Brookes 2007; Donat and Ullrich 1971; Ford 2003; Grupe and Vogel 1997; Grupe et al. 2013; Hills and Lucy 2013; Hirst and Clark 2009; Kokkotidis 1999; Mays et al. 2007; Obertová and Wahl 2007; Richardson 2005; Sattenspiel and Harpending 1983; Sayer 2010; Séguy and Buchet 2013; Séguy et al. 2013; Steuer 1988; Wahl and Kokabi 1988). As already mentioned in the beginning, the number of burials per phase does not necessarily reflect the number of individuals in the living population, as either population growth or raised mortality levels can lead to increasing numbers of graves in a cemetery.

A theoretical experiment using a standard medieval population profile demonstrates this erratic effect. The first population modelled increases over the complete period of 100 years; the second population also increases in the first 80 years but is affected by a catastrophic event in year 80 which kills c. 50% of the living population within one year. Both populations are modelled with precisely the same parameter values for mortality and fertility. Although the living populations show very different dynamics within the 100 years, the two cemeteries are filled with the same number of burials, c. 500 in year 100. Moreover, the strongly decreased living population in the catastrophic scenario is completely absorbed in the cemetery: exactly the same number of burials (here c. 120 burials) is produced as a result of the disaster as during steady population growth in a much larger population. The difference can only be spotted when the age structures of both cemeteries are compared. The ratios of individuals deceased in the young adult age categories are slightly higher in the catastrophic cemetery than in the natural growth cemetery and the natural growth cemetery has more deceased infants than the disaster cemetery (Fig. 29 and 30). A typical situation in cemetery archaeology is that the 100 modelled years are subdivided into two equal phases, each consisting of c. 50 years: in both scenarios, more individuals are interred in phase 2 than in phase 1, but the living populations show contrary developments. Conversely, lower mortality rates and decreasing population size can consequently both result in a reduction of graves between one phase and the next. Confusion can further be caused by unknown rates of migration (Séguy and Buchet 2013), especially in the 'Migration Period' (Alt et al. 2014). The effects of migration will be examined in more detail in chapter 5.7.

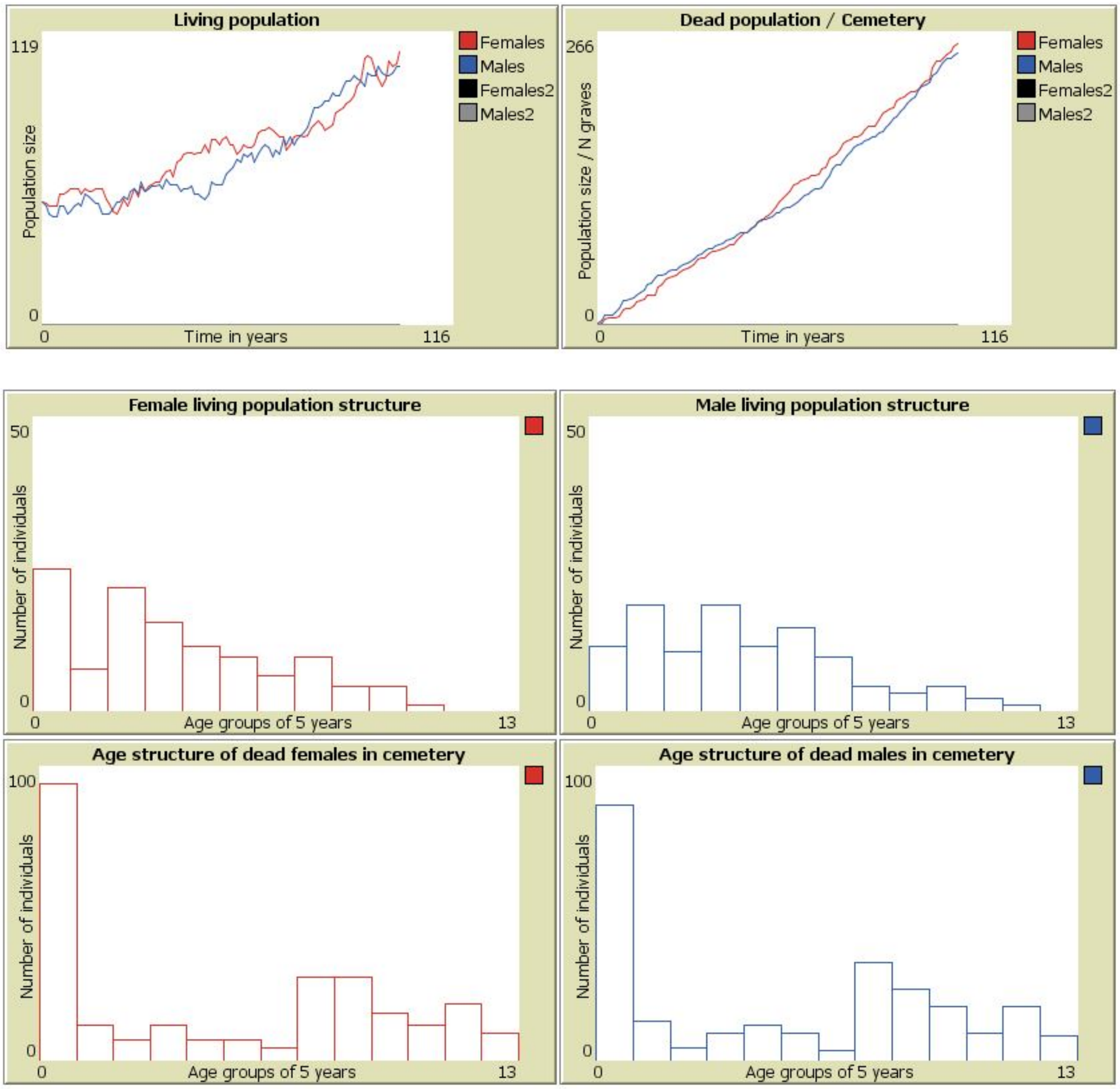


Fig. 29 Growing population, from c. 100 individuals to 200 individuals over a period of 100 years. C. 500 burials are produced during that period.

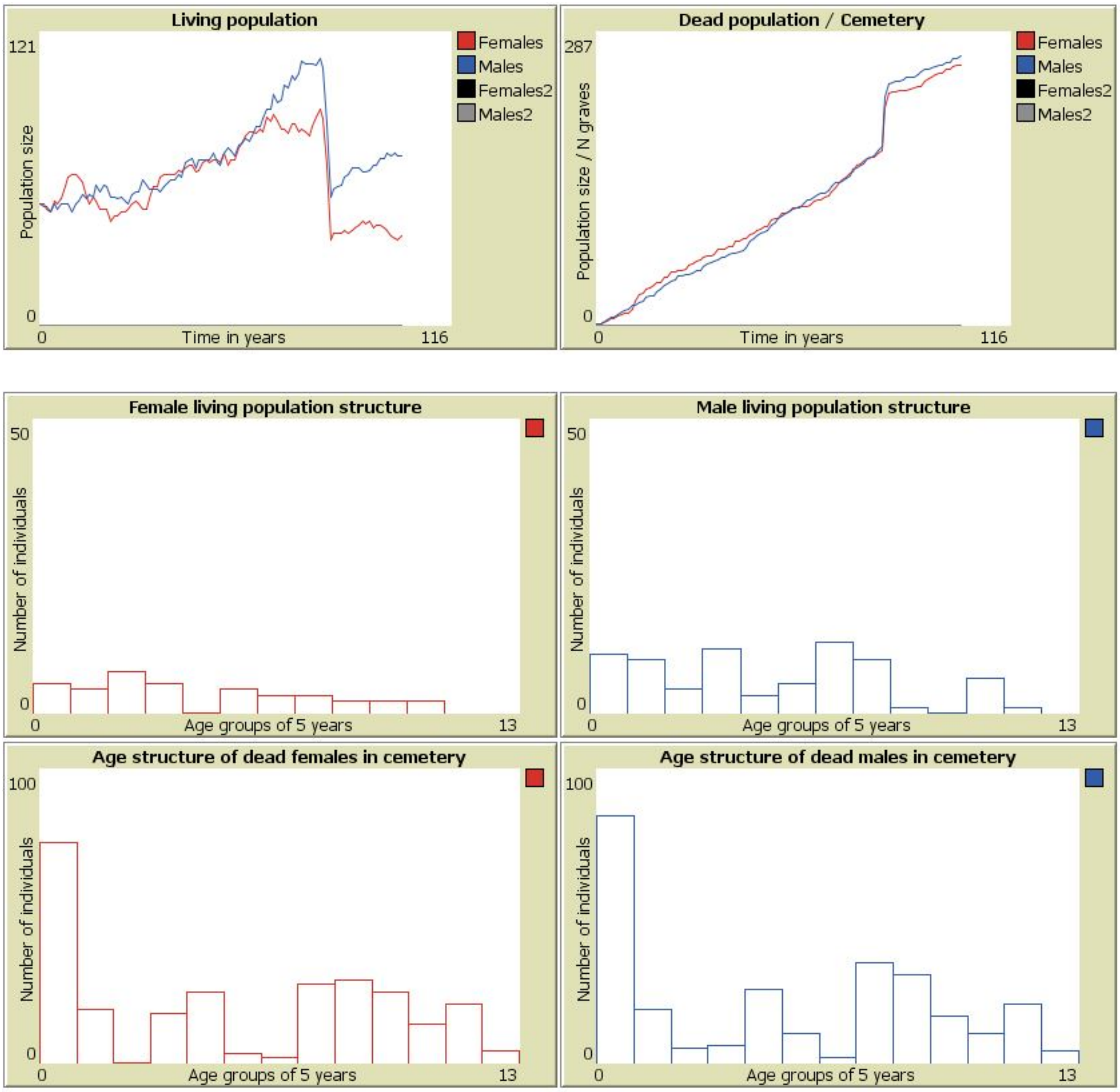


Fig. 30 Population with catastrophic event in year 80, killing c. 50% of the living population. The overall population size is 100 individuals in year 0 and 100 individuals in year 100. C. 500 burials are produced during that period.

In the experiment, it could be observed that the age structure of the adolescent and young adult population reacted to the demographic signal, and population growth compared to population decline led to a different ratio of individuals within that age group compared with the other age categories. Based on this finding, Bocquet-Appel and Masset (Bocquet-Appel 2008a; Bocquet and Masset 1977; Séguy and Buchet 2013) proposed a number of indices, i.e. ratios between specific age categories, as indicators of population structure and population growth. The Juvenility Index, for instance, (JI=$D_{(5\text{-}14)}/D_{(20+)}$), compared the number of juveniles aged 5 to 14 years with the number of adults aged 20 years and over to exclude the contentious issue of under-recorded infants and focus on age groups which can be well-distinguished even in skeletal samples which are not well preserved. The JI also avoids the problem of the exact ageing of adults. The estimator methods were reported to work correctly compared with other indicators of growth in the period of growth started by the Neolithic revolution (Bocquet-Appel 2011; Downey et al. 2014). However, the problem of the juvenility index is that it works with cemetery information, and as established by now, category 2 cemetery data can be influenced by a wide variety of factors, including but not limited to population growth. Séguy and Buchet (2013, 95-96), for instance state that the 5 to 14 years age category is not only sometimes underrepresented because of preservation and selective burial customs; it also poses the problem that those individuals at the upper and lower age limit have to be either included or excluded in the calculation of the index. And as the individuals aged 5 to 14 years are often few in archaeological sites, the inclusion or exclusion of just one individual can mean that the index jumps from growth to stagnating population and vice versa. But small sample size and issues of age category transitions are general problems of palaeodemography.

5.3.2 General indicators of population growth

Growth rates at regional levels are usually studied in archaeology using changing numbers of features in the landscape or changes in the abundance of material remains uncovered over time. The changing number of dwellings, settlements, agricultural features and production, changes in the landscape (Chamberlain 2006; Donat and Ullrich 1971; Steuer 1988; Zimmermann et al. 2009) and the accumulation of radiocarbon dates, e.g. the Summed Calibrated Radiocarbon Date Probability Distribution (SCDPD) method (Downey et al. 2014), can all act as rough demographic proxies for prehistoric populations (Crombé and Robinson 2014; McLaughlin et al. 2016). At some level, they represent signals of living populations (category one data), i.e. more signals suggest population growth and fewer decline. The problems associated with dead populations are not relevant as long as the signals are not directly compared with numbers of burials per period, for instance, then the effects described above have to be taken into account.

The resolution of growth rates is also an important consideration. Single archaeological sites can behave counterintuitively compared with regional developments, or even the demographics of kingdoms and countries. But in general, population developments are often estimated in history based on overall trends which can at least be used to calibrate archaeological demographics under normal conditions. For instance, the growth rates of populations over long periods of time (Benedictow 1996; Hedges 2011) can be used to assess standard scenarios at the micro level. This is why preindustrial profiles are often calculated for different standard growth rates in the demographic literature (Séguy and Buchet 2013).

5.4 Family structure and households

Family sizes and structures are a result of both social and biological demographic factors. Models of populations using mortality patterns, fertility estimates, average ages of marriage etc. result in specific family sizes per point in time. The PCS can further track the actual number of deceased children per woman and the number of surviving offspring as well as checking which child still has a living mother and which children have become orphans. Apart from subdividing the average living population into average households of a specific size based on the number of contemporaneous dwellings in settlements (Hamerow 1993), actual models of nuclear families (parents and their children) and extended families – to which dependents such as related orphans, grandparents, widows and widowers are added based on the demographics of a population – can be used to assess the substructures of populations. Later ideas of medieval household structures and family size can be assessed and compared with the interpretations found in the literature on daily lives in the Anglo-Saxon period using historical documents, e.g. Domesday Book and the 1377 data, where at least heads of households, their wives and adult children are documented per settlement in a parish. A major problem is posed by the changing definitions of heads of households and households over the course of the medieval period, between different kinds of documents and between regions (Ackerman 1976; Benedictow 1996; Brooke 2002; Campbell 2000; Crawford 2009; De Moor and Van Zanden 2010; Dyer 2001; Gilchrist 2012; Hinton 2013; Shahar 1991). An early medieval perspective of nuclear family sizes and household structure will be gained using models of the settlement and cemeteries of Mucking (chapter 8) and the analysis of the overall demographic signal collected for medieval and early modern south Oxfordshire (chapter 7).

5.5 Population size and stabilisation phase

The size of modelled populations strongly affects both overall survivability and the stability of signals observable. Stochastic micro-models such as the PCS can be used to analyse the effects of chance on mortuary profiles, e.g. the ratio of subadults in a cemetery, as well as artefact and disease frequencies. Kölbl (2004) was the first to study how long a site would have to be in use until relatively stable demographic signals could be observed. The initial years of a cemetery are characterised by a relatively small number of burials. These few burials do not necessarily reflect any demographic parameter or parameter network at work in a population; instead, they are purely governed by the contingency of who dies first, second etc. Only after a larger number of burials has been accumulated do demographic signals become apparent and stabilise. Kölbl found that the effect of the initial stabilisation phase was considerable.

She states that mortality has a strong effect on the initial stabilisation phase, whereas fertility has none. Populations with many individuals who die early (high mortality) more quickly assume a state with stable signals than populations with low mortality rates. Populations with low overall mortality need more time for the transition of their demographic signals between living group and cemetery.

The examples she modelled need c. 50 to 80 years until stable population signals are assumed (Kölbl 2004, 109-120).

The composition of the initial population also has a considerable effect. Populations which migrate to a new settlement and start burying their dead in a new cemetery often have a different composition (high ratios of young adults, especially males) from populations which are already stabilised, e.g. because they have not moved and merely picked a new spot for burial (Kölbl 2004, 119). Migrant populations need at least one generation to assume a more consolidated state (migrant populations are described in more detail in chapter 5.7 below).

One of the most important factors which define the length of the stabilisation phase is the overall size of the modelled population (i.e. the size of the population that uses a specific cemetery). She modelled stationary populations of 40, 200 and 500 individuals and found that the standard deviations of the demographic signals developed from c. 10% in the population of 40, to c. 5% in the population of 200 to c. 3.5% in the population consisting of 500 individuals (Kölbl 2004, 120-129). Unfortunately, Kölbl did not record the average duration until stable signals were reached. Using the same standard medieval mortality profile and parameters for on average stationary populations are modelled in the following theoretical virtual experiment: population sizes of 40 and 500 are modelled for 200 years and both the mean age and the mean age at death in the population and a theoretical disease rate are recorded. For the disease rate, 50% of females and males are infected at the age of 20 years. The rate of subadults and the disease frequency are tracked in both the living population and the cemetery:

Fig. 31 shows the result for population size 40. After the start of the modelling run the average age at death in the cemetery decreases from c. 45 years to the age of c. 29 years expected within the first 80 years. Only after the initial stabilisation phase of approximately 80 years does the cemetery signal become stable. The mean age of the living population fluctuates more strongly throughout the 200-year period but needs no stabilisation phase. The disease frequency recorded as a percentage of the total living population and the total cemetery population for both females and males fluctuates strongly in the initial years and resumes a general downward trend after year 30. The c. 15% infections expected in the cemetery population are assumed for both males and females after c. 80 years. The infection frequency in the living population is generally unstable at a population size of 40 individuals. As populations in early medieval Europe rarely reached levels of 100 or over (Hamerow 1993; Hamerow 2002; Hamerow 2012; Kölbl 2004), this experiment demonstrates that a degree of humility is advisable whenever cemetery signals are interpreted: pathology frequencies, artefact numbers and demographic signals in the initial phases documented in cemeteries do not represent reliable data. The initial decades in archaeological cemetery sites are entirely and universally governed by contingency.

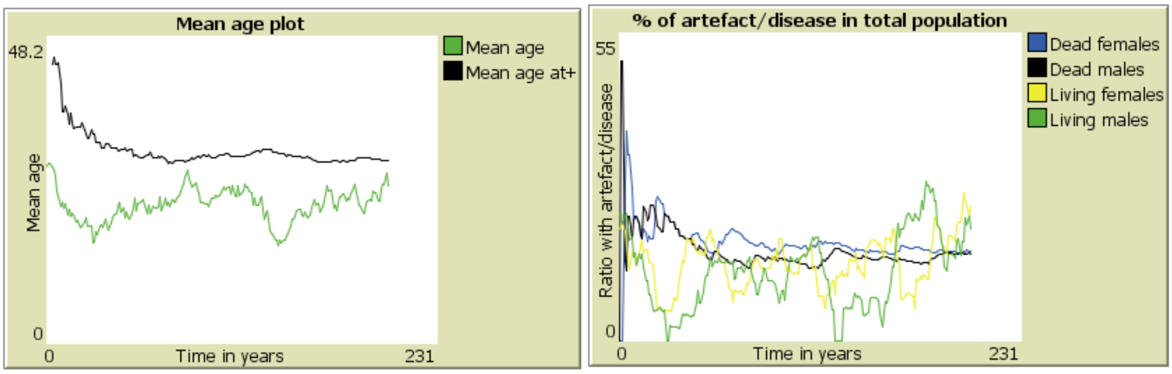


Fig. 31 Time until relatively stable parameter signals are reached at population size 40, at the average age composition of living population and cemetery and at a theoretical disease frequency.

Fig. 32 shows the result for a population size of 500. The effect of population size decreases. The initial stabilisation phase decreases compared with the experiment above to c. 50 years from the start of the experiment. Both the cemetery and the living population signals are more stable at a population size of 500 compared with the experiment with 40 individuals. During the 200-year period, the 500 living individuals have produced c. 3000 burials. Such population sizes are rare in archaeological discovery, even when data excavated in large regions are aggregated.

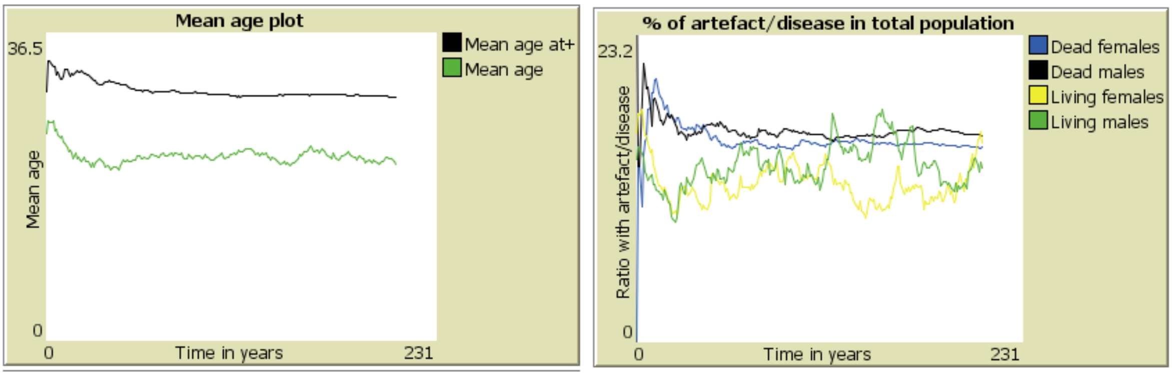


Fig. 32 Time until relatively stable parameter signals are reached at population size 500, at the average age composition of living population and cemetery and at a theoretical disease frequency.

What Kölbl has not discussed is that parameter changes, e.g. a change in infection rates from one period to the other, also need some time to stabilise. Fig. 33 shows an experiment in which the same 500 individuals are modelled as above, but a change in infection rate (increase from 50% to 80%) happens in the 100th year of the simulation. The increase takes c. one generation (c. 35 years) to be fully represented in the living population. The cemetery signal in the graphs in Fig. 33 equals an average including all the burials before. The signal increases over time as more and more individuals with higher infection rates are buried, superimposing an increasing number of post-change burials with the pre-change burials. But in archaeological cemetery analysis, the frequencies per phase are almost never calculated in a way that includes all previous phases, but separately.

If archaeologists manage to differentiate between burials in phase 1 (pre 100) and phase 2 (post 100), e.g. due to dating methods which include all – or at least a representative proportion of – burials, the burials dating to the first years within phase 2 are, again, few in number and the parameter instability is exactly the same as in the initial period.

Archaeological interpretations of phase transitions and changes between phases – the quintessence of burial archaeology – need to take into account that short phases lead to parameter instability because they also reduce the numerical basis. Counterintuitively, the shorter the phase, the less stable the data obtainable in small cemetery sites (Fig. 34). This means, for example, that absolute chronologies down to generations might not represent a good basis on which to tackle demographic and structural interpretation in small cemeteries (Bayliss et al. 2013; Sayer 2010). Ideally, there must be a balance between phase length and the reliability of the sample governed by the absolute deposition rate of burials per phase. And in most cemeteries dating to the early medieval period, the rate of burials over time leads to a lengthy stabilisation phase, e.g. the approximately 80 years of the experiment above (Fig. 31). If the phase length is shorter, e.g. by trying to date burials into shorter chronological phases than 80 years, we risk losing, not gaining information. The stochastic aberrations of small archaeological populations challenge current research methodologies at their core but also, coincidentally, represent a mirror image of the accuracy and precision obtainable from the recently reviewed dating methods (Bayliss et al. 2013).

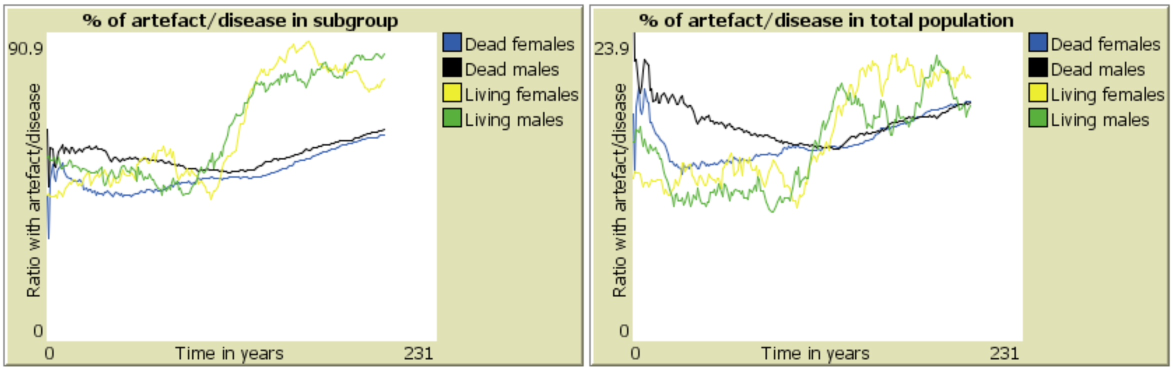


Fig. 33 Change of infection rate from 50% to 80% at year 100. The change needs c. one generation (here c. 35 years) to be fully represented in the living population. The accumulating cemetery signal reacts much more slowly to the change.

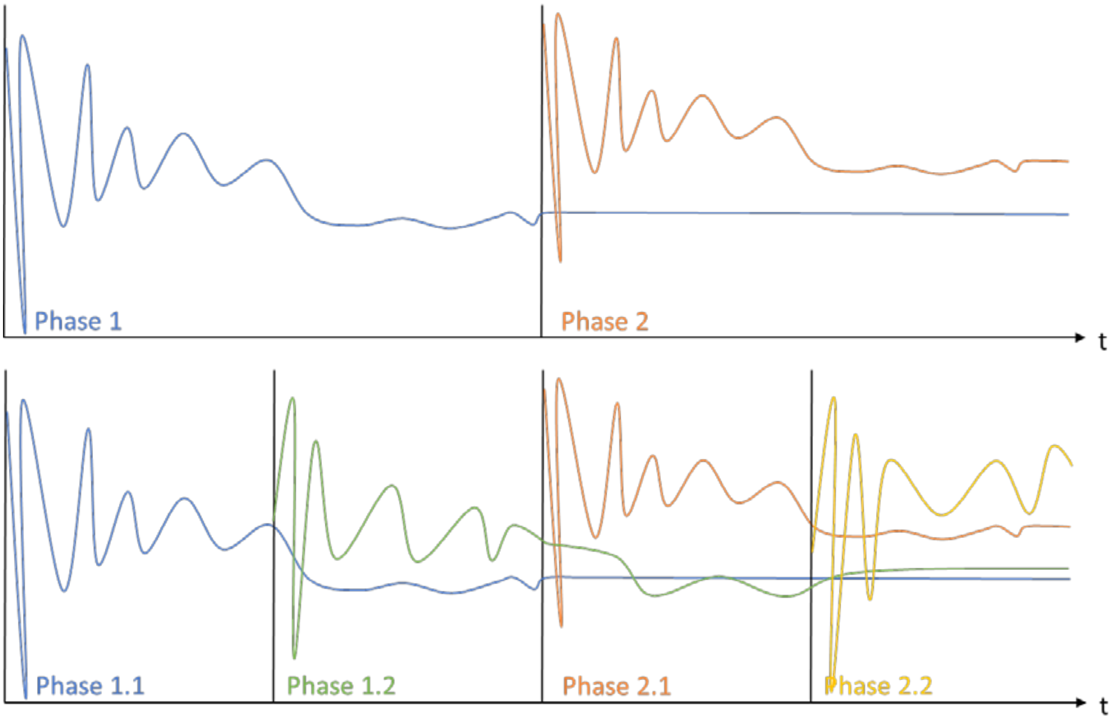


Fig. 34 Theoretical model of the problem caused by the stabilisation phase in cemetery data. Short chronological phases increase the likelihood that cemetery data have not left the strongly fluctuating state at the end of one phase.

The overall size of a population affects not only the frequencies of demographic parameters, pathologies and artefacts within the cemetery, but also the overall survival probability of the population.

5.6 Population size and probability of survival

Isolated small living populations, e.g. small immigrant populations, small co-resident communities, villages and hamlets, are affected more strongly by the effects of chance than larger populations. But which communities are large enough to survive on their own without the need to be part of a larger network of settlements to bolster their longevity by intermigration? In the following experiment the initial population structure is randomised and only defined by an upper and a lower age limit. A number of living populations of different sizes are modelled over the period of 300 and

1000 years in an equilibrium of fertility and mortality, to test the resilience of these populations against the chance of ceasing to exist before the last modelled year; this shall be called 'probability of survival'. Even under stable circumstances, small isolated populations sometimes die out due to the effects of chance, for instance in the event that the young adult females, who are responsible for the reproduction of the population, all die.

Two mortality profiles were chosen, to include both a minimum mortality approach using the WHO 1999 (Lopez et al. 1999) and a mortality pattern which represents a typical medieval population (here the mortality pattern of Wharram Percy was used (Mays et al. 2007)). The graphs show the percentage of isolated populations of different initial sizes which survived for 300 years and 1000 years after 1000 repetitions. Populations that did not survive are defined as populations which counted 0 living individuals before reaching year 300 (or 1000). Each dot in Figs. 35, 36 and 37 represents one experiment, which was repeated 1000 times per single parameter set.

1) Surprisingly, the viability of populations depends more on the period of survival (here: 300 or 1000 years) and the initial population size (here: 20, 50, 100, 200, 500 and 1000 individuals) than on the mortality pattern of the population, which defines the turnover-rate of births and deaths and the length of generations (Fig. 35 and 36).

2) The medieval population was only minimally less stable than the WHO 1999 with the exception of the smallest initial population sizes (20 and 50 individuals), where the mortality pattern seems to matter (Fig. 37).

3)The critical population sizes for long-term stability (over 90% probability of survival) are approximately 50 individuals for 300 years and 200-300 people for 1000 years. For the 300-year period, this is surprisingly close to the population sizes reported for early medieval and prehistoric populations (Chamberlain, 2006, Donat and Ullrich, 1971, Hamerow, 2002).

4) The 300-year model is the more realistic scenario in a medieval/historical context. At the level of 20 living individuals, the WHO 1999 survived in 70% of cases, whereas the medieval population's probability of survival was as low as 44%.

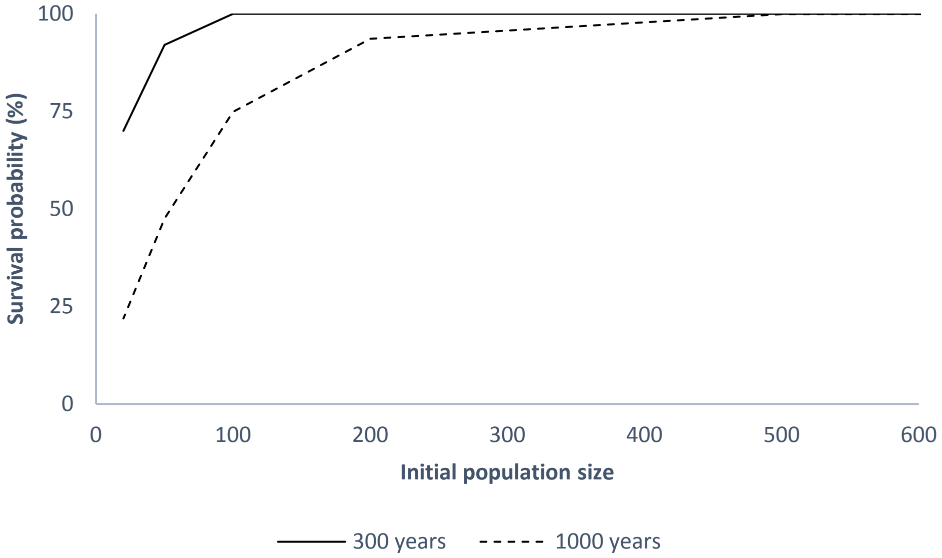


Fig. 35 Modern global WHO 1999 mortality pattern. Percentage of surviving populations after 300 and 1000 years of existence.

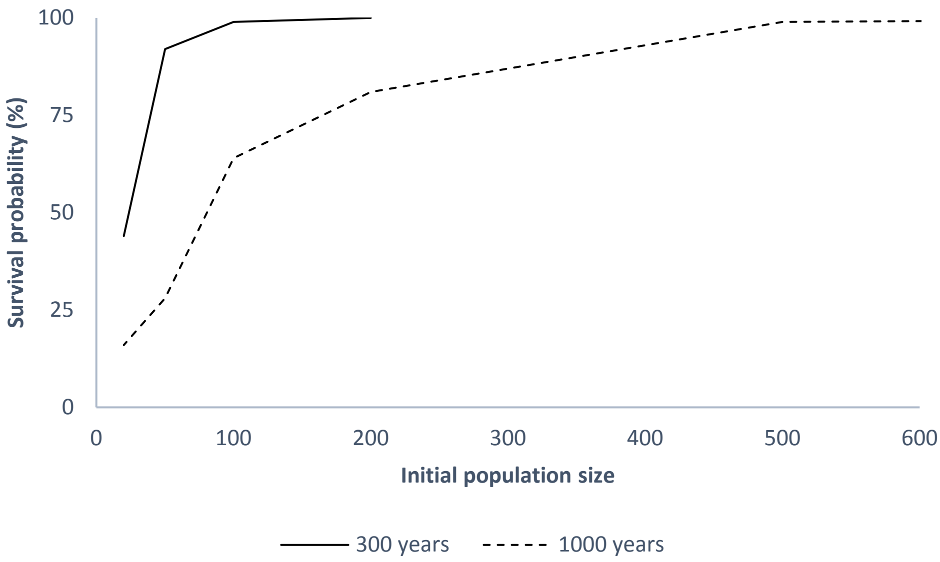


Fig. 36 Medieval mortality pattern. Percentage of surviving populations after 300 and 1000 years of existence.

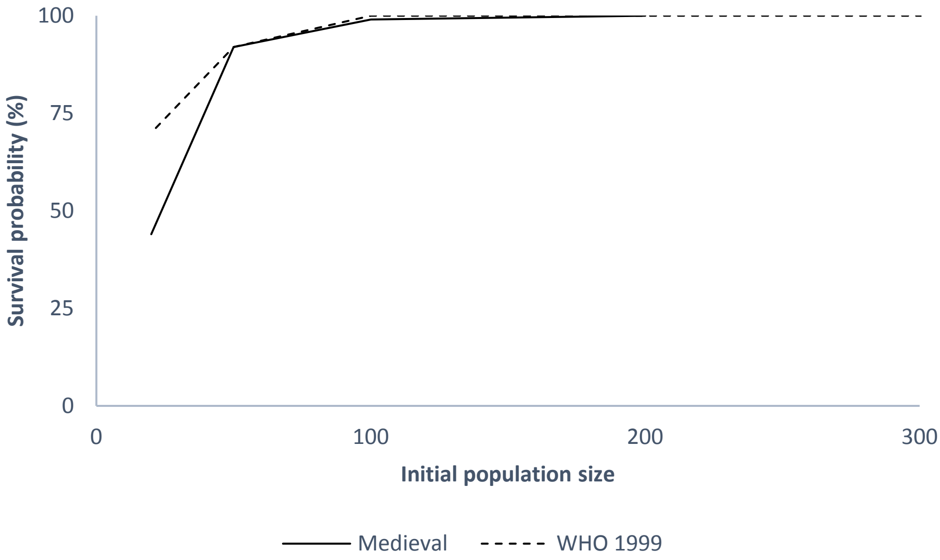


Fig. 37 Medieval and modern global WHO 1999 mortality patterns. Percentage of surviving populations after 300 years of existence. The medieval population is almost as resilient as the modern population, with the exception of the smallest population sizes. Below the level of 50 individuals, the different mortality regimes start to become important.

The relatively simple experiments (Fig. 35 to 37) show that isolated medieval and prehistoric communities of sizes well below 50 individuals have a high chance of dying out, solely based on the mathematical effects of chance affecting low numbers. Isolated communities of circa 20 individuals are not viable for long periods of time. The general stability of such populations depends very much on their pure size. Settlements with more than 50 individuals (such as Mucking (Hamerow 1993; Hirst and Clark 2009)) have a natural resilience to extinction, and would have remained longer in a landscape purely based on the size-dependent mathematical stability shown here. Based on the mathematics of these experiments, one can speculate whether smaller units in the early medieval landscape were more temporary in nature and came into existence and vanished more rapidly than settlements of 50 or more individuals. The demographic viability of populations (dependent on size and time of existence) becomes an interesting parameter if one discusses the spread and success of settlements in the early medieval period. The mortality pattern is less important, because the WHO 1999 and the medieval populations do not react very differently after the population has reached a certain size (Fig. 37).

The results of this experiment can be generalised in the context of the early medieval period. The initial living population size was an important parameter for the success of a settlement. It is also interesting that the critical population numbers are very close to the average numbers calculated for most early medieval (and prehistoric) rural settlements (Ausenda, 1997, Donat and Ullrich, 1971). One can speculate whether the settlement sizes of circa 50 and slightly lower were the result of this intrinsic element defining the longevity of human settlements. The experiment also shows that a highly dispersed settlement structure with group sizes of less than 20 individuals requires some degree of interaction on a biological level, e.g. the movement of women for marriage outside the own groups/exogamy, the migration of young adult men etc., in order to remain relatively stable. As high rates of interaction between communities were probably common in the early medieval period – as demonstrated, for example, in cases of community burial sites and complex burial activities (Hills and Lucy 2013; Sayer 2014), extremely isolated communities might not have existed in reality. Migration between settlements could have stabilised small dispersed populations. Further research is required to understand whether settlement landscapes with populations of small sizes were less resilient and less stable because of the higher chance of fluctuations of the elements of the system.

Reciprocally, as soon as group sizes of 50 individuals and more are reached, there is no mathematical need for more intermigration to stabilise the populations. For example, populations as large as the one that existed at Mucking, with more than 90 individuals present at any point in time (Hamerow 1993; Hirst and Clark 2009), could exist relatively isolated for a few hundred years. As soon as population numbers of a community exceed a threshold, the settlement can remain a defining element of the landscape for a long period unless, of course, the population's demographics are changed. Such changes would have to push the population out of the equilibrium of mortality and fertility or strongly reduce the population size below the threshold, for instance, in mass migrations, catastrophic events, etc.

5.7 Population networks and migration

Although we need to understand isolated populations before we can understand population networks, isolated human populations are rare. The interaction between populations within larger networks is a common theme of archaeological and demographic research. This section describes the modelling of biological interchange between populations. The demographic interaction between populations defined by a certain stability of settlement can take place on different levels. Mass migrations are mostly short-term events, which, however, often have a great impact on the cultural tradition and changes in material culture in archaeological and historical periods (Alt et al. 2014; Burmeister 2000; Härke 2011; Hedges 2011; Müldner 2013; Parker Pearson 2003; Pattison 2008; Pattison 2011; Thomas et al. 2006; Thomas et al. 2008). On a less visible scale, the constant migration of certain parts of populations, e.g. females in a patrilocal society, exogamy and the migration of workers and slaves, also defines the interaction between settlements in a landscape (Hajnal 1965; Hajnal 1982; Sayer 2014). The effect of such interaction between populations on the survival probabilities and demographics in the early medieval period are unknown. But before the survival probability and stability of interacting population networks can be modelled in a parallel way, as with isolated populations in the previous chapter (5.6), the intermigration between populations must be measured. Recent advances in genetics and stable isotopes have tackled the problem of migration and exogamy. Large-scale population movement can now be measured based on modern genetic signals and aDNA (Alt et al. 2014; Härke 2011; Hedges 2011; Leslie et al. 2015; Pattison 2008; Pattison 2011; Renfrew 2009; Thomas et al. 2006; Thomas et al. 2008), while small-scale movement can be studied using traditional osteological and stable isotope methods, e.g. the movement of females in patrilocal societies (Alt et al. 2014; Alt et al. 1995; Bentley et al. 2009; Haak et al. 2008; Meyer et al. 2015; Price et al. 2006). The problem of mass migrations is complex, and the demographic element of the migration in particular is often not studied by both archaeologists and geneticists. Reviewing the genetic research on the early medieval British Isles, Hills (2009) criticises the demographic simplicity of the underlying models and the disregard for changes possible during the long periods of human history and population movement. PCS models of populations interacting on the level of mass migrations are possible. But as research into small-scale migrations and exogamy has not yet received the same critical review I will present one example of how the PCS can be utilised to analyse the difference between the living populations we are interested in and the static cemeteries which contain the data. In the following experiment, two populations interact by exchanging females. Population 1 is small (c. 50 individuals at any point in time), and Population 2 is large (c. 1000 individuals) and represents the background population of settlements situated around Population 1. Population 1 receives a steady rate of young adult female immigrants aged 15 to 25 years (0.005 per year), and 0.005 females per year aged 15 to 25 years emigrate from Population 1 into Population 2. The ratios of first generation immigrants in the living population and the cemetery are compared in Fig. 38. The graph shows that the ratio of immigrants is different in the living and the cemetery population at each point in time, even under stable conditions, for a period of 200 years. Further, at year 75, the signals cross and the relationship becomes inverse. During the first generation the cemetery lags behind the living population signal by approximately one generation, and after the point of inversion the relationship between the signals becomes more stable without losing the offset caused by the initial differences over the period of 200 years. In this hypothetical experiment, the overall mean ratio of immigrant females is 17.8% in the living population and 17.6% in the cemetery. But what does such a number mean if the dynamics within the 200-year period are unknown? Archaeologists and researchers in archaeological genetics need to take into account the demographic dynamics of migration, e.g. the generation delay and the period it takes until a population network has assumed a stationary state. Processes need to be described; ratios and percentages that collapse hundreds of years into one number contain little information about the reality experienced by migrants and locals over time.

Fig. 38 Exogamy experiment. Percentage of first-generation immigrant females in the living population and the cemetery.

5.8 Artefact and disease frequency

In this section, the modelling of differences within populations is described – towards a ‘palaeoepidemiology’ including both pathological and artefact data. Age-dependent differences within populations are already modelled using the PCS, based on age differences in mortality and reproductive success. Differences can be between biological sexes and gender groups, and be defined by infection with a specific disease or the acquisition of another health disorder which leads to demographic differences between the diseased and the healthy (Roberts and Cox 2003; Roberts and Manchester 2005; Wood et al. 1992). The presence and absence of artefacts is often used to describe vertical and horizontal strata within archaeological populations. The archaeological literature is full of ways to identify and interpret differences of ritual, wealth, political roles, social rank, occupation etc. (Härke 2000; Härke 2002; Härke 2014; Parker Pearson 2003). But how can cemetery data be used to describe a population’s subdivisions in the PCS? A few experiments demonstrate that the demographic transition between the living and the cemetery population causes many problems for studies of subpopulations of archaeological cemetery sites.

Wood et al. described what many researchers had already suspected for a long time in a seminal article in 1992 (Wood et al. 1992; Wright and Yoder 2003): as aberrant changes of human bones need time to develop, sudden deadly diseases would not be recognisable in the skeletal record. Mostly unchanged skeletons might have belonged to individuals who suffered from the most acute diseases and died from them before any bone changes could develop. Reciprocally, individuals showing blatant, striking and long-term changes were probably healthier, as they survived for an extended period or even recovered from the diseases instead of dying from them. Basing arguments on this observation is, however, almost impossible as it requires handling the absence of evidence using contextual means.

Even more important than this general point are the three lines of evidence that Wood et al. focussed on in their article. Demographic data and disease frequencies from skeletal samples might be biased based on three factors: *demographic non-stationarity*, *selective mortality* and *hidden heterogeneity of frailty* (susceptibility to illness).

Demographic non-stationarity has an effect on both demographic estimates of past populations and on palaeoepidemiologic data. Inter-site comparisons are only feasible if both populations had similar demographic dynamics, because different or unknown demographic dynamics lead to counterintuitive complex offsets between the living and dead signals.

Selective mortality comes into play when disease prevalence is calculated on the basis of a skeletal population. In archaeology, we (almost) never have access to the living population and the ratio of infected individuals within that group, and are therefore forced to simulate it virtually. What we *have* got is a proportion of the infected individuals who did, in fact, die after they had developed changes in the skeleton. This results in a selection effect if the disease increases the risk of death, thereby producing an overestimation of the actual frequency in the complete population. To put this more bluntly, this means that those individuals with a higher risk of dying are probably the ill ones and they will be more numerous in the cemetery than the survivors.

The *hidden heterogeneity in risks* is a much more complex problem, arising from the fact that each individual has a different susceptibility to illness and that age-dependant aggregate mortality is not actually the real mortality of the individual. Archaeological data are not precise enough to estimate such values individually (Wood et al. 1992).

5.8.1 Population size and random stochastic behaviour

Fig. 39 shows the influence of chance, i.e. random stochastic behaviour, on the development of 10 populations and their cemeteries, with exactly the same starting conditions and the same parameter values which are most likely to produce stable population developments. The initial population size is 50 (25 females and 25 males) with random ages between 0 and 50 years.

I have further given a part of the population (here 20%) of the same modelling runs shown in Fig. 39 an artefact at a specific point in their lifetime (here males aged 20), which they would then also be buried with in a simple 1:1 relationship. There is no data/artefact loss in the modelled cemetery, to illustrate the optimal scenario for burial archaeologists: assuming that the grave goods represented artefacts which were also carried during the individuals' lifetimes. This experiment could be similar to a rite of passage where males receive an artefact when they come of age, e.g. a sword in an Anglo-Saxon context. Fig. 40 shows only chaos and the fact that the initial 20% are neither reconstructed in the average living signals nor in the cemetery signals. At best, some of the dotted cemetery signals reach 10%, which might be a reflection of the 20% value as only males received the virtual artefact in this experiment. Although the averages of the living population and the cemetery signal seem to underrepresent the rite of passage parameters, they do not entirely deviate from each other on average. However, the living population signal is much less stable than the accumulating cemetery population signal, and at any point in time they can have very different values. If the virtual cemetery was excavated at such a moment, the artefact frequencies in the cemetery would not be representative of the artefacts currently in the living population. Average long-term trends can, however, be studied under norm conditions although archaeological populations of sizes of c. 50 individuals would probably be as unstable and governed by chance as the modelled scenarios. It is therefore not advisable to place much value into small differences in artefact frequencies from small to medium-sized cemetery sites; in addition, the modelled examples do not belong to the smallest archaeological populations as they reach numbers of burials of c. 200 to 300 (Fig. 39). Fig. 41 shows the results for a living population of four times the size (c. 200 living individuals and more than 1,200 graves). Exceptionally large sites cemeteries such as Spong Hill (Hills and Lucy 2013) and larger regions have the potential to yield much better results.

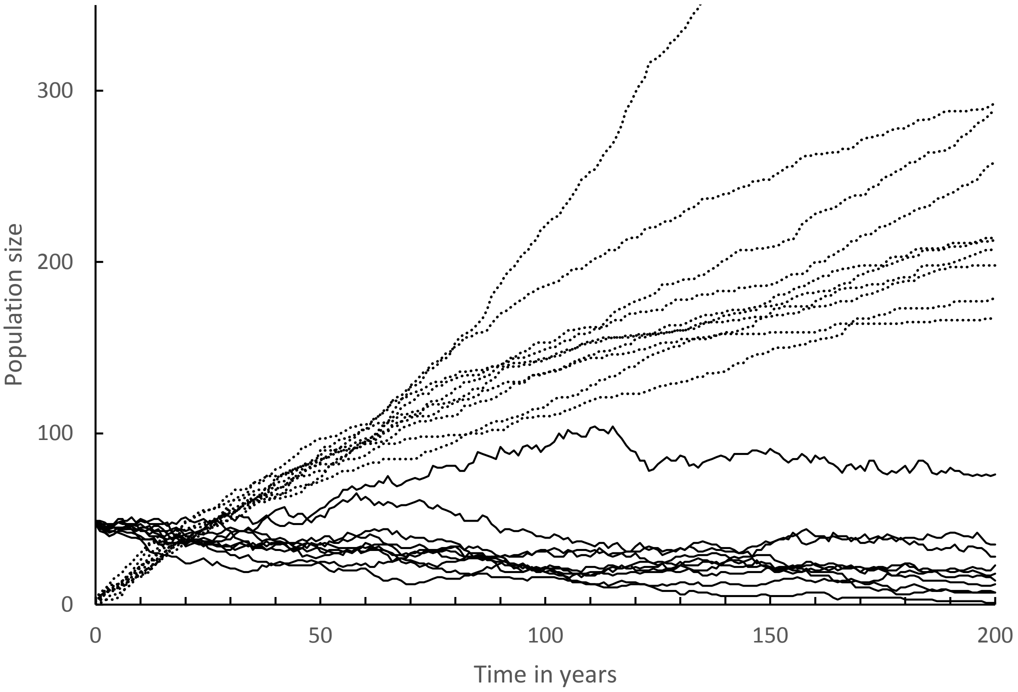


Fig. 39 Ten modelled populations (full lines) and their cemeteries (dotted lines) with a starting population of 25 males and 25 females and the same parameter values for all 200 years.

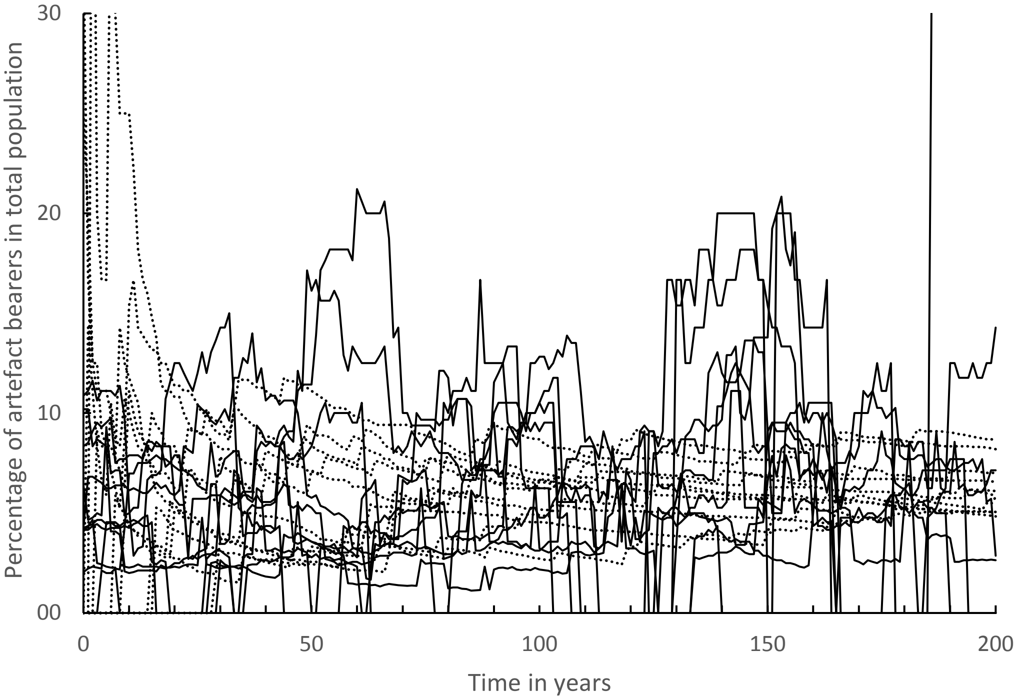


Fig. 40 The percentage of artefact-bearers in the total living population (full lines) and in the cemetery (dotted lines) recorded for the 10 modelled populations shown in Fig. 39.

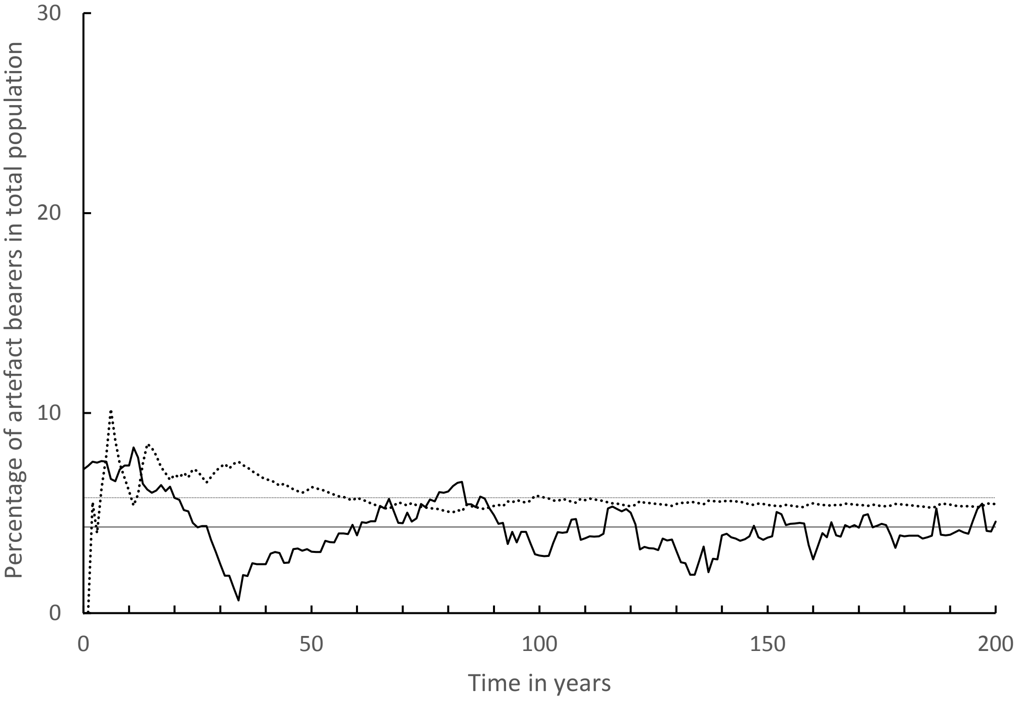


Fig. 41 The percentage of artefact bearers in the total living population (full line) and in the cemetery (dotted line). This population is four times the size of the initial population sizes in Fig. 38 and the signals are much more stable: an average of 4.3% of individuals have the

artefact at any point in time in the living population, whereas an average of 5.8% are buried with it.

5.8.2 Demographic nonstationarity

The following experiment shows the same initial conditions (20% of living males aged 20 receive an artefact and are buried with it) for three populations: one stationary population, one growing population and one declining population (Fig. 42). An initial population size of 1,000 individuals was chosen to minimise random stochastic effects. In Fig. 43 we can see that the artefact rates in the complete population are slightly lower than the frequencies in the stationary state (difference of c. 20%) and the declining population produces signals which are slightly higher (up to 10%) than in the stationary state. If the demographic state of the populations is unknown (which is the case in most archaeological populations), a variation in artefact frequency of up to 30% could still represent equal initial conditions. Without modelling, the slight difference between the living signals and the dead population signals would also remain unnoticed. All three living population signals are 30% lower than the frequency averages in the cemetery. As this is independent of population growth, it seems to be dependent on the age an artefact is received.

One can see that the artefact distribution regime, i.e. the initial input data, and the ratios of artefacts in the living and cemetery populations are different entities. If we have prior knowledge about the artefact distribution regime, e.g. in terms of the relevant age groups, much better results can be obtained and the 20% is reproducible by both the living signal, and the dead signal under all three demographic conditions (Fig. 44). In that case, the possible deviation between the living population signal and the dead population signal depends solely on the size of the population. As the growing population represents a larger sample size, its signal is more stable than the other two signals in the smaller populations.

All in all, demographic nonstationarity has a relatively small but still noticeable effect of up to 30% offset. In a growing population, a higher proportion of young individuals is present in the living population. Therefore, the overall ratio of individuals reaching the relevant age 20 is proportionally smaller than in a static or declining population. The more information about age-specific subgroups is obtainable, the better the reconstructions of artefact distribution in archaeological populations and the selection mechanisms active in the populations. This finding highlights the importance of osteological age estimation in funerary archaeology.

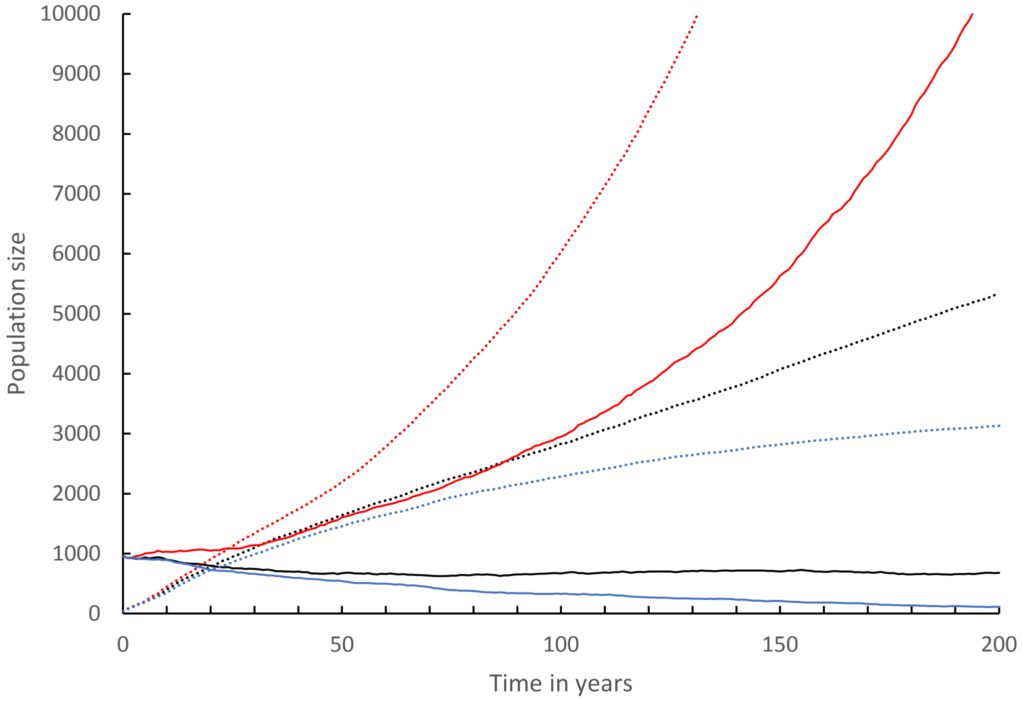


Fig. 42 A stationary (black), growing (red) and declining (blue) population.

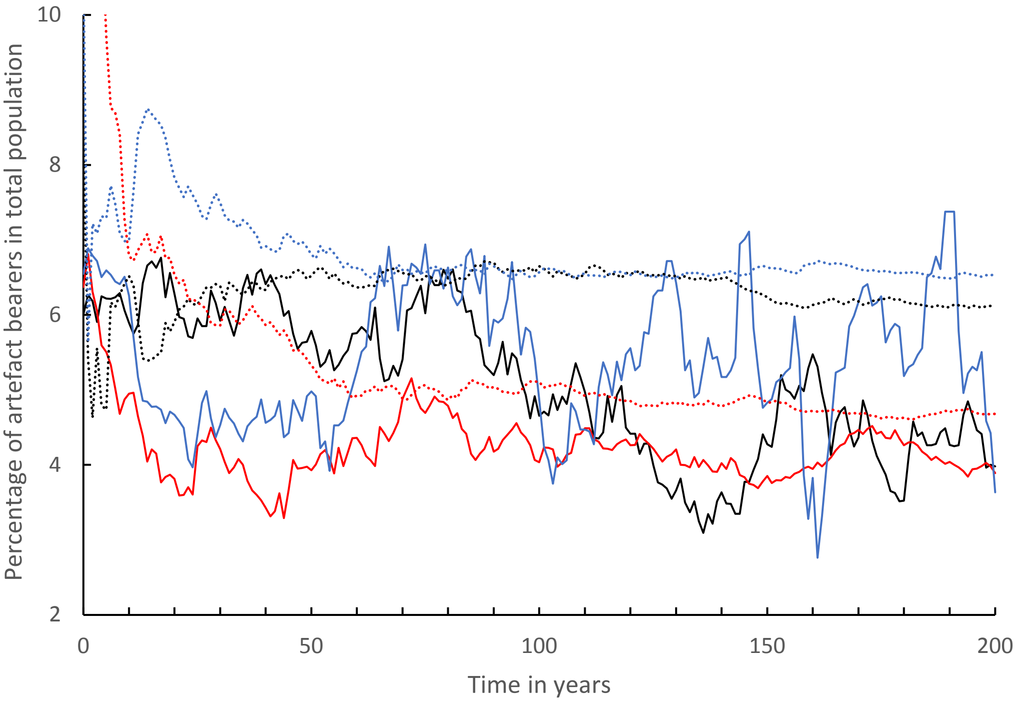


Fig. 43 Different modelling results for the three different demographic dynamics can be observed even though the input that 20% of males aged 20 receive an artefact is the same in all three populations.

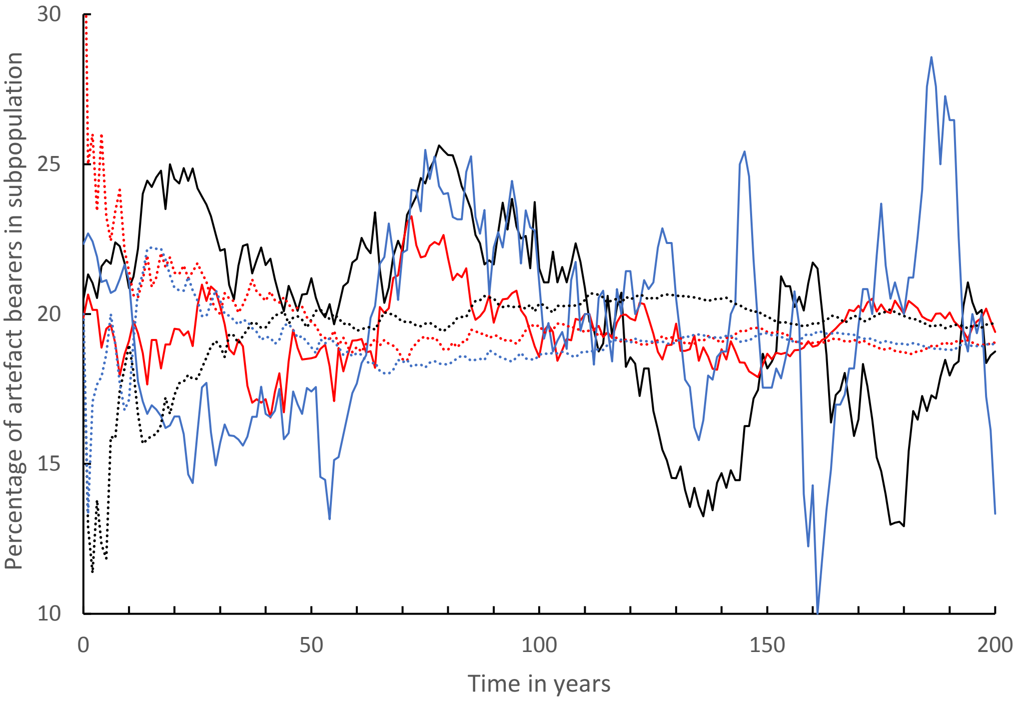


Fig. 44 The same three populations' signals in the subgroup of males aged 20 and over. This however, requires prior knowledge about the artefact distribution routine (20% of males aged 20) in the living state, which is almost never obtainable in archaeological cases.

5.8.3 Example of a complex dynamic population

Wood et al. (1992) state that changes in fertility have a much higher impact on the age-at-death distributions of a cemetery population than changes in mortality. This can be observed in a hypothetical scenario where both fertility and mortality are changed in a catastrophic scenario. A population suffers a period of stress – for instance, because the population size has reached a carrying capacity level. Simultaneously, the population changes its fertility level from growth to relative stability. The following experiment was conducted in the NetLogo interface to capture a variety of recorded dynamics. Although only two input parameters are changed, the reaction of output parameters is diverse and complex.

Scenario: A population grows due to high fertility rates (TFR 6) for 100 years, then suffers a brief (25-year) period of stress during which repeated catastrophic increases in mortality reduce the population almost to its initial population size. The population simultaneously adapts to a new reproduction regime in the period of stress (TFR 4.1) in order to remain stationary for the following 100 years after the catastrophic events. At the same time, two theoretical artefact distributions are observed in the living and the cemetery: female individuals aged 50 receive an artefact in 50% of cases, and males aged 20 receive an artefact in 50% of cases.

Selected observations: The 25 years of catastrophic events (Fig. 45), although highly visible in the upper two plots, are almost swallowed up in the cemetery signals of the lower 4 plots, which in all recorded parameters exhibit only a slight depression. The living population reacts more strongly to the catastrophic mortality surges in the transitional period with a general increase compared to the minor decline in the cemetery signals. However, the catastrophic signal is still relatively modest compared with its effect on the overall population size. During the catastrophe period, the mean ages in the living and the dead group are equal, or later even briefly inversed, and the peaks in the living population signals in the artefact graphs (yellow and green) can be explained firstly by stronger stochastic aberrance as the population total drops considerably, and secondly by the fact that many children in the initially growing population are at higher risk of dying and produce more deaths than the fewer adults. Therefore, the mean age in the living population increases because the older individuals are more likely to survive and the mean age at death decreases slightly because of the higher number of dying children. The signals of the mean ages, the births and – surprisingly – also the artefact ratios differ consistently between the living and the cemetery in the first 100 years of population growth. This difference decreases with the fertility change to a stationary state after the stress period. The last 100 years of stability (lower TFR) have better aligned signals for the living and the dead, although slight offsets are still discernible. While the artefact frequencies in the living population are lower than the same ratios at any point in time in the cemetery in the lower right-hand plot for the percentages in the complete population, the dynamic is reversed in the lower left-hand side plot with the data for the age-specific subgroups (only males aged 20 and over and females aged 50 and over). The ages at which an artefact is received have an influence on the frequency dynamics. Whenever artefact data from cemeteries are used to characterise living populations, such as the artefact distribution routines in this experiment or the actual frequencies of artefacts in the living population at any point in time, age data and some knowledge about the demographic dynamics are important. If we lack this info, modelling various scenarios can illustrate the uncertainty of the obtained results and the sensitivity of the parameters involved.

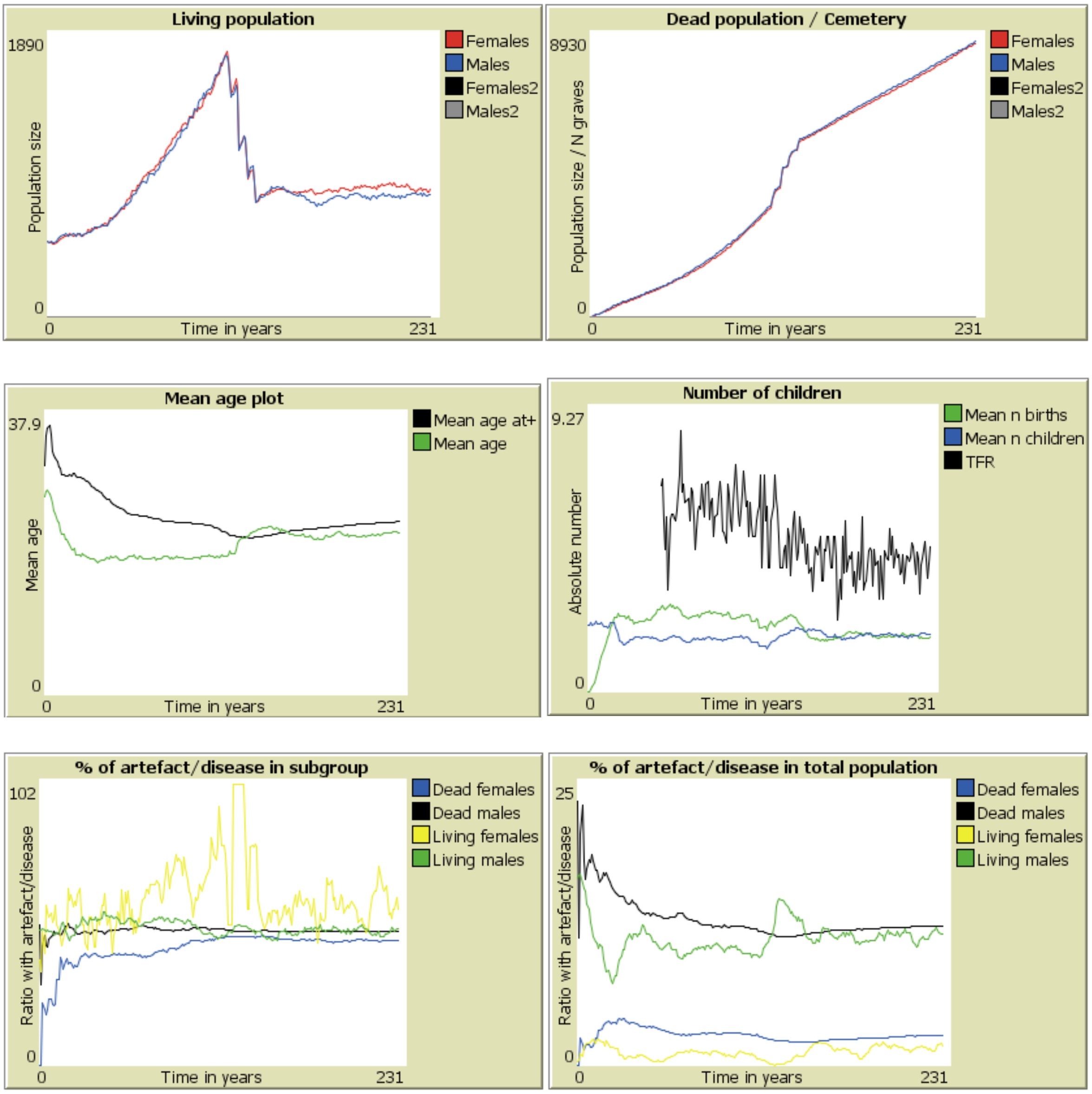


Fig. 45 Output for a dynamic scenario in the NetLogo interface.

5.8.4 Hidden heterogeneity in risks

The previous experiment (Fig. 45) has shown that some dynamics can affect different parts of a population more strongly than others. Individual health levels, therefore, might not correspond with the aggregate population average. The modelled catastrophic mortality surges further increased the risk of the age groups who already have higher probabilities of dying, i.e. the subadults and elderly. But what happens if unknown parts of the population have different hazards from other parts of the population? In archaeology, different socioeconomic strata not reflected in the burial record, e.g. in the equalising medieval Christian burial rite, could be exposed to different hazards or be affected differently by these hazards due to frailty or susceptibility levels deviant from the norm. Wood et al. (1992) have also identified other factors influencing heterogeneity in risks: genetic causes, microenvironmental variation and temporal trends in health. All of them are relevant in archaeological populations, but are equally hard to study in an archaeological setting. Specific frailty and the reaction of subpopulations forming the aggregate population to various hazards are still an understudied field, and at this stage an awareness of the problem to pinpoint individual levels of health hazards compared with the population aggregate is sufficient.

With the exception of the catastrophe routine utilised in the case study above, where parts of the population can be more strongly affected by death hazards, the PCS models individual risks as randomised values over the aggregate mortality profile of the population. As soon as information about relevant differences between subpopulations is obtainable (e.g. due to secondary information), i.e. if the subpopulations are no longer ‘hidden’, it is better to model them as two separate populations with different aggregate health levels. This would further allow the modelling of various levels of interaction between the two. But as stated in the original publication and later reviews, the heterogeneity problem needs rather more biological, genetic and epidemiological input, and archaeologists are more or less helpless consumers of this information (DeWitte and Stojanowski 2015; Wood et al. 1992).

5.8.5 Selective mortality

While many archaeologists are aware of the problem of demographic nonstationarity, selective mortality is a concept which has not yet been applied to material culture in archaeology. In the following experiment, 20% of males aged 20 receive an artefact in a stationary population of c. 1000 individuals alive at one point in time, modelled over 200 years. The artefact frequencies are recorded in both the living and the cemetery populations while three scenarios are explored:

(1) The acquisition of the artefact has no impact on the mortality of the individual (black).

(2) Upon acquisition of the artefact, the mortality of the individual is increased by 60% (red).

(3) Upon acquisition of the artefact, the mortality of the individual is decreased by 60% (blue).

The effect of selective mortality was introduced by Wood et al. (1992) in the case of skeletal symptoms of diseases. Their influence on mortality is obviously more direct than in the case of grave goods. However, it is not far-fetched that artefacts carry strong socioeconomic significance (Härke 2000; Härke 2014; Parker Pearson 2003) and although they are not the direct cause of selective mortality, they might represent a variety of influences such as better or worse overall living conditions, increased or reduced access to better and more diverse foodstuffs and significant differences in daily workload. Artefacts might even be better signifiers of socioeconomic differences resulting in differentials in health and living conditions than single skeletal symptoms such as Cribra orbitalia, i.e. the example used by Wood et al. (1992).

The results of the experiments are plotted in Fig. 46 for the total population and in Fig. 47 for the subgroup of males aged 20 and over. The selective mortality effect causes strong changes to the living population signals (plus or minus c. 25% to 30%) compared with negligible offsets in the cemetery signals (c. 5%). The input artefact distribution of 20% going to males aged 20 and over is captured by the cemetery signals and the living population signals under norm conditions. The living rates in the total population are slightly offset compared with the cemetery signals (Fig. 46). The signal of the living is consistently lower than the cemetery signal in the graph for the total population. In contrast, the cemetery signal in the subpopulation plotted in Fig. 47 exactly reproduces the 20% input value. And under the condition of no mortality change, the average living population signal (black) is consistent with the cemetery signal.

A caveat regarding this experiment is the unknown strength of the artefact-linked influence on the probability of dying due to socioeconomic differences. It remains to be tested whether 60% more or less mortality is within realistic limits. As medieval mortality of individuals aged 20 to 24 is approximately seven times higher than modern mortality of the same age group, a change of 60% seems not entirely unrealistic (Duering 2014; Lopez et al. 1999).

In conclusion, archaeologists utilising cemetery data and frequencies based on age subgroups can correctly characterise the artefact distribution routine even when the presence and absence of artefacts is linked with selective mortality. But without modelling, it is impossible to describe the actual frequencies in the living population correctly, i.e. the information archaeologists need in order to study human life in the past.

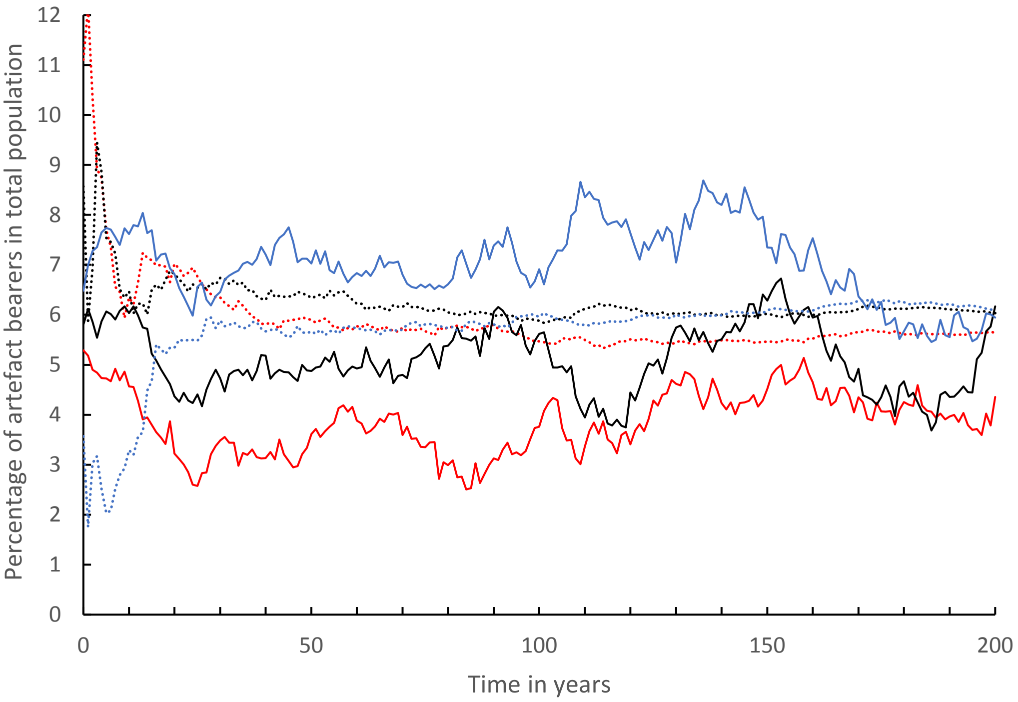


Fig. 46 20% of males aged 20 receive an artefact in a stationary population. Artefact frequencies are shown for the total living population (full lines) and the cemetery (dotted lines). Three scenarios are compared: (1) The acquisition of the artefact has no impact on the mortality of the individual (black). (2) Upon acquisition of the artefact, the mortality of the individual is increased by 60% (red). (3) Upon acquisition of the artefact, the mortality of the individual is decreased by 60% (blue).

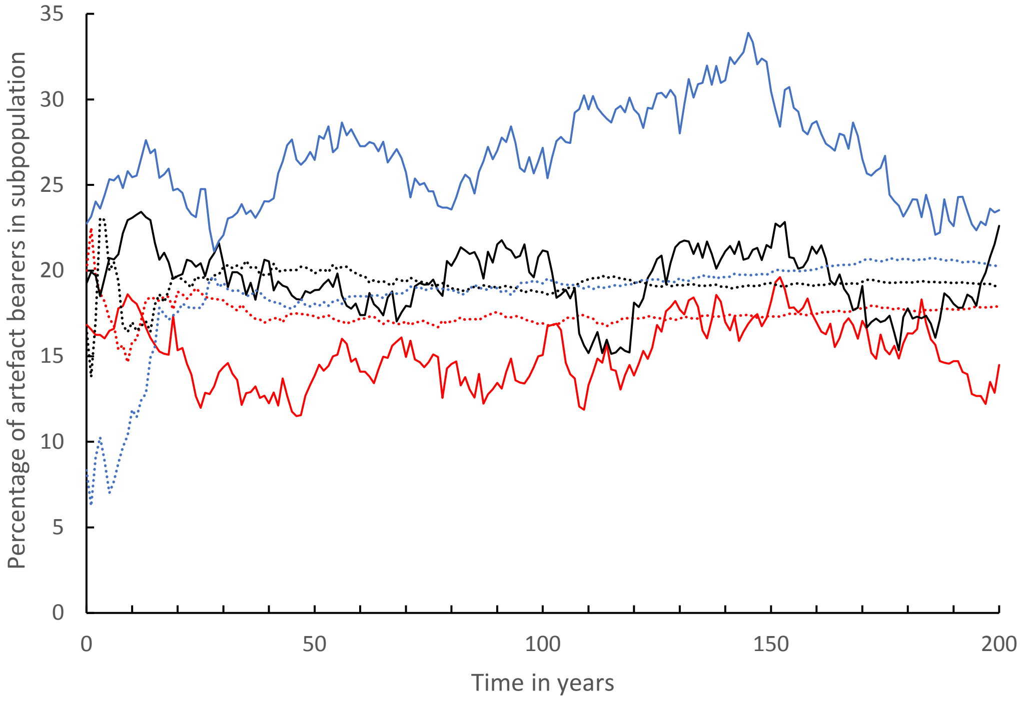


Fig. 47 20% of males aged 20 receive an artefact in a stationary population. Artefact frequencies are shown for the subgroup of living males aged 20 and over (full lines) and the subgroup of deceased males aged 20 and over (dotted lines). Three scenarios are compared: (1) The acquisition of the artefact has no impact on the mortality of the individual (black). (2) Upon acquisition of the artefact, the mortality of the individual is increased by 60% (red). (3) Upon acquisition of the artefact, the mortality of the individual is decreased by 60% (blue).

5.9 Methodological conclusions

5.9.1 Living populations and cemeteries

The definitions of the terms '*population',* often used to describe the individuals buried together in one cemetery but also used to refer to a larger group, and '*community'* which is more likely to be used in the context of single living populations and settlements, are complex, elusive and need to be defined in each individual case. The definitions of both *populations* and *communities* should be regarded as dynamic working hypotheses, given that narrow definitions are impractical in scientific research and often do not capture the whole range of cases in reality. For example, we need to be aware of the fact that while most analyses in archaeology and palaeodemography require a stationary population hypothesis, the past reality was dynamic and far from static (contrary to Acsádi and Nemeskéri (1970)) (Séguy and Buchet 2013). Furthermore, most small populations in archaeology are counterintuitively studied as if stochastic effects which distort collected numbers and rates were small or even non-existent, although we know that as shown above, the effects of low numbers are immense and often govern the data more strongly than the actual properties of the past populations. A demographic modelling approach to archaeological populations allows for subpopulations and population networks to be hypothesised and created virtually, while at the same time providing archaeologists with a basis from which the properties of such populations can be studied experimentally; for instance, it is possible to model the instability of such small populations. The most practical way to build a population is via the basic parameters of life and death described by demographers long ago: mortality, reproduction and growth (Courgeau et al. 2016; Séguy and Buchet 2013). Modelling helps to visualise and analyse the difference between living populations and cemeteries. Cemeteries are often described as 'populations' in archaeological, and especially osteoarchaeological research, when, for instance, incidents of skeletal pathologies are collected based on a 'population' of deceased and excavated individuals and compared against another ‘population’ in the literature. But cemeteries are not real ‘populations’, as they never existed as a network of individuals at any point in time; therefore, comparisons of cemetery ‘populations’ are complex and lead to incorrect results whenever the statistical complexity is not appreciated. Any description of burial communities or skeletal populations already presupposes elements of a living group – not only in the language used, but also in the analytic models applied. Modelling possible living populations while at the same time virtually ‘creating’ their cemeteries is a better way of understanding cemetery sites. The Osteological Paradox (Wood et al. 1992) and new interpretations of Anglo-Saxon cemeteries stress the complexity of cemetery formation processes, e.g. the presence of subpopulations and the regional network (Hills 2009; Hills and Lucy 2013; Sayer 2014). Cemetery archaeology consequently needs to deconstruct the term ‘population’ and develop a more probabilistic, scenario-based and humble approach to study the populations behind the cemeteries. This is what this thesis seeks to do.

The main lessons learned from the examples:

1 Cemeteries are different from living populations in many ways and the terms ‘*population’* and ‘*community’* need site-specific definitions, starting with simple working hypotheses which are transformed into complex demographic, epidemiological and social scenarios over the course of the analysis.

2 Size matters, and many archaeological samples do not contain enough individuals to yield any demographic information beyond random statistical noise.

3 Time matters, i.e. the phase lengths and periods sites were in use because of (2).

4 Dynamics over time occur in systems which are as small as early medieval populations, even when parameter values remain constant.

5 Understanding demographic parameters is useful when modelling (archaeological) populations, including their mathematical complexity, sensitivity and relative importance. It is, for instance, very important to measure fertility in archaeological populations and the

adult mortality problem focussed on by palaeodemography is less relevant in population models than childhood mortality and fertility.

6 Demographic parameters are influenced by both biological and social effects. These should be considered together.

7 The modelling of migration and exogamy also shows that living and cemetery populations react differently. Demographic modelling promises to calibrate results obtained in stable isotope and genetic migration studies.

8 Cemeteries are, further, very likely to contain multiple subpopulations with different mortality regimes, e.g. different social strata with differential access to foodstuffs and goods. These differences need to be measured based on the observations made in the Osteological Paradox article (Boldsen 2005a; Boldsen 2005b; Boldsen 2008; Boldsen and Milner 2011; Wood et al. 1992). But the results in the study are not restricted to biological and pathological data; instead they also affect the material culture associated with burials.

5.9.2 The 'Archaeological Paradox'

The study of artefacts in cemeteries requires demographic information, both on the individual level (age, sex) and on the aggregate population level. The virtual experiments conducted here show the practical impact of the effects described in the Osteological Paradox (Wood et al. 1992) on the interpretation of material culture in conjunction with the biological and demographic evidence. Basic approaches in cemetery archaeology can be improved by the application of demographic modelling approaches although the PCS can be utilised equally well for pure osteoloarchaeological research, e.g. the palaeoepidemiological modelling. As the insights gained occupy exactly the point after which the data have been procured and before interpretative procedures start, they do not replace traditional methodologies but seek to improve them. By introducing the Osteological Paradox in more general archaeological research, the fourth point mentioned in the chapter "Is there hope?” (Wood et al. 1992) can be addressed. A more profound understanding of the heterogeneity of the excavated populations in terms of migration, social rankings etc. can be reached by including the vast artefact evidence characteristic of cemetery sites in many periods and regions.

1 In all archaeological cases that involve the extrapolation from a static dead population to the dynamic living population, simple frequency comparisons are highly problematic. Artefact frequencies which were calculated without tackling the problem first described for disease frequencies in the Osteological Paradox by Wood et al. (1992) are most likely incorrect in the living population. It is therefore legitimate to call this a general Archaeological Paradox.

2 The mathematical procedures required are complex enough that computer technology must be applied to solve them. The Archaeological Paradox is a problem for which modelling with the PCS can present practicable solutions.

3 The layman’s description of the Osteological Paradox – the case of high mortality rate diseases which produce no symptoms in the skeleton – is less important in the case of artefact studies in cemetery archaeology. However, the three underlying effects described by Wood et al. (*demographic nonstationarity, selective mortality and hidden heterogeneity in risks*) cause problems in archaeological interpretation.

4 The problems of demographic nonstationarity and selective mortality can be addressed by applying the demographic modelling software, PCS. Demographic nonstationarity has a milder effect than selective mortality. But whereas selective mortality almost entirely affects the living population signal, demographic dynamics also bias the cemetery frequencies.

5 One must be aware of the problem of hidden heterogeneity in risks. The aggregate is not informative of every single individual’s state of health. But archaeologists cannot do very much about this general palaeodemographic problem. As soon as differences in frailty

between subpopulations are observed, they are best modelled separately and are then no longer hidden.

6 Selective mortality is a very valid concept for artefact studies in cemetery archaeology. As soon as artefacts define population subgroups, e.g. social strata differentials, different mortality between the subgroups can cause problems when interpreting artefact frequencies.

7 A lot of problems can be avoided when frequencies of artefacts are published for specific age groups and sex and also for probable subpopulations. Crude frequencies based on population totals are strongly governed by uncontrollable demographic effects.

8 Artefacts are more complex than diseases because the processes of acquisition and loss, as well as their attachment to the individual, is less direct than with diseases. Only grave goods that represent a state of the life of the individual and artefacts which were acquired through rites of passage during the life of the person are relevant for the Archaeological Paradox. Objects which solely represent a state after the death of the individual, such as a grave good placed in the burial due to a ritual which is not contingent on the deceased individual’s life, do not play a role in the mathematical processes described here. But the presence and absence of grave goods that signify socioeconomic differences within populations have particular potential to cause paradoxical behaviours in living population frequencies.

VALIDATION STUDIES

6 The Costs of Late Marriage. Modelling medieval marriage ages and fertility[2]

Chapter 6 represents a validation study which explores the parameter sensitivity of fertility in medieval populations and demonstrates that demographic data combine biological and social elements, i.e. nitrogen stable isotope data informative of the weaning age of children and historical marriage ages. Furthermore, an alternative deterministic mathematical model is run alongside the PCS to validate results methodologically. Later medieval osteological data and modern WHO data were used to independently test the results of the PCS and to develop contextual understanding for the range of possible fertility values for early medieval populations modelled in the following case studies.

This chapter challenges current interpretations of female medieval marriage age. The starting point of the female reproductive phase, i.e. the age at which a women gives birth to her first child, which would normally be situated soon after marriage in the European medieval setting, is one of the most sensitive parameters with respect to the survivability of small human populations, i.e. villages and dispersed settlements characteristic of around 95% of the population in the early medieval period in Northern Europe (Benedictow 1996; Hamerow 2002; Hamerow 2011; Hamerow 2012). The accompanying results suggest that the challenging demographic situation of populations of the earlier phases of the medieval period do not allow for a late onset of human reproduction. Most importantly, the factor of long periods of child-spacing studied in bio-archaeological stable-isotope research on weaning (Fuller et al. 2003; Henderson et al. 2014) is probably incompatible with late marriage. Thus, in most medieval populations within the whole period, and especially during the

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[2] This chapter represents research undertaken together with Dr Thomas Woolley and Rosalyn Leaman from the Mathematical Institute, University of Oxford. The majority of the text represents my own original work. I have highlighted the section written by the mathematicians.

Anglo-Saxon period, it is improbable that the average female marriage ages were as high as 21 to 25 years of age as suggested in current archaeological and historical research on medieval life and marriage (Gilchrist 2014: 106-107; Sayer and Dickinson 2013: 293).

Our understanding of demographic change in the medieval period strongly depends on information about social and biological parameters which influence female fertility. In the absence of direct data, modelling approaches utilising skeletal and historical mortality can be used to assess different marriage patterns. This chapter demonstrates the value of collaborative research between archaeology and mathematical modelling for contextualising scientific findings in historical demography, osteoarchaeology and palaeodemography.

A key question in archaeology is the reproduction of demographics of populations from the written sources and skeletal human remains that are left behind. Good historical data on demographic aspects are rare for the earlier phases of the medieval period and very much skewed towards the nobility (Gilchrist 2012; Hinton 2013; Isabel Davis et al. 2003; Shahar 1991). Information obtained by historical demographers about late medieval and early modern populations is still dominated by small, problematic datasets before the middle of the 16th century (Ackerman 1976; Bumpass 1969; Coale 1992; McCarthy 2004; Schofield 1985a; Schofield 1985b). For example, the study by De Moor and Zuijderduijn (2013) based on portraits in the early modern Low Countries can hardly be interpreted as a representative cross-section of society, while the 404 parishes yield data starting in the first half of the sixteenth century (Kelly and Ó Gráda 2012; Wrigley and Schofield 1989). But the 1000 years defined as medieval are hardly represented in the historical record and more reliable data are available for the period after AD 1541 (Wrigley and Schofield 1983; Wrigley and Schofield 1989). On the other hand, Italian sources are more abundant from the beginning of the 15th century including information for c. 10,000 individuals from different social strata and environments, such as the countryside surrounding Lucca, Tuscany, and Varese, Lombardy, and the urban populations of Legnago and Florence (Dalla-Zuanna et al. 2012).

Archaeological information on marriage, fertility and mortality is even harder to obtain. However, skeletal populations have the advantage of being abundant from the Migration Period through to the Early Modern Period. Fertility and marriage cannot be directly studied, but can be modelled or otherwise estimated based on the mortality data obtained using skeletal ageing methods and secondary information of the archaeological context (Crawford 2007; Duering 2014; Duering and Wahl 2015; Gowland and Chamberlain 2002). Skeletal ageing methods and the projection of mortality curves based on life table calculations have their own intrinsic problems which are discussed above (Bocquet-Appel 2008a; Bocquet-Appel and Masset 1982; Chamberlain 2006; DeWitte and Stojanowski 2015; Hoppa and Vaupel 2002a; Hoppa and Vaupel 2002b; Johansson and Horowitz 1986; Kemkes-Grottenthaler 2002; Konigsberg and Frankenberg 2002; Konigsberg et al. 1997; Milner and Boldsen 2011; Milner and Boldsen 2012a; Milner and Boldsen 2012b; Wittwer-Backofen et al. 2008; Wood et al. 2002; Wood et al. 1992).

Of course, not all skeletons survive and methodological ageing inaccuracies might bias the materials used. What is left is an incomplete record of history, which needs to be interpolated. As an aid to put this interpolation on a rigorous footing this chapter presents the construction and results of two numerical models, which were designed to emulate living populations and their cemeteries. The idea is that the two models offer different ways of understanding a medieval population, as well as provide new tools for archaeologists to test their ideas on simulated populations. Equally, each model offers an independent test for the results of the other. As describe above, the PCS is a stochastic agent based model that provides highly detailed information on each member of the population.[3] The accompanying deterministic model (DM) is comprised of a set of differential

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[3] Agent-based models such as the PCS are stochastic, a term from mathematics. It means that the behaviours of each individual agent are subject to randomness. Aggregate data can be used to study the

equations and is derived from the PCS.[4] The DM is able to offer similar results to the PCS from a simplified view of the interactions, whilst also offering analytical links between the parameters and resulting effects. Here, the models have been parameterised using data drawn from the (osteo-) archaeological and modern demographic record. However, the parameters are easily manipulated offering future researchers a quick and simple way of testing their data and hypotheses.

As a way of validating the power of micro simulations of historical and archaeological populations compared to Malthusian macro models (Hatcher and Bailey 2001; Kelly and Ó Gráda 2012), this chapter focuses one of the most important parameters in such a model, i.e. the marriage age of females and its influence on their reproductive phase. In the Christian European medieval context, it is reasonable to assume that the majority of first births happened around or soon after marriage (the problem of illegitimate children was described above). The close link between the age of first marriage and the age at which women have their first child is long established lore (Bennett et al. 2013; Hajnal 1965; Hajnal 1982; Isabel Davis et al. 2003; Kelly and Ó Gráda 2012; Laslett 1971; Lesthaeghe 1971; Marini and Hodsdon 1981; McCarthy 2004; Morgan and Rindfuss 1999; Murray 2001; Nath et al. 1993; Schofield 1985b; Zhang 2000). This research does not assume that illegitimate births, e.g. children from relationships with slaves, contributed considerably to the normal demographic signal and there is awareness that marriage concepts were more complex in Germanic law codes than in the later Christian phase (Ade et al. 2008; Benedictow 1996; Brooke 2002; Donahue 2007; Gies 1987; Gilchrist 2012; Sayer 2014; Sayer and Dickinson 2013; Shahar 1991). The models discussed here represent a simplified version of reality and are mainly concerned with the female line which is the more relevant in terms of reproduction.

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system probabilistically. For example, from data we can prescribe an average age of death. However, this age of death is only true when averaged over the population as a whole. An individual agent may die sooner or later than this age suggests, but we expect the individual death ages to be clustered around this mean value. As such, the PCS requires multiple repetitions to assess the general behaviour of the populations. However, the PCS also offers the opportunity to follow the modelled life history of each individual in the model.

[4] In contrast, there is no randomness in the DM. The DM acts like an averaged version of the PCS, and, thus, does not represent every single individual in the model.

Historical demographic literature assumes relatively high marriage ages for medieval women, of up to 25 years on average with reference to the seminal study of late medieval and early modern demographic regimes in Northwest Europe by Hajnal (1965) (Bennett et al. 2013; De Moor and Van Zanden 2010; Gilchrist 2012; Hajnal 1982; Shahar 1991). Hajnal linked this demographic state observed in the seventeenth and eighteenth century British Isles, Low Countries, German speaking countries, northern France and Scandinavia (including Iceland and excluding Finland) with a different neolocal household system that emerged when markets and wages became more important and the influence of the Church redefined marriage as a contract between two individuals in contrast to the earlier joint and patrilocal household system where marriage was negotiated between families, i.e. heads of households (De Moor and Van Zanden 2010; Hajnal 1982). A large study of early modern historical data suggests that females married late in England between AD 1541 and 1871 (Wrigley and Schofield 1989).

There is plenty of historical evidence that the late marriage system was restricted to northwest Europe and that Southern Europe and the Arab world adhered to a system of early marriage (Dalla-Zuanna et al. 2012; Engelen and Puschmann 2011). Conservative observations still place the emergence of the late marriage regime into the sixteenth and seventeenth centuries (De Moor and Van Zanden 2010; De Moor and Zuijderduijn 2013; Hajnal 1982). The difference between urban and peasant populations must also not be forgotten. Rural populations tend to have lower marriage ages than the growing proportion of inhabitants of towns during the medieval period (De Moor and Van Zanden 2010). Can the exceptional demographics of early modern Northern Europe be informative of the fertility regime of the earlier medieval period which is cautiously attempted (Gilchrist 2014; Sayer and Dickinson 2013)? The assumption of late female marriage, however, contrasts with the older historical literature that stresses early marriage in patrilocal agricultural populations (Hajnal 1965; Hajnal 1982).

The biological observation of the age at which human beings become fertile (Grupe et al. 2005) combined with the medieval legal practice that permitted the marriage of girls aged as early as 12 years and boys at the age of 14 years (De Moor and Van Zanden 2010; Donahue 2007; Hajnal 1982; Reynolds 1994) suggests that medieval women could become pregnant as early as in their 12th to 16th year of life. Comparisons with ethnographic data reveal that the average age at first birth and the age of marriage is mostly not as low as the above mentioned biological minimum but rarely rises above 20 years (Bumpass 1969; Coale 1992; Engelen and Puschmann 2011; Fox et al. 1979; Guo et al. 2015; Laslett 1971; Lesthaeghe 1971; Westoff 1992; Zhang 2000; Zhang 2014).

As the marriage age has a strong impact on demographic models of medieval populations, the following analyses which concept of medieval marriage is the most probable for the majority of the peasant population in the early medieval and medieval periods, for which a growing number of osteological datasets are being excavated (Benedictow 1996). This also seeks to raise awareness of the fact that researchers in historical demography, anthropology and archaeology have already demonstrated the influence of nuptiality and fertility on population growth (Lesthaeghe 1971; Wood et al. 1992). The power of the PCS and DM presented here is that the mortality patterns of excavated cemetery populations can be tested against different fertility/reproduction parameters which can either be estimated by osteoarchaeologists such as child-spacing, i.e. the average delay between births, or approximated in relation to the estimated parameters such as the fertile age phase and the actual probability of birth per year. It is, therefore, possible to test marriage ages defining the age when medieval women have their first child against the viability and longevity of modelled populations.

6.1 Materials

To minimise the problems of skeletal ageing this research employs a ‘minimum mortality’ profile, i.e. the WHO 1999 global average (Lopez et al. 1999) and a ‘maximum mortality’ approach based on the skeletal population of the medieval village of Wharram Percy, Yorkshire. The iconic rural medieval settlement and graveyard site of Wharram Percy dates to AD 950 to 1850 and has some well-known advantages: a relatively large number of individuals, most of which date to the medieval period (N = 687), well preserved skeletal remains, very detailed osteological analysis, high/representative ratio of sub-adult individuals (Mays 2004; Mays et al. 2007). However, if a proportion of individuals were under-aged in the Wharram sample, the actual aggregate mortality might have been lower. This is exactly why the Wharram population is very well suited as a maximum approach to rural mortality in medieval England. The mortality is parametrised in five-year age groups comparable to life tables (0-4.9, 5-9.9, 10-14.9 … 55-59.9, 60 and over) (Chamberlain 2006).

Further, the weaning behaviour that is strongly indicative of the delay time between each birth (the so-called child-spacing) has been studied in detail in the Wharram population. An average child-spacing value of 2.5 years is consistent with Mays’ and Fuller’s analysis of the nitrogen signals of the subadult population (Fuller et al. 2006a; Fuller et al. 2006b; Mays et al. 2007). The nitrogen stable isotope signal supports a weaning at age two or just before age two (Fuller et al. 2003). If one adds the time of pregnancy, an average delay between births of a minimum of 2.5 years is realistic.

6.2 Methods

To simplify comparison with the DM the PCS an abbreviated version of the PCS methodology is repeated in this section. Using the PCS, if the age distribution of a skeletal population is known (data of the dead population) one can reconstruct the mortality and fertility rates and the average living population structure in form of the standard case (0 growth, 0 migration) by a life table. More information on how this standard tool in demography is calculated can be found in Chamberlain (2006, 27-31). Based on the static state, dynamic parameter changes and changing population sizes can be modelled with the PCS. The PCS can therefore be utilised to conduct site-specific explorative models (Duering 2014; Duering and Wahl 2014b) and also allows more theoretical experiments on general parameter sensitivities such as shown here. Marriage itself is not modelled here, like Pollard (1969) did, but this research assesses marriage on the basis of its effect on the probabilities of population survival and population growth.

The PCS simulates discrete time points, which we define to be a single year. During each time step each agent of the population is uniformly randomly assigned a number between 0 and 1. This number is compared against the mortality probability, which is calculated from the mortality rate. Based on this comparison the agent is either thought to have died, or lives until the next discrete time point. In the case that the agent dies the agent is removed from the living population and added to the dead population. Similarly, for each female agent who has not given birth within the last 2.5 years and is within the reproduction age limits we randomly generate a number another uniform random number between 0 and 1. This random number is compared to the birth rate, to see if the agent gives birth, in which case a new agent of age 0 is added at the start of the next time point. Having simulated the death and birth operations for all applicable agents we update each agent’s age by one year and restart the algorithm. This work flow process can be seen in Fig. 48 and the parameters in the PCS in Tab. 7.

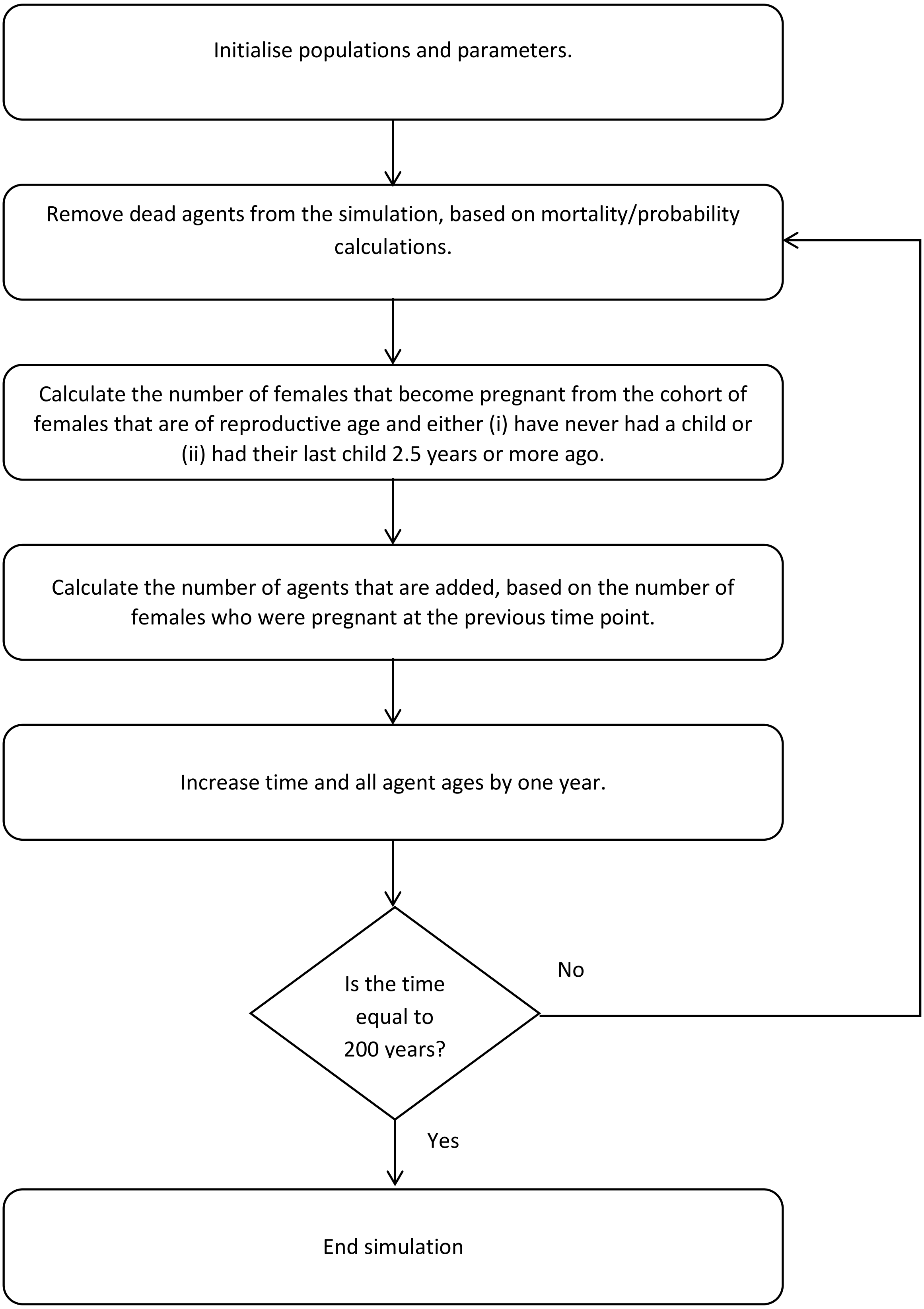

Fig. 48 Flow diagram of the PCS operations.

Initial Population	
Number of female individuals at time step 0	50 agents
Number of male individuals at time step 0	50 agents
Minimum age of the individuals of the initial population	0 years
Maximum age of the individuals of the initial population	50 years
Reproduction	
Minimum age of reproduction for females	Varied between 15 and 25 years
Maximum age of reproduction for females (menopause)	45 years
Ratio of female versus male new-borns	0.5
Temporal delay between births in years	2.5 years
Probability of reproduction at a point in time	Varied between 0.4 and 0.7

Tab. 7 Parameter definitions as used in the PCS.

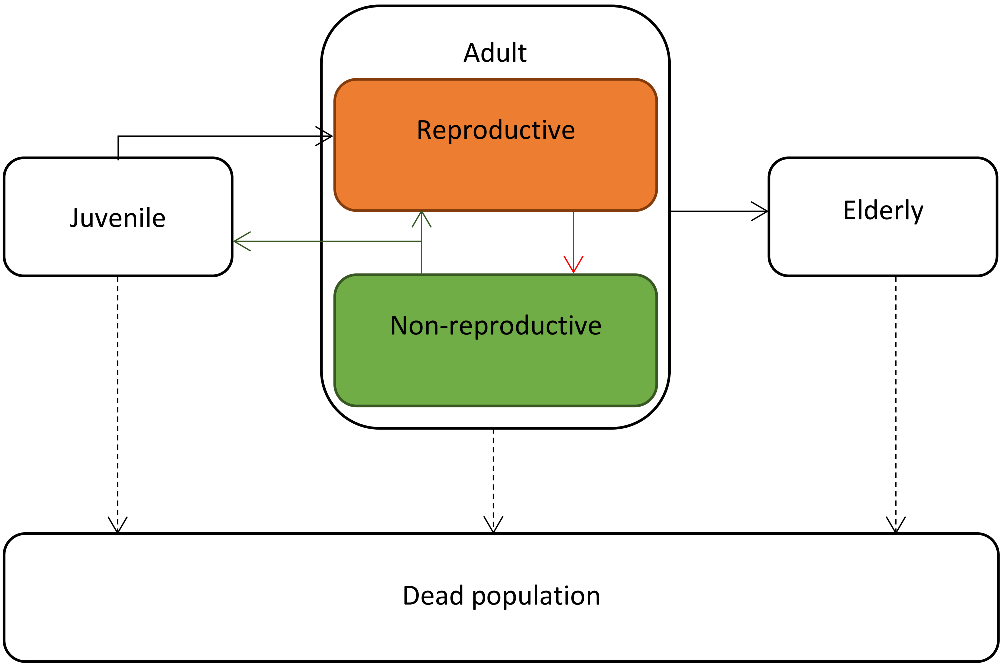

Fig. 49 Schematic diagram of the dynamics taking place in the DM model.

[5]*The DM simulates the same operations of birth, death and aging, however, it includes a number of further simplifications. Firstly, it assumes that all of the operations occur at a constant rate, rather than stochastic rate. Secondly, the population is turned into a continuum, rather than a discrete set of agents. Both of these assumptions are quite valid if the populations are large enough (for example, on the order of 100 people). Essentially, they allow the average effects of the simulations to be seen without the individual stochasticity of the agents slowing the simulations down. Thirdly, time is taken to be a continuous variable, not a discrete variable, which, of course, is more realistic. Fourthly, instead of having a highly discretised form of age the population is separated into three age categories: (i) the juvenile population,* f_j*, (ii) the adult population and (iii) the elderly population,* f_e*. The population transfers from one age compartment to the next through the use of delayed differential equations. Critically, only adult populations are able to reproduce, thus, the adult category is further split into two categories: (iia) reproductive,* f_r *and (iib) non-reproductive* f_{nr}*. The (iia) category contains all females who are able to get pregnant, whereas (iib) contains all the females who are either currently pregnant, or have given birth less than 2.5 years ago. Fifthly, and finally, just as in the PCS we assume that marriage was monogamous and, thus, the birth rate simply depends on the number of reproductive women available as there were always enough men in the population to match the women. These dynamics are illustrated in Fig. 48 and governed by the following equations:*

$$\begin{array}{c}\text{Evolution of the}\\ \text{Juvenile}\\ \text{population}\end{array} \quad \frac{\mathrm{d}f_j(t)}{\mathrm{d}t} = \underbrace{\frac{b}{2}T_p f_a(t-3/4)}_{\text{Juvenile production rate}} - \underbrace{\frac{b}{2}T_p T_c f_a(t-3/4-R_a)}_{\text{Aging to adult}} - \underbrace{d_j f_j(t)}_{\text{Juvenile mortality}}, \tag{1}$$

$$\begin{array}{c}\text{Evolution of the}\\ \text{Adult}\\ \text{Reproductive}\\ \text{population}\end{array} \quad \frac{\mathrm{d}f_r(t)}{\mathrm{d}t} = \underbrace{\frac{b}{2}T_p T_c f_a(t-3/4-R_a)}_{\text{Aging to adult}} - \underbrace{b f_r(t)}_{\text{Pregnancy rate}} + \underbrace{b T_p T_s f_r(t-3/4-2.5)}_{\text{Non-reproducible females becoming reproducible}} - \underbrace{\frac{b}{2}T_p T_c T_a f_a(t-3/4-45)}_{\text{Aging to elderly}} - \underbrace{d_a f_r(t)}_{\text{Adult mortality}}, \tag{2}$$

$$\begin{array}{c}\text{Evolution of the}\\ \text{Adult}\\ \text{Non-Reproductive}\\ \text{population}\end{array} \quad \frac{\mathrm{d}f_{nr}(t)}{\mathrm{d}t} = \underbrace{b f_r(t)}_{\text{Pregnancy rate}} - \underbrace{b T_p T_s f_r(t-3/4-2.5)}_{\text{Non-reproducible females becoming reproducible}} - \underbrace{d_a f_{nr}(t)}_{\text{Adult mortality}}, \tag{3}$$

$$\begin{array}{c}\text{Evolution of the}\\ \text{Elderly}\\ \text{population}\end{array} \quad \frac{\mathrm{d}f_e(t)}{\mathrm{d}t} = \underbrace{\frac{b}{2}T_p T_c T_a f_r(t-3/4-45)}_{\text{Aging to elderly}} - \underbrace{d_e f_e(t)}_{\text{Elderly mortality}}. \tag{4}$$

---

[5] This section was written by Dr Thomas Woolley and Rosalyn Leaman and has to be treated as separate from the thesis. The information presented is, however, essential for the validation of the PCS.

where b is the birth rate, d_j*,* d_a *and* d_e *are the death rates of the juvenile, adult and elderly population, respectively and the coefficients denoted by T are the delay parameters, that correctly scale the populations due to the time delays in the kinetics (Abia et al. 2005; Murray 2002; Woolley et al. 2012). These parameters are collected together in Table 8.*[6]

Variable	**Name**	**Units**
f_j	Juvenile population	# people
f_r	Reproducing population	# people
f_{nr}	Non-reproducing population	# people
f_e	Elderly population	# people
f_a	Adult population	# people
t	Time	years
b	Birth rate	/year
d_j,	Juvenile death rate	/year
d_a	Adult death rate	/year
d_e	Elderly death rate	/year
R_a	Initial, reproduction age	years
$T_p=\exp(-3/4d_a)$	Pregnancy time population scale	No units
$T_s=\exp(-2.5d_a)$	Child spacing population scale	No units
$T_c=\exp(-R_a d_j)$	Juvenile aging scale	No units
$T_s=\exp(-(3/4+45-R_a)d_a)$	Adult aging scale	No units

Tab. 8 Parameter definitions as used in the DM.

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[6] This is the end of the section written by Dr Thomas Woolley and Rosalyn Leaman.

By modelling an initial population of 100 individuals (50 males and 50 females) over 200 years[7] multiple times in the PCS with different rates of reproduction, one can find an approximate demographic structure by averaging over the different realisations. However, as the PCS represents a stochastic model, any individual modelling run will not be stationary.

Critically, the only parameter one must infer for the model is the birth rate. The birth rate is chosen to ensure that the population was 'stationary'. Specifically, we take our stability criterion to be that our population has at least 90% chance of surviving a 200 year interval. With an initial marriage age of 15 years (biological and legal age minimum, see above) and a child spacing of 2.5 years the Wharram Percy mortality rate can be stabilised (as defined above) by choosing a birth rate or 'probability of reproduction' of 0.425 per year. This is the probability that a fertile female will become pregnant in a given year, given that she is not already pregnant and that she has not given birth in the last 2.5 years. The probability of reproduction produces a Total Fertility Rate (TFR) of 5.1 children per woman, which is the number of children that a woman is expected to have over her entire reproductive life time, which ends with menopause at the age of 45 years.[8] With the same initial marriage age and child spacing the WHO 1999 global population (Lopez et al. 1999) data can be stabilised given a probability of reproduction of 0.193 per year, resulting in a TFR of 2.3 children. Although unrealistic when based on the Wharram Percy fertility regime, the modelling of the WHO 1999 mortality will provide a good comparison in terms of a minimum mortality approach. A list of parameter definitions as used in the PCS can be found in Tab. 8.

Dependent on the age of first marriage, we change the age at which females begin to give from the biological minimum of age 15 years to an age of 25 years. For each 'initial reproduction age' the

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[7] The choice of number of simulated years is based on the observation that archaeological sites in the early medieval period tend to stay stable for roughly 100 to 200 years before they are given up or change dramatically.

[8] TFR = [(age of end of fertile period – age of start of fertile period) / child-spacing] × probability of reproduction

living and dead populations are initiated, simulated and recorded over 200 years. Note that, due to the probabilistic nature of the simulations, it is entirely possible that populations will become extinct during the 200 years. These completely dead populations were also noted, allowing the production of a survivability probability. Further effects such as the high celibacy rates of the later medieval period, which reduce the reproductive population even further (Dalla-Zuanna et al. 2012; De Moor and Van Zanden 2010; Hajnal 1965; Hajnal 1982; Schofield 1985b), are not taken into account here as they do not change the interpretation of our modelling results.

6.3 Results

Fig. 50 shows the effect of varying the starting age of the female reproductive phase (used as proxy for marriage age, see above). The results modelled with the PCS and DM are based on the assumption that the population is stationary at an initial age of 15 years, a child-spacing of 2.5 years and a probability to reproduce dependent on the delays of child-spacing of 0.425 per year (for full stability definition see above). If the initial reproductive age, R_a, is increased from 15 to 20 years then approximately 40% of the populations become extinct before year 200, whereas 80% of the populations die out if R_a is further increased to 25 years. By dramatically increasing the marital fertility, also known as the reproduction probability, *b*, from 0.425 per year to 0.7 per year one can increase the survivability of the population, but, even with this excessively high reproduction rate, it is impossible to reach 100% survivability. To put this into context: an increase of the probability to reproduce from 0.425 per year to 0.7 per year in the model equals an increase of the TFR from 5.1 to 8.4 children. For comparison, the TFR in the Arab world fell roughly from 8 to 5 children between 1950 and 2005 (including changes in marriage ages etc.) (Engelen and Puschmann 2011).

The experiment is then repeated for the WHO 1999 global mortality pattern using the PCS. In contrast to the Wharram Percy data mortality pattern is minimally affected by a marriage age of 25

(Fig. 51). The high marriage ages have a minimal effect on survival probability for 200 years in a modern global mortality population with comparably low mortality rates. However, when under-ageing problems of the skeletal methods and sample bias are taken into account, European medieval populations would probably still have mortality patterns closer to the Wharram maximum mortality approach than the WHO minimum mortality pattern employed here.

Fig. 52 and 53 show the impact of early and late marriage ages on the development of the population size based on both the Wharram Percy and the WHO mortality patterns. Furthermore, the similarity between the DM and PCS results provides a good level of confidence that the simulations are modelling the same aspects of the problem, even though they are modelling them in different ways. Independent of a population’s mortality, the size of the population decreases exponentially as the marriage age is increased linearly from 15 to 25 years. Thus, a society with a marriage age of 25 years would be on average over 80% smaller than a society with a marriage age of 15. Fig. 54 and 55 illustrate this relationship in a different way by showing that the reproduction age’s effect on population size is independent of absolute population size. The results illustrated in Figs. 54 and 55 are based on the Wharram Percy mortality profile. The immense impact of the initial age of female reproduction on growth rates shown is further consistent with earlier models of fertility transitions for a wide range of populations around the world between 1900 and 1970 (Lesthaeghe 1971).

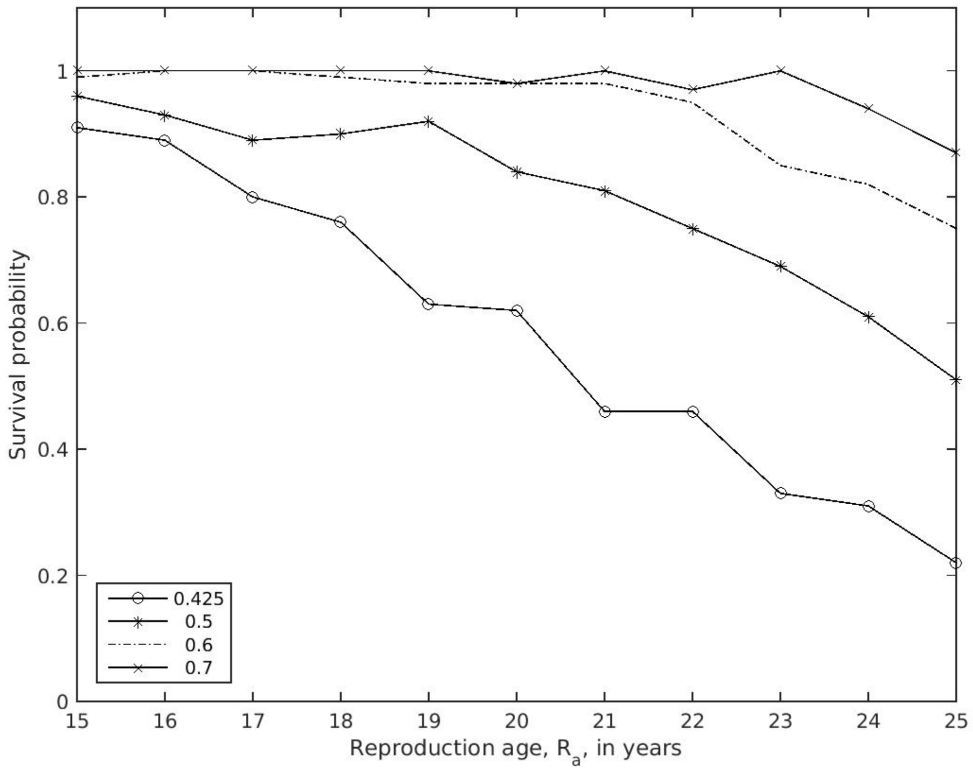


Fig. 50 Average survival probabilities of modelled Wharram Percy populations over onset of reproduction age, assessing the ratio of survived populations after 200 years of existence. Each parameter set was repeated 100 times. The onset of reproduction age equals initial marriage ages, i.e. the start of the reproductive phase for females. Each curve represents a different birth rate as illustrated by the legend.

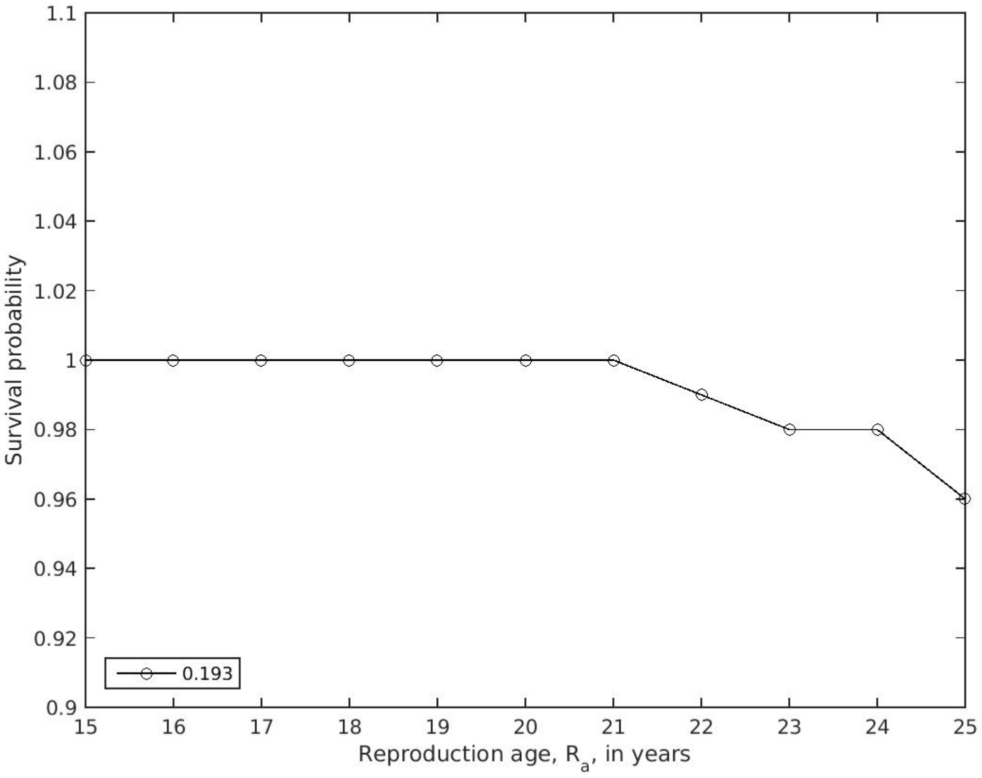


Fig. 51 Average survival probabilities of modelled WHO 1999 global populations over onset of reproduction age, assessing the ratio of survived populations after 200 years of existence. Only the stationary state with a probability of reproduction of 0.193 per year is modelled.

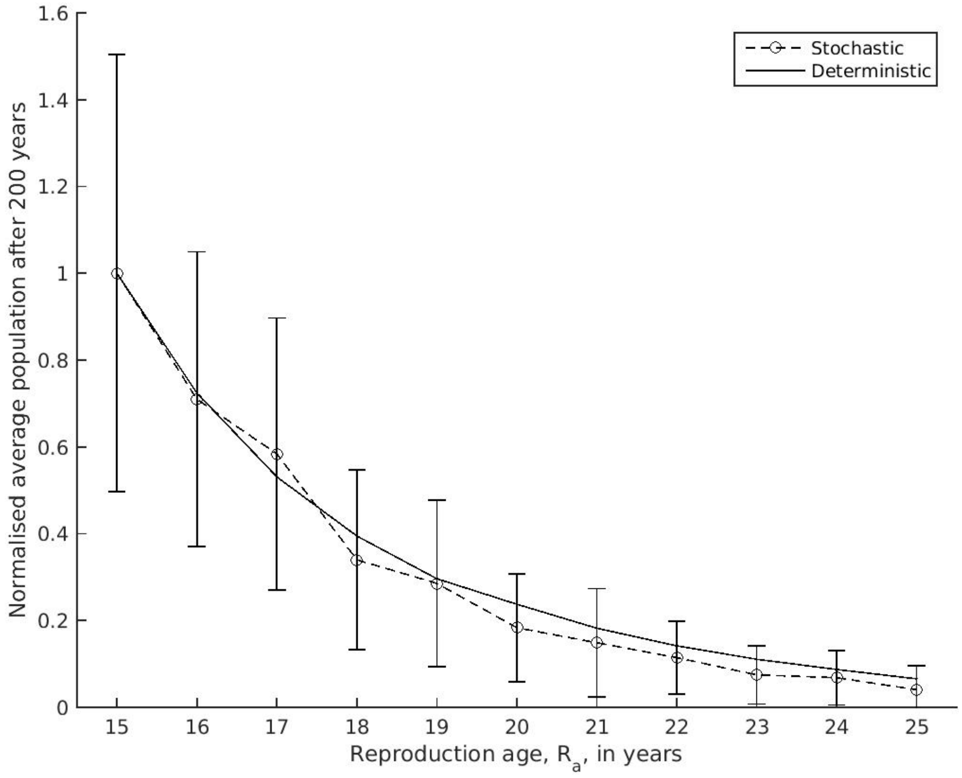


Fig. 52 The normalised effect of increasing the reproduction age on the population over onset of reproduction age, based on the Wharram Percy mortality profile. Specifically, for each reproduction age, the average population was calculated after 200 simulated years and 100 repetitions. Each average was then divided by the average population after 200 years for the reproduction age of 15 years. Hence, the average populations for the higher initial reproduction ages are given relative to the 15 year case. Error bars: 1 standard deviation of results of stochastic model.

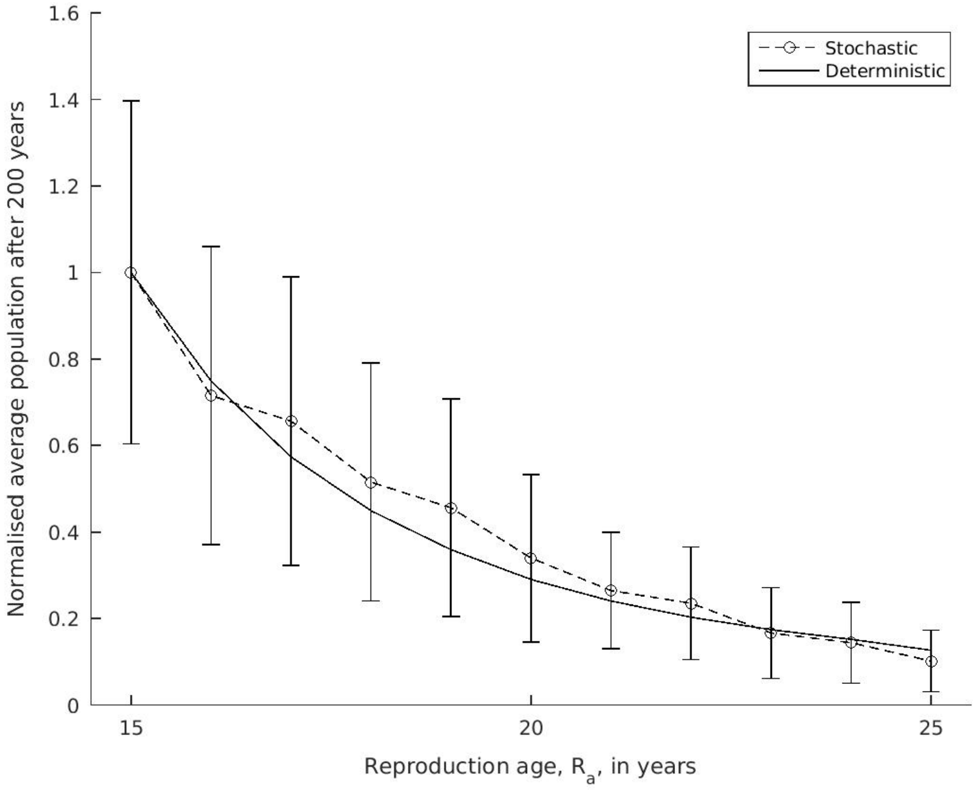


Fig. 53 The normalised effect of increasing the reproduction age on the population over onset of reproduction age, based on the WHO 1999 global mortality profile. The normalisation behind this plot follows the same method as Fig. 52. Error bars: 1 standard deviation of results of stochastic model.

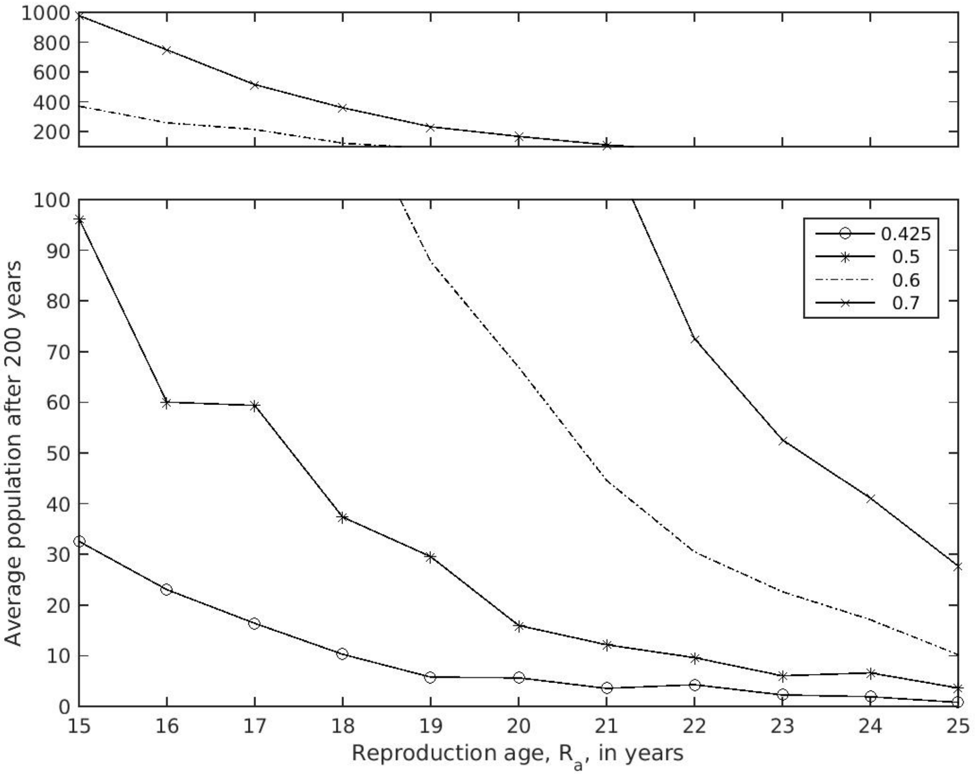


Fig. 54 Wharram Percy data. The effect of the onset of reproduction age on population size after 200 years when both the reproduction age and the probability of reproduction are varied.

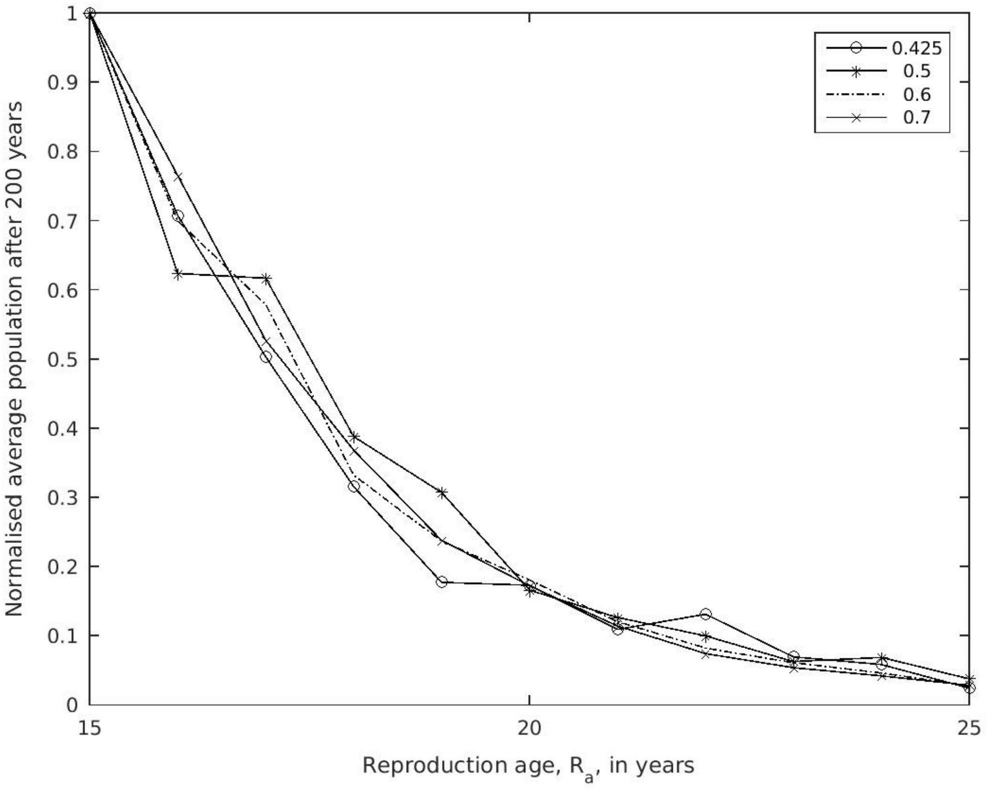


Fig. 55 Wharram Percy data. Normalised average population size after 200 years over onset of reproduction age based on the results shown in Fig. 54. The effect of the increase of the reproduction age from 15 to 25 is independent of the population size and the absolute marital fertility rate.

6.4 Discussion

Current views amongst historical demographers see a strong connection between marriage patterns and socioeconomic development in the early modern period, e.g. wages, new economic systems and the urbanisation process (Brooke 2002; Bumpass 1969; De Moor and Van Zanden 2010; Dyer 2001; Gies 1987; Gilchrist 2012; Hajnal 1965; Hajnal 1982; Kelly and Ó Gráda 2012; Lesthaeghe 1971; Rendall et al. 2011; Schofield 1985b). This close link between the demographic regime and the socioeconomic system can be observed in the modern development of the Arab world where average marriage ages have risen from c. 20 to c. 26 years between 1960 and 2005

(Engelen and Puschmann 2011). The same study also shows that the Western world started with average marriage ages for women of between 21 and 24 years in 1970 rising to between 26 and 32 years in 2005. Are medieval dynamics really as strongly reflected in average marriage ages as the enormous changes conducive of such modern demographic transitions?

Here, it was demonstrated that late marriage ages coupled with high (infant) mortality are not conducive for growing populations. In particular, producing enough children to support the growth rates of the seventeenth century would be practically impossible with delays between births of 2.5 years. Females marrying later than age 25 years miss at least half of their fertility potential when compared with modern Danish fertility curves, which peak at age 25 years (Hoem et al. 1981). Grupe et al. studied weaning strategies in the medieval town of Schleswig. The isotopic signature of children from a more urbanised early phase suggests a decreased breastfeeding phase (c. 2 years) compared with the later phase in which the town fell back into a more agricultural way of life (c. 3 to 4 years of breastfeeding) (Grupe et al. 2013). Shorter breastfeeding periods could affect the child-spacing, i.e. the interval between births. The urban lifestyle (less work, access to wet nurses etc.) might therefore permit part of the female population to maximise its fertility after a generally later marriage compared with the less frequent births in an agricultural population (Benedictow 1996; Hajnal 1982). Further, wet nurses were of considerable importance in late medieval and early modern urban populations whereas peasant women usually breastfed their children themselves (Shahar 1991).

The low literacy rates of females in the Arab world shown in Engelen and Pushmann’s study (2011) – e.g. less than 20% of women could read and write in Yemen before 1995 – raise another issue. Ages collected from historical documents are seldom challenged methodologically (Richard 2004; Schofield 1985b; Wrigley 1997). Even though the data collectors themselves might be literate and numerate, how would they deal with couples who were innumerate and, thus, did not know their ages? Economic historians have found a way to measure numeracy based on the ‘age heaping’ effect. When exact ages are unknown or must be guessed, people around the world tend to round up or round down to numbers ending in 0 and 5 (Baten et al. 2010; Crayen and Baten 2010; De Moor and Zuijderduijn 2013). The overall data might therefore be problematic, although this does not necessarily mean that the ages were consistently rounded up. But as the marriage ages of males are generally higher than the age of their wives (Drefahl 2010; Fox et al. 1979; Zhang 2014), there is also a tendency for women to adjust their age to fit that of their husband – a typical observation still prevalent today (Földvári et al. 2012). The low awareness of time and age in early modern Russia reconstructed by Kaiser and Engel for instance sheds some doubt on the historical narrative of the late marriage pattern even in the late medieval and early modern populations (Kaiser and Engel 1993). The observed high marriage ages of females might primarily be an effect governed by later marrying males, artificially dragging the female age averages with them. This would still be consistent with the historical literature on the socioeconomic changes (De Moor and Van Zanden 2010; Hajnal 1965; Hajnal 1982) but less catastrophic with regard to population survival. However, data based on family reconstitution are more reliable than direct historical age data and Wrigley and Schofield have assessed the representativeness of their sample (1989, 33-64).

High average marriage ages produce further problems regarding family planning and birth control for the long unmarried phase. High celibacy rates and strong divisions between the sexes were a common feature of the late medieval and early modern periods (note that celibacy rates were much lower in Southern Europe (Dalla-Zuanna et al. 2012)). But could ten years of the fertile phase of the average female of the population total be controlled all the time? Measures of contraception would have to be common in demographically detectable quantities. Was it really possible to delay reproduction as long as marriage in the majority of the population through norms, religious dogma and a rigid social system? This, however, is an unresolved problem. Whereas Riddle (Riddle 1991; Riddle 1992) is convinced that early abortion and plant medicines with contraceptive effects were common, Frier’s demographical assessment of Roman populations and review of Riddles arguments demonstrate that contraception and family planning are modern features of human society and had virtually no demographical effect before (Frier 1994). If effective contraception was virtually unknown, late marriage could cause considerable problems in terms of high numbers of illegitimate children.

Late marriage further increases the risk of discontinuity from one generation to the next. Heads of households need to make sure that their sons and daughters are married according to their wishes. If they marry relatively late, the chance increases that the heads of households will already have died. Inheritance continuity and social stability would be compromised if marriage was delayed to age 25. The effect of this would only be decreased by more advanced and complex social systems, where, for instance, a family can only be founded when a specific educational level is reached or some income has been gathered by wages.

One piece of evidence in support of delayed marriage in the later medieval period comes in the form of evidence relating to prolonged courting activities and *minne* from the High Middle Ages onwards. Long periods of waiting due to delayed marriage led to a culture of promise and chastity (Brooke 2002; De Moor and Van Zanden 2010; Isabel Davis et al. 2003; Kelly 1975; Lucas 1983; McCarthy 2004; Murray 2001; Reynolds 1994) which also left considerable traces in the material culture, e.g. in the form of gifts between betrothed parties (Standley 2013). Interestingly, however, the marriage ages of noble females were often demonstrated to be very low. For instance, in a study of the British ducal families between 1330 and 1954, females married at an average age of 17.1 years until 1479 (males: 22.4 years) and still at an average of 19.5 years until 1679 (males: 24.3) (Hollingsworth 1957).

Sayer and Dickinson (2013) even argue that ‘late’ average female marriage ages might go back to the Anglo-Saxon period, based on the observation that there is a peak in female skeletal remains aged 20 to 30 years compared with the age groups of 15 to 20 and 30 to 40 years (p. 293, Fig. 4). They argue that deaths during childbirth can explain this finding and stress that the risk is especially high for mothers who have their first child. Based on this demographic analysis and further archaeological evidence, they propose that Anglo-Saxons "(…) engaged institutions which controlled female sexuality: Late marriage, cultural and legal taboos and an emphasis on mature fertility (…)" (Sayer and Dickinson 2013). Sayer and Dickinson have found the same mortality peak in Indian ethnographic parallels (p. 291-293). However, they have neglected to note that studies of similar traditional Indian populations reveal average marriage ages of 15 to 17 (Nath et al. 1993). The observed mortality peak corresponds instead with the female fertility curve that is highest in the mid-twenties (Grupe et al. 2005; Hoem et al. 1981) and the declining but still consistently high mortality rates in the following age groups tell us that births happened during the complete fertile phase, which is further consistent with Frier's (1994) results of rather limited demographic impact of family planning in early historical populations. There is no reason to believe that the mortality peak between age 20 and 30 is inconsistent with Hajnal's early marriage pattern (De Moor and Van Zanden 2010; Hajnal 1965; Hajnal 1982). The average ages of the first marriage for males are not discussed here as their effect on fertility is limited. Males were probably often considerably older than their wives (Cain 1983; De Moor and Van Zanden 2010; Drefahl 2010; Hajnal 1965; Hajnal 1982).

6.5 Conclusions

Having simulated medieval population dynamics through two different approaches, namely using the stochastic Population and Cemetery Simulator (PCS) and the deterministic model (DM), respectively, one can be confident in the consistency of the results regarding the influence of marriage age on population size. Specifically, the population size and survival are highly dependent on the initial age of reproduction. Moreover, the close correlation between initial age of reproduction and the average age of first marriage can be used to demonstrate that the North

European marriage pattern is not generally applicable to rural agricultural medieval populations before the fifteenth century – including Anglo-Saxon populations.

The cost of late marriage is high. Populations with mortality patterns close to that of Wharram Percy would run high risks of dying out even if the probability of reproduction is strongly increased. Further, the harsh overall effect of late marriage on population size is very similar in both mortality patterns, including the WHO 1999 global. Although the WHO population size is greatly decreased, the modelled populations only become extinct less than 10% of the time. As the late marriage pattern (=female marriages at c. 25 years of age) is also closely connected with socioeconomic changes as proposed by Hajnal (De Moor and Van Zanden 2010; Hajnal 1965; Hajnal 1982), the patrilocal household and low fertility regime of agricultural populations in the periods before 1400 are more consistent with average marriage ages of 15 to 22 years. Ethnographic and historical studies of populations in similar socioeconomic conditions around the world support early marriage ages for medieval Europe (Andorka 1994; Bumpass 1969; Cain 1983; Dalla-Zuanna et al. 2012; Engelen and Puschmann 2011; Fox et al. 1979; Guo et al. 2015; Kaiser and Engel 1993; Kumari 1997; Laslett 1971; Lelis 2003; Lesthaeghe 1971; Rheubottom 2000; Westoff 1992; Zhang 2000; Zhang 2014). The fascination with late marriage age is understandable because it can be utilised to argue for redefined roles of women in society (De Moor and Van Zanden 2010; Kelly and Ó Gráda 2012). However, this research shows that the average woman is likely to have married before or around 20 years of age in the majority of medieval populations. However, if population size and the relative number of children compared to adults was to be kept under control in an increasingly complex late medieval and early modern society, regulations and norms affecting marriage ages were a powerful way of controlling population size and avoiding catastrophe (Kelly and Ó Gráda 2012; Rendall et al. 2011). This idea dating back to Malthus and Hajnal (Hajnal 1965; Hajnal 1982) probably does not represent conscious behaviour but rather an emerging demographic effect of an urban lifestyle.

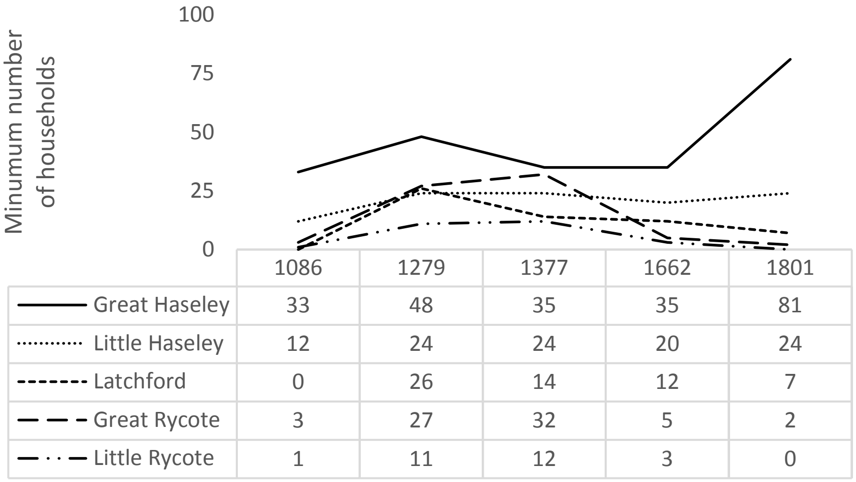
7 Modelling the population dynamics of a medieval parish in south Oxfordshire

The following second validation study tests PCS models (usually reliant on cemetery data) against a historical dataset which includes only data relating to the living population and shows that some information can be gained by modelling on a macro-picture level using data of the period between the early medieval and the early modern period. It is designed to bridge the gap between the periods and illuminate how living population data, i.e. population size and settlement dynamics can be tackled using the PCS. This validation study is particularly relevant from the perspective of the combination of incomplete historical and archaeological datasets. Can crude data from a period of over 700 years contribute to our understanding of the demographics of medieval settlements? What lessons can be learned for the interpretation of early medieval settlements and their demographics?

Stephen Mileson, Chris Wickham and Stuart Brookes have collected demographic data for parishes in south Oxfordshire for 'The South Oxfordshire Project: perceptions of landscape, settlement and society, c.500-1650', based at the History Faculty, University of Oxford (Mileson 2012). The settlements of Great Haseley, Little Haseley, Latchford, Great Rycote and Little Rycote were chosen to conduct this demographic validation study. A part of the project was to model the overall population development based on parish registers and tax polls between 1086 and 1801 using the PCS. This will lead to a better understanding of the appearance of the settlement landscape, which is crucial to understanding how "inhabitants understood and shaped their environment" (Mileson 2012, 85). This model focusses on the living population only; the aim is to model the development of the population of all five settlements based on the historical information obtainable for the number of households as proxy for population size. The questions addressed in the following are (1) whether the demographic modelling offers some insight into the reliability of the historical data and (2) if and, if so, under which circumstances it is possible to reconstruct a population over the 715 years which follows the historical proxies.

7.1 Materials

The minimum number of households was estimated based on historical data collected by Stephen Mileson for the parish of Great Haseley, in the ancient Ewelme hundred, for five points in time (Fig. 56) (Mileson 2012). The actual population size was only obtainable for 1801 and to minimise problems of projecting population size numbers, the following model relies on the development of the heads of households only. Further, the internal differences between the settlements are not modelled, e.g. the decline of Great and Little Rycote compared with the peaking population of Great Haseley. Instead, the population proxy used here is a sum of the numbers in all five settlements (Fig. 56, 57 and Tab. 9). This simplified approach is justified as the data have a number of severe shortcomings; for instance, comparison of the number of heads of households between 1086 and 1279 is highly problematic as the unrecorded population is unknown. Possible changes in recording regimes and increasing social differentiation over the two decades further complicate data comparison (Hinton 2013). The recorded population of heads of households for 1377, for example, included only adults aged 14 years and older. The 1662 number is based on recorded taxpayers, but it is known that all over England, data were collected differently in 1665. Although consistently fewer taxpayers are recorded almost everywhere in 1665 than in 1662, this is not a sign of population decline (pers. comm. with S. Mileson and S. Brookes). Finally, the 1801 number represents the number of recorded houses, which is another problematic proxy for household numbers. But as both the numbers of houses and the actual population numbers are known for 1801, a crude check of the 1086 historical demographic estimate of 4.5 individuals per household can be conducted (Hinton 2013). The 33 households in 1086 are estimated to amount to a population of c. 149 individuals. Using the same logic, the 81 houses in 1801 would amount to a population size of 365. But the recorded number is actually 393. Consequently, an average of 4.9 individuals belonged to one household in 1801. The difference is surprisingly small, with only 0.4 individuals more per household in 1801 than in 1086. Hinton (2013) argues that there is an unknown number of additional individuals unrecorded in Domesday Book data, which would raise the 4.75 estimate by an unknown amount. It is therefore not completely unreasonable to model 715 years of population development in south Oxfordshire based on the data available, although the information of medieval and early modern demographics is notoriously unreliable. The data are further underpinned by the general population development of England and Wales up to the 17th century. The curves are very similar (Chamberlain 2006; Wrigley and Schofield 1989).



	1086	1279	1377	1662	1801
Great Haseley	33	48	35	35	81
Little Haseley	12	24	24	20	24
Latchford	0	26	14	12	7
Great Rycote	3	27	32	5	2
Little Rycote	1	11	12	3	0

Fig. 56 The minimum number of households estimated for five communities in south Oxfordshire at five points in time, covering a period of 715 years.

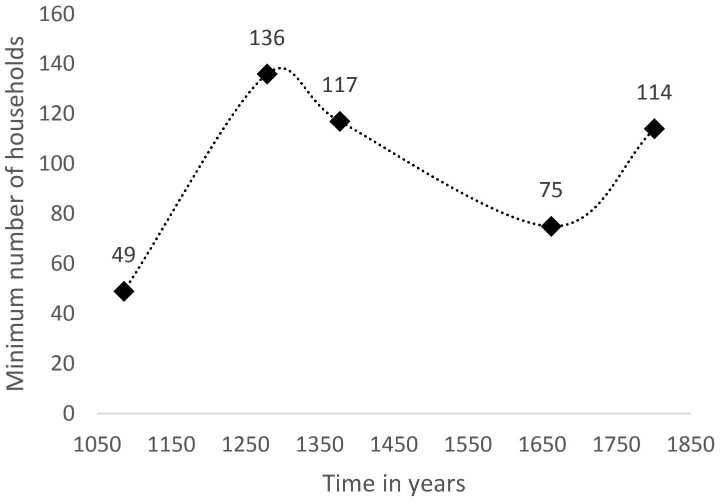


Fig. 57 The sum of the minimum number of households of all five settlements is used as a proxy for the development of the population of the parish.

	1086		1279		1377		1662		1801	
	hh	p*	hh	p*	hh	p°	hh	p	hh	p
Great Haseley	33	149	48	216	35	71	32-35		81	393
Little Haseley	12	54	24	108	24	44	18-24		24	165
Latchford			26	117	14	34	12		7	35
Great Rycote	3	14	27	122	32	60	5		2	15#
Little Rycote	1	5	11	50	12	30	3		0	
SUM	49	222	136	613	117	239	20	0	114	593

*Population estimates for 1086 and 1279 assume household sizes of 4.5.

°Population numbers for 1377 exclude sub-adults aged 14 years and under.

#Great and Little Rycote combined.

Tab. 9 The household data compared with actual population counts; data collected by S. Mileson. hh: number of households, p: population size.

7.2 Methods

The PCS is used to model a population based on a standard medieval mortality profile. The Wharram Percy mortality profile is employed based on the same reasons explained in chapter 6 (Lewis and Gowland 2007; Mays et al. 2007). Migration is often the driving force behind major changes in population size. If migration is necessary to explain the data, the population development recorded can be tested by modelling a population closed to migration which has to grow and decline based on internal dynamics. If the modelled population can follow the recorded changes in population size using internal dynamics of fertility and mortality, migration is not necessary to explain the data. If, however, the changes to fertility and mortality need to be extreme, i.e. almost biologically impossible, it is reasonable to argue that external effects led to the observed development. Although, for instance, the Black Death is included in the 715-year period, I will not use catastrophic mortality events to alter the population but will completely rely on changes in fertility. While both mortality and fertility can be used to model changes in population size over time in closed populations (Séguy and Buchet 2013); fertility has a more direct impact on population development and is reported to react more directly to socioeconomic and ecological changes than mortality (Bumpass 1969; Cain 1983; Dalla-Zuanna et al. 2012; De Moor and Van Zanden 2010; Hajnal 1965; Hajnal 1982; Kelly and Ó Gráda 2012; Séguy and Buchet 2013; Wood et al. 1992). The results presented below represent one possible scenario of population development modelled for 715 years. The number of households in the PCS is modelled based on the size of the nuclear families present at any point in time (2 parents plus the average number of children per female alive per step in time modelled).

7.3 Results

It is impossible to reconstruct the trend of the minimum number of households in Fig. 57 without changing parameters. The stochastic changes of such populations are certainly not strong enough to grow and decline the populations as indicated by the historical data. The trends can only be reconstructed if parameters are changed, i.e. by changing fertility over time. By changing the endogenous parameter fertility I succeeded in artificially rebuilding the overall population development over the 715-year period. The most difficult element was growing the population quickly enough in the first two centuries and then reversing the process at the point of its exponential reaction to decline within c. 100 years in order to reach the 1377 figure. The graph in Fig. 58 represents the development of the overall population size of the parish. Fig. 59 shows the development of the nuclear family numbers and a number of other crude estimates of household sizes. The graph in Fig. 60 plots the changes in fertility necessary to produce the pattern of population growth and decline in the parish shown in Fig. 57. Compared with Fig. 27 showing the development of the TFR in the Arab world in the last decades, it is possible to estimate whether such changes are within or outside the range of dynamics expected for a preindustrial population. The changes in the Arab world during their modern demographic transition from preindustrial societies to modern industrialised countries (Engelen and Puschmann 2011) are equal to the changes necessary in the modelled scenario for the medieval parish. The necessary TFR changes are theoretically possible, but would require, and go alongside, strong social and cultural changes. It is unlikely that changes in rural south Oxfordshire between 1086 and 1801 were as strong as during a 20th century demographic transition; this result is also corroborated by the observations made on changes within the medieval period (Hajnal 1965; Hajnal 1982).

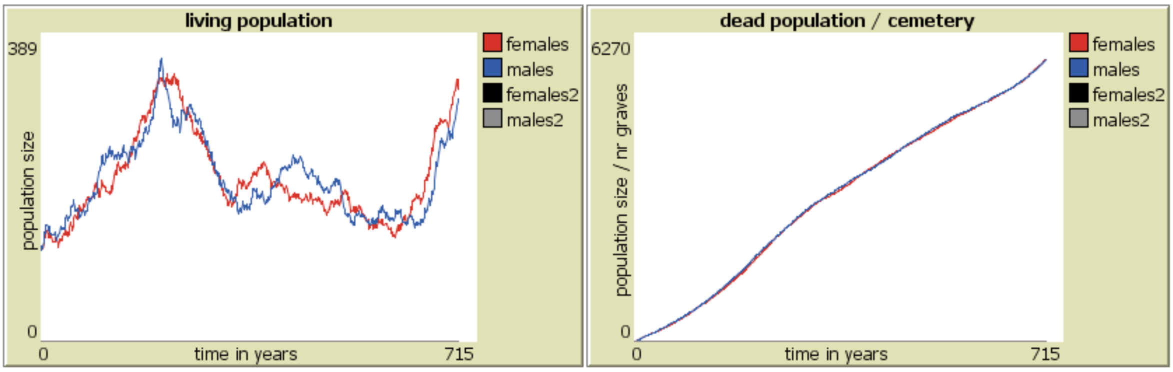


Fig. 58 Living and cemetery population development of one single run, overall parish, 715 years.

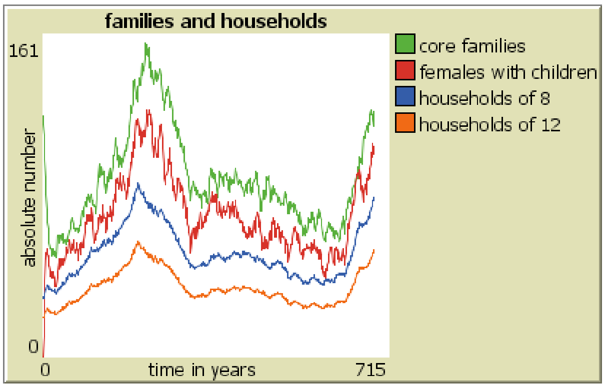


Fig. 59 The PCS's 'core' (i.e. nuclear) family plot (average number of children per female + 2 parents) can be compared with the household estimates for the parish (Fig. 58).

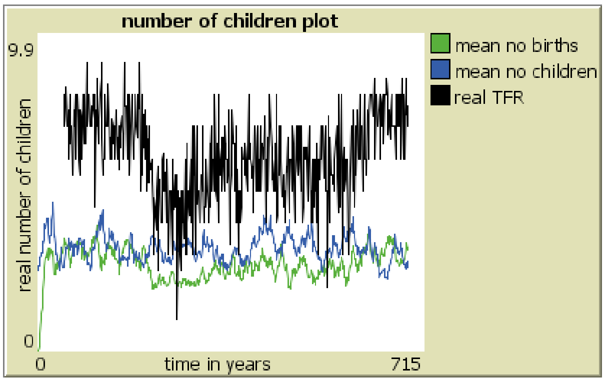


Fig. 60 The Total Fertility Rate (TFR) changes necessary to reproduce the population signal as indicated in the historical data: TFR 7 to TFR 4.6 to TFR 5.5 to TFR 6.3.

7.4 Discussion

Changes of TFR of c. 3 children per woman as observed during the demographic transition of the modern Arab countries (Engelen and Puschmann 2011), would also require to be reversed quickly between the second and third point in time defined by the historical records of the Oxon parish, which would mean not only one but multiple strong demographic changes. In a dynamic system such changes could be possible under a combination of the effects of mortality and fertility which was not modelled here and represents a valuable future route, especially if contextual information on catastrophic events is available in the historical records.

Furthermore, the average number of children aged one for each modelled year reproduces the average number of baptised children (c. 10 per year) between 1583 and 1646 (data from S. Mileson) very well: 200–300 modelled individuals produce c. 10–12 children aged 1 (newborns) per year. This can be regarded as an independent plausibility check for the conducted model.

Looking at single villages, e.g. Great Rycote between 1086 and 1279, does not change the overall picture. The population growth from 3 to 27 households in Great Rycote is possible but unlikely to be an endogenous development. Migration between the settlements could account for that, and migration between Great Haseley and the surrounding parishes is likely to produce such population changes. In Fig. 56 one can observe that the settlement of Great Haseley increases its population size dramatically whereas most of the other communities decrease in size. Without taking further contextual information into account, it can be suggested that some kind of centralisation process took place in the early modern period alongside immigration and population growth. Following the reasoning in Hatcher and Bailey (2001), further models on the small scale for short periods in time are the necessary next step. Then comparisons between the dynamics in the settlement landscape, economic and political organisation described by Mileson (2012) and the demographics can lead to a more detailed picture of the development of the parish in south Oxfordshire.

The theoretical information obtained on the stability of settlements of small size in chapter 5.6 leads to a further line of thought. Suppose that communities within the parish were relatively isolated entities over extended periods of time, or at least for a few subsequent generations within the c. 700-year period, for example, so that when some individuals died they were not immediately replaced by immigrants. Then the stochastic instability, which does not affect the complete parish, could have had an effect on the small sites individually. The complete regional population is of a size beyond 50 to 100 individuals, so that stochastic dynamics are unlikely to lead to the decline and extinction of the population. However, the smaller settlements as individual elements, such as Great and Little Rycote, are of a size small enough to be at risk. Latchford and Little Haseley are also at risk but might have survived merely based on the element of chance. Great Haseley has always had a sufficient population size to be unaffected by stochastic risks to population survival. The effect of the overall size of populations can probably be observed in the case of the five settlements: smaller sites (Latchford, Little Haseley, Great and Little Rycote) are less stable elements in the landscape than larger sites such as Great Haseley. This case study is surprisingly consistent with the theoretical models in chapter 5.6, although it is certainly unreasonable to exclude migration processes, especially when considering the growth of Great Haseley and the parallel decline of the two Rycotes.

The actual population data extrapolated from the minimum number of households are reasonable with an average of c. 4 to 5 individuals per nuclear family (PCS model)/ per household (historical estimate) for 1086 and 1801. This is consistent with models of medieval patrilocal nuclear families in the literature (Benedictow 1996; Hajnal 1965; Hajnal 1982). The modelling results work quite well for the household data for 1086 in comparison with the estimated population size for that period (model: 240, data: 228) (Tab. 6). As said above, they also work again for 1801. However, this relationship between households, nuclear families and actual population size does not work for 1377 (model: 660 vs. data: c. 480 (239x2 because c. 50% of population is sub-adult)). This might be explained by a change in the definition of the term 'household' over time. The 1377 households do not represent nuclear families modelled with the PCS, and in 1377 fewer individuals seem to be included in the households or more parts of the population were excluded in the population counts in 1377 than only those aged 14 years and under. Both the historical data for households and population sizes are not comparable over the centuries and are problematic proxies for measuring population growth and decline. Archaeological cemetery populations have the potential to contain much more detailed and fine-grained demographic information than historical demographic data from the medieval period.

7.5 Conclusions

Crude models using the PCS can be conducted using the historical data and lead to the following conclusions:

The research shows that the definition of the term 'household' must have changed drastically between 1086 and 1377, and again between 1377 and 1801. If Domesday Book calculations are used on 1377 data, they lead to much higher population sizes than recorded for that period. This blurring factor is a caveat regarding the validity of the following conclusions.

Stochasticity alone is much too weak to explain the strong changes recorded in the historical records in models of the complete parish. Parameter changes, i.e. social and biological changes, are necessary to explain the strong demographic dynamics. The smaller of the individual settlements, however, are at risk of dying out caused by the effects of low numbers.

Endogenous fertility changes can barely reconstruct the household growth and decline rates. The dynamics recorded are extremely strong which is why exogenous factors, most likely migration and a reorganisation of the settlement structure, are necessary to explain the drastic demographic changes given that the historic data contain any demographic information representative of past developments. The different developments of the villages support this explanation. Again, demographics are proved to be influenced by both biological and social factors.

CASE STUDIES

8 Modelling the families and households of Mucking, Essex

The Anglo-Saxon site of Mucking, Essex, will be used as a case study for analysing the relationship between houses, households, nuclear families and demographic dynamics between the settlement and cemeteries, i.e. the number of buildings used by the living population and the average size and composition of a household. In the following experiment, I initially suppose that the settlement and the cemetery data can be combined as if all elements excavated were used by one 'population', an entity which can consist of more than one sub-population. A demographic analysis is conducted that uses the PCS to link the living represented by the settlement context, and the dead in the cemetery. I will test the plausibility of the published interpretations and aim to produce more information about the biological composition of the households, e.g. the number of nuclear families, the relation between heads of households and buildings, the projected subadult population, the overlap of generations and the complexity of family structures under high mortality regimes, e.g. the problem of care of orphans. By continuing to model the population for an additional 100 years, it is further analysed what might have happened to the population in the following 7th century.

8.1 The site

The settlement and two cemeteries of Mucking, Essex, were excavated in the 1960s and 1970s. Fifty-three posthole buildings and 200 sunken-featured buildings could be identified on the c. 18ha site. Two cemeteries were also uncovered. The settlement was published in 1993 and the cemeteries were published in 2009 (Hamerow 1993; Hirst and Clark 2009). The site covers a relatively large area and the settlement shifted its position over time (Fig. 61). It is postulated that the dwellings were only used for brief periods of time before they were given up and new ones were built (Hamerow 1993). Mucking is unique as published settlement and cemetery data are obtainable from the same archaeological site. Although some general caveats remain, such as the problem of the two separate still incompletely excavated cemeteries in contrast to the one shifting settlement with many undated structures. Tipper (2004, 52) argues that complex middening processes might have obscured the phasing proposed by Hamerow (1993) and as some of the structures show signs of rebuilding, he interprets the contexts as a north and a south cluster of dwellings which might represent two settlements present at the same time. And even if we acknowledge that a clear spatial patterning of finds exists, Hamerow's description of the site as "…a shifting hamlet, at times perhaps more than one" shows that the settlement structure is complex (1993, 86, 90; Hamerow 2012, 69). The way in which the two cemeteries can be linked with the complex multifocal settlement remains unknown, as the phasing of the cemeteries also does not allow a direct link to be established (Hirst and Clark 2009). Further, the general problem exists that peripheral areas which have not been excavated could theoretically yield further contexts or burials although we know for a fact that parts of cemetery one were destroyed (Hamerow 1993; Hirst and Clark 2009).

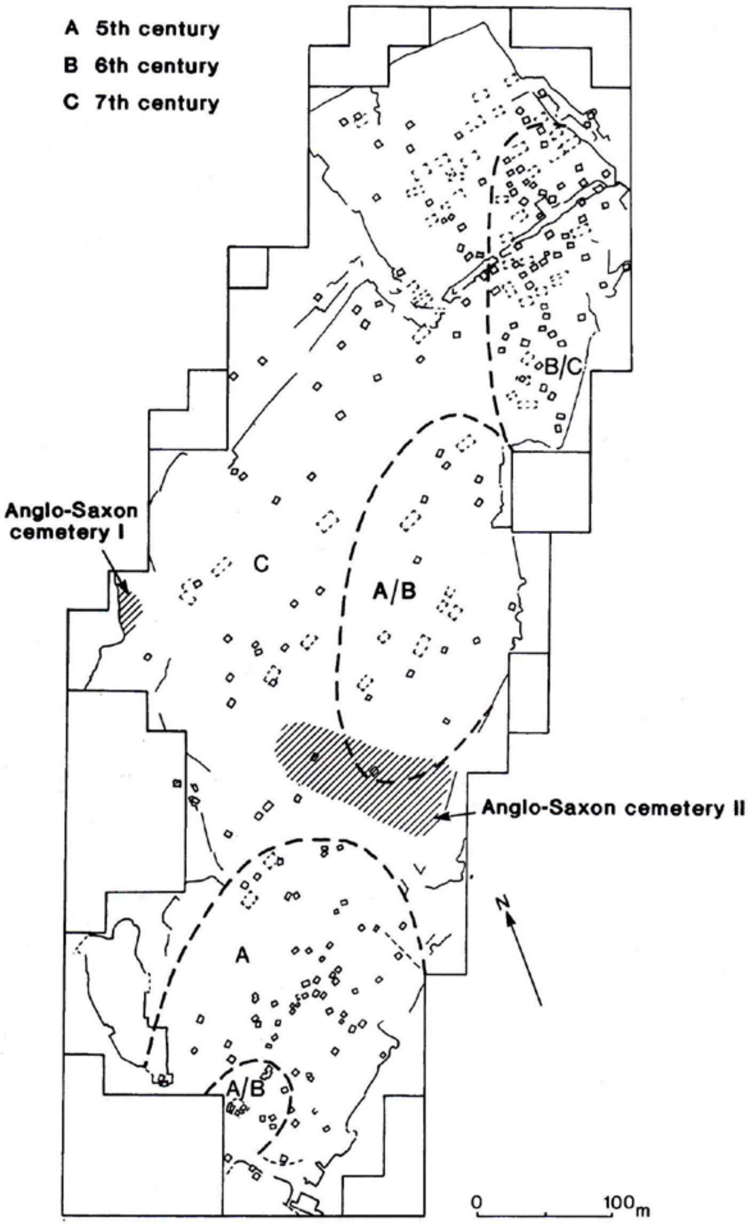


Fig. 61 The early medieval settlement of Mucking and the two cemetery sites (Hamerow 1993, Fig. 195).

Another problem is the general condition of the human remains from the two burial grounds of Mucking. Some of the skeletal elements were eroded due to the conditions of the soil, and the demographic analysis did not yield ages for 173 (21 %) of 808 diagnosed individuals (of a maximum estimate of 970 burials in both cemeteries). Furthermore, the age groups used in the osteological analysis were relatively large as the only differentiations made were between Infant/child, Adolescent and Adult (Hirst and Clark 2009). These broad age categories are not fine enough to calculate a life table. Because of the data issues it seems to be advisable to utilise a hypothetical mortality profile. The test mortality profile is based on the overall Alamannic mortality pattern published in Kokkotidis (1999), including an infant mortality rate similar to the data calculated for Wharram Percy (Mays 2004) to account for the ‘missing infant’ problem of the early medieval Alamannic data. A plausibility test is conducted for the demographic data of Mucking, combining the two cemetery sites, to check whether the mortality pattern(s) employed can roughly reproduce the age distribution in the cemeteries excavated at Mucking.

8.2 Materials

The published data are converted into parameters of the model as described below. All parameters used for this experiment can be found in Tab. 10, including the parameters which are not explicitly stated in the following.

PCS DATA SHEET VIRTUAL EXPERIMENT NO Mucking 1

<table>
<tr><th rowspan="4">Research Question</th><th rowspan="4">Observed Parameters</th><th>Number of Repetitions</th></tr>
</table>

<table>
<tr><th>Research Question</th><th>Observed Parameters</th><th>Number of Repetitions</th></tr>
<tr><td rowspan="3">Model one plausible dynamic scenario which is consistent with the settlement and cemetery.</td><td rowspan="3">Whole range of demographic parameters, especially population size and size/number of nuclear families.</td><td>1</td></tr>
<tr><th>Time / Duration of Run</th></tr>
<tr><td>200</td></tr>
</table>

<table>
<tr><th colspan="8">Initial Population / Starter Generation</th><th colspan="2">Mortality (qx)</th></tr>
<tr><th colspan="4">P1</th><th colspan="4">P2</th><td>0-4</td><td>0.25</td></tr>
<tr><td>Nf</td><td>Nm</td><td>Lage</td><td>Uage</td><td>Nf</td><td>Nm</td><td>Lage</td><td>Uage</td><td>5-9</td><td>0.104</td></tr>
<tr><td>50</td><td>50</td><td>0</td><td>50</td><td>-</td><td>-</td><td>-</td><td>-</td><td>10-14</td><td>0.058</td></tr>
<tr><th colspan="8">Reproduction / Fertility</th><td>15-19</td><td>0.047</td></tr>
<tr><td colspan="2">Minrage</td><td colspan="2">Maxrage</td><td>Fbratio</td><td>Childsp</td><td colspan="2">Reproprob</td><td>20-24</td><td>0.109</td></tr>
<tr><td colspan="2">16</td><td colspan="2">40</td><td>0.5</td><td>2</td><td colspan="2">0.375</td><td>25-29</td><td>0.135</td></tr>
<tr><th colspan="8">Selective Data Loss in Cemetery</th><td>30-34</td><td>0.142</td></tr>
</table>

<table>
<tr><td colspan="2">Chance</td><td colspan="2">Min Age</td><td colspan="2">Max Age</td><td>35-39</td><td>0.162</td></tr>
<tr><td colspan="2">0</td><td colspan="2">-</td><td colspan="2">-</td><td>40-44</td><td>0.191</td></tr>
<tr><td colspan="6">Catastrophes</td><td>45-49</td><td>0.253</td></tr>
<tr><td colspan="2">On/Off</td><td colspan="2">Delay</td><td colspan="2">X Mort</td><td>50-54</td><td>0.299</td></tr>
<tr><td colspan="2">Off</td><td colspan="2">-</td><td colspan="2">-</td><td>55-59</td><td>0.375</td></tr>
<tr><td colspan="6"></td><td>60+</td><td>1</td></tr>
<tr><td colspan="6">Artefacts / Diseases</td><td colspan="2">Mortality based on:</td></tr>
<tr><td colspan="3">Male</td><td colspan="3">Female</td><td colspan="2" rowspan="3">Kokkotidis 1999 except q0-4 estimated based on Wharram Percy, Mays et al. 2007</td></tr>
<tr><td>Iniage</td><td>Prob</td><td>X Mort</td><td>Iniage</td><td>Prob</td><td>X Mort</td></tr>
<tr><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="8">Exogamy / Migration</td></tr>
<tr><td colspan="2">Probabilities</td><td colspan="3">Female</td><td colspan="3">Male</td></tr>
<tr><td colspan="2">P2 to P1</td><td colspan="3">-</td><td colspan="3">-</td></tr>
<tr><td colspan="2">P1 to P2</td><td colspan="3">-</td><td colspan="3">-</td></tr>
<tr><td colspan="2" rowspan="2">Migrant Age</td><td colspan="2">Min</td><td>Max</td><td colspan="2">Min</td><td>Max</td></tr>
<tr><td colspan="2">-</td><td>-</td><td colspan="2">-</td><td>-</td></tr>
</table>

Tab. 10 Data sheet for the model of the Mucking case study.

One hundred twenty-five to 149 average living population size represent a maximum estimate for Mucking (Hirst and Clark 2009). Hamerow (1993, 89-91) calculated the average population size based on the population actually excavated to an approximate number of 90 people at any one point in time. The *starter population* in the model therefore consists of 50 females and 50 males as a minimum approach.

The *duration of the simulation* is 200 years, covering the period between AD 425 and 625 (Hamerow 1993; Hirst and Clark 2009). For the final part of the experiment, in which the development of the population in the 7th century is projected, the simulation is continued for a further 100 years.

As a crude *estimate of household sizes,* the published number of c. 12 individuals per structure at any one time is employed (Ausenda 1997). This is why the model records one household per any 12 live individuals. The PCS also records the number of households if 8 people lived in one building (Donat and Ullrich 1971), the real number of nuclear families as given by the average number of children per female plus parents and the proportional distribution of males, females and children in the living population.

The changing settlement and burial numbers over time have allowed Hamerow and Hirst and Clark to assume a *dynamic development* of the site with a relative increase of the buried population of c. 22 % from the 5th to the 6th centuries (Hamerow 1993; Hirst and Clark 2009). Multiple dynamic simulations are conducted and one scenario is chosen and analysed below which fulfils the following criteria: the estimated cemetery must be relatively close to 970 burials after 200 years (both cemeteries combined) and the buried population shows an approximate increase of c. 22% from the 5th to the 6th century. Hirst and Clark fall prey to the typical category error of confusing the increase of the living and the cemetery population sizes (Hirst and Clark 2009) and falsely interpret the 22% increase of burials into an equal increase of the living population which is not necessarily the same.

8.3 Results

Fig. 62 shows the development of the living and the cemetery populations. The total numbers reconstruct the excavated burials per period very well. This virtual cemetery grows from the 5th to the 6th century at a rate of 23% to 830 burials. The number of burials fluctuates very strongly depending on the development of the living population, and it is difficult to find a scenario with a specific growth rate. The living population starts off with c. 100 individuals and, after a consolidation phase, grows to approximately 140 people alive at year 200. The actual living population growth, therefore, is slightly stronger than the increase of burials in the cemetery in this virtual run. The dynamics of the living population at Mucking might have been stronger than the 22% growth estimate based on the cemetery data.

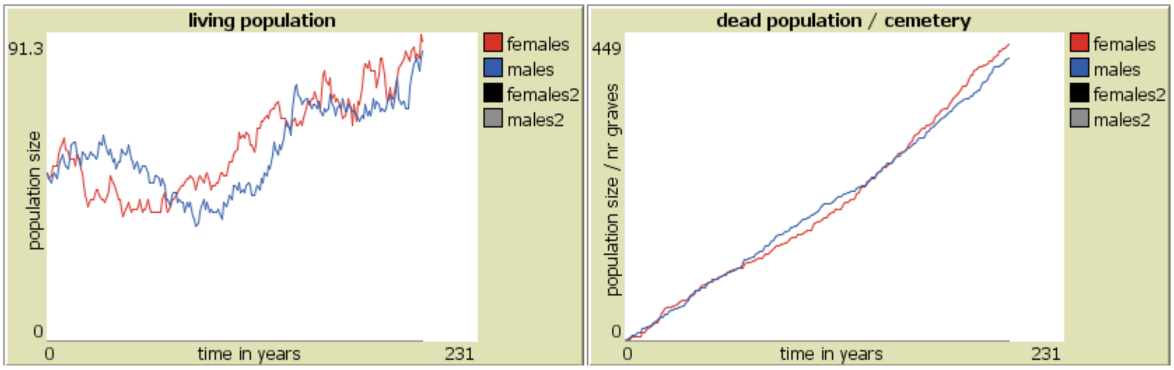


Fig. 62 One plausible simulation run. The development of the living population (left) and the virtual cemetery (right) over time; blue: number of males, red: number of females.

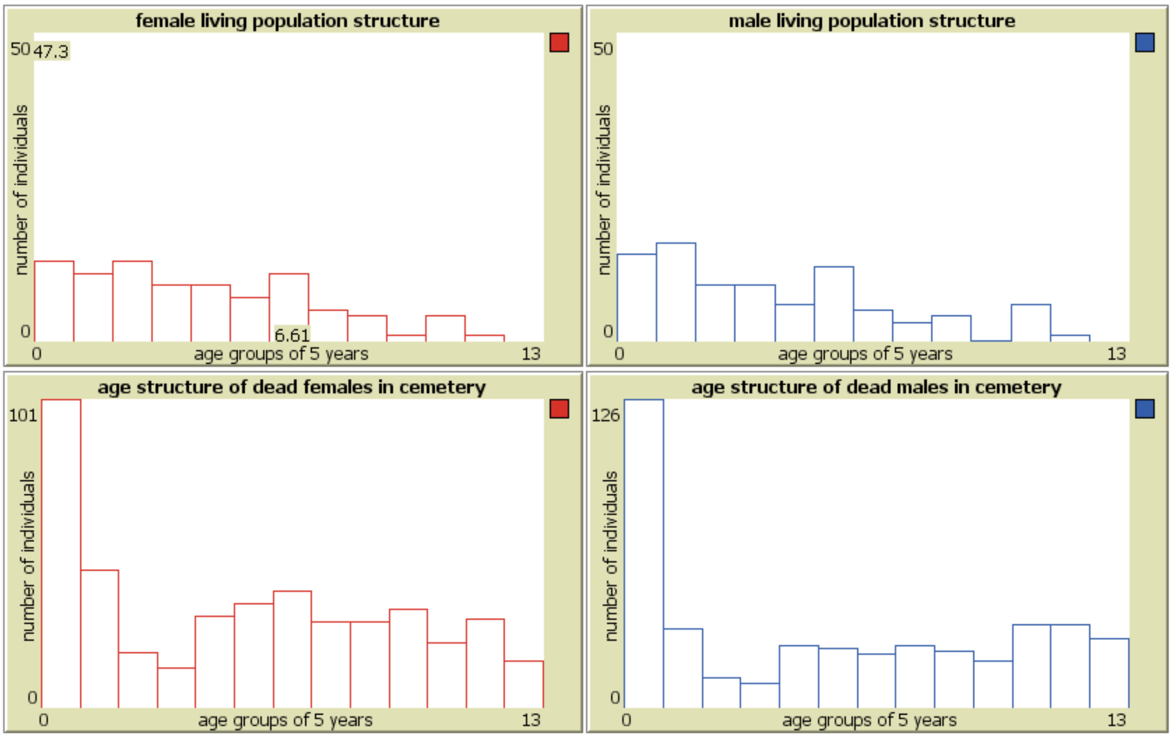


Fig. 63 The living (above) and the buried population (below) at year 200; blue: number of males, red: number of females. The age categories of 5 years are 0-4, 5-9, 10-14 to 60 and over. The final living population grew to 140 and at the same time the cemetery reached 830 burials.

The modelled age composition of the population in the living population (at year 200) and the accumulated cemetery are shown in Fig. 63. The high number of dead infants (the first of the 13 5-year age groups in the diagram) stands out. Judging from the comparison with the early medieval standard profile, the 226 subadults excavated at Mucking actually only represent a fraction of the children that actually died over the 200-year period (Fig. 64). The ‘missing infant’ phenomenon is commonly observed in Anglo-Saxon and Alamannic cemeteries dating to the 5th to 6th centuries and is consistent with general expectations (Crawford 2007; Kölbl 2004; Séguy and Buchet 2013). The high number of adolescents in the Mucking sample (Fig. 64) can be explained by the bone preservation issues and the fact that almost 200 individuals had to be distributed over all age categories because they could not be aged (Hirst and Clark 2009). The general effect of under-ageing caused by the skeletal ageing methods could also account for the high number (Bocquet-Appel 2008a; Bocquet-Appel and Masset 1982; Bocquet-Appel and Masset 1996; Gowland and Chamberlain 2002; Hoppa and Vaupel 2002a; Hoppa and Vaupel 2002b; Séguy and Buchet 2013). A third possibility for the increased number of individuals aged 15 to 20 years could be that the Mucking sites include a number of victims of one or more catastrophic mortality events which increase the middle age groups compared with the typical attritional mortality pattern (Atkin in preparation; Gowland and Chamberlain 2005; Margerison 1997; Margerison and Knüsel 2002). The offset might, fourthly, be explained by social filtering factors which are active when different types of cemetery sites are used by different populations at the same time, e.g. regional ancestral and local burial grounds (Sayer 2014). Based on the little we know about the age composition of the buried population in the two cemeteries of Mucking, the simulated values cannot be ruled out as being relatively consistent with the excavated material, although the shortcomings of the data are equally revealed.

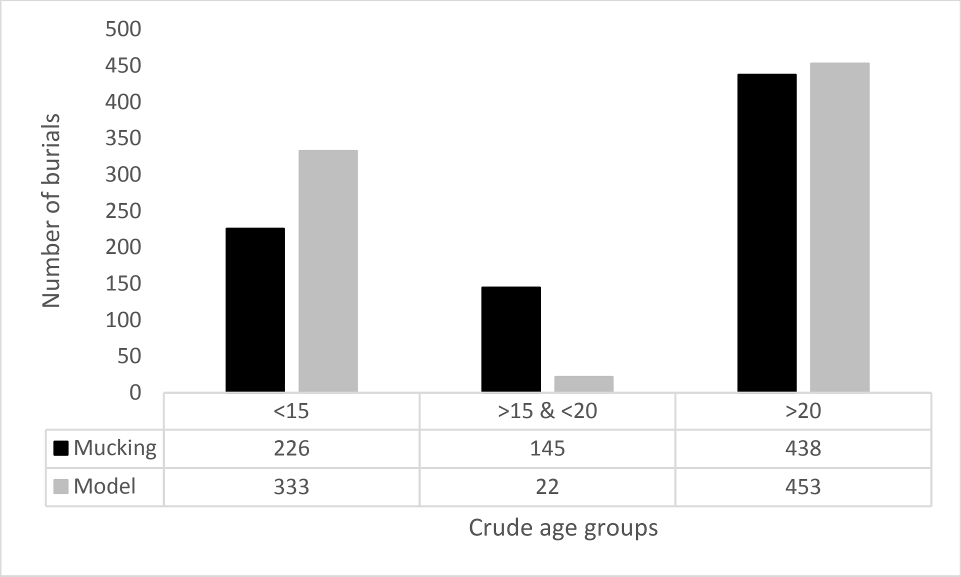


Fig. 64 The virtual (grey) and the excavated (black) number of burials per age group. 173 of the individuals in the excavated cemeteries of Mucking had to be distributed over all age groups, and there are clearly burials of children missing in the two cemetery sites in comparison with the modelled cemetery. The typical 'missing infant' problem might account for the observable differences in the first two age groups.

When modelling a population using the PCS, many more parameters can be observed alongside the population size development and the age distribution in the living population and cemetery. Parameters which characterise the studied population in its biological and social network are the average age-at-death (dropping here from age 29 to 25 during the modelled period) and the average age of the living population (fluctuating at c. 20 years) (Fig. 65). These parameters mainly depend on the utilised standard medieval mortality curve and the growth rate of the population. Growing populations have more individuals in the younger age groups than in the older age groups (Kölbl 2004; Séguy and Buchet 2013). Pre-modern populations are very young, and most of the activities in people's lives must have happened relatively early. The proposed average medieval marriage age of c. 25 (Gilchrist 2012; Sayer and Dickinson 2013; Shahar 1991) is highly unlikely in the case of the rural village of Mucking as it would be well after the peak of the average age in the living group and equals the average age at death. This would be problematic for population survival (see also chapter 6).

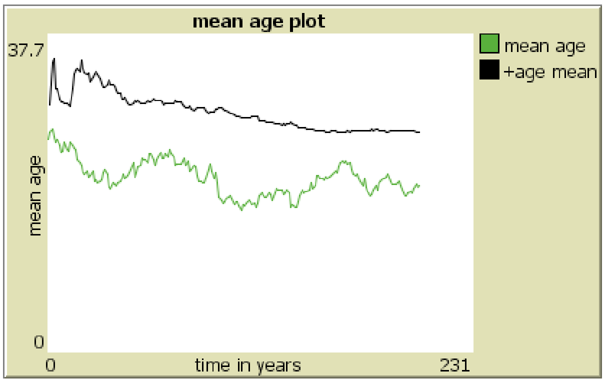


Fig. 65 The development of the average age in the living population (fluctuates at c. 20 years) at any one time and the mean age at death in the virtual cemetery (drops from 29 to 25, potentially because of the growth of the population).

The fertility levels of the population can be estimated very well as they represent a highly sensitive parameter (for parameter sensitivity see chapters 5.2 and 6) (Kölbl 2004; Paine and Harpending 1998; Robbins 2011). Fertility depends on the utilised standard medieval mortality curve. The most likely simulation runs based on the cemetery's growth rate of 22% were between TFR 4.1 and 4.3 children per female in the reproductive phase. Populations modelled with a TFR of 4.0 decline rapidly, whereas, populations with a TFR of more than 4.3 grow exponentially. Fig. 64 shows that the TFR is a relatively hypothetical value as a high proportion of the females die before they reach menarche. The very small numbers of females who reach menarche cause the fluctuations observed in the model (Fig. 66). The average number of births and children per reproductive female can be estimated very well, as they fluctuate much less (Fig. 66) and constitute parameters which can be used to describe average nuclear family sizes. The number of nuclear families can be calculated over time to the values presented in Fig. 70. The numbers are based on the average number of children linked with one biological mother. Combined with the information presented in Figs. 67 to 69, the effect of the premodern demographic situation on how families would have looked like in early medieval Mucking becomes obvious. A high proportion of the population belonged to the subadult age category (c. 50%) with c. 10% of newborn individuals. Different ways of measuring the subadult age cohort (i.e. either aged below 14, 18 or 21) do not really change the overall picture (Fig. 67). 30% of the children would have lost one parent (this number is based on the broken mother-child links due to the death of mothers) which can be used to predict the approximate probability of losing both mother and father before the age of 21 years. The rate of (full) orphans, i.e. individuals who have lost both parents before reaching age 21, fluctuates around c. 10%.

Moreover, the impact of old age can be studied. Fig. 69 shows that in an overall average of 6 families both one grandchild and one grandparent were alive at the same point in time. Compared with the development of the number of nuclear families (Fig. 70) – from c. 20 in the first years of the simulation run to 40 just before the 200th year – this demonstrates that grandparents often died before seeing their grandchildren grow up. The major role in the upbringing and knowledge transmission through the generations rests on the parent generation. Grandparents might have played a more decisive role on the level of the complete community or in networks of multiple families.

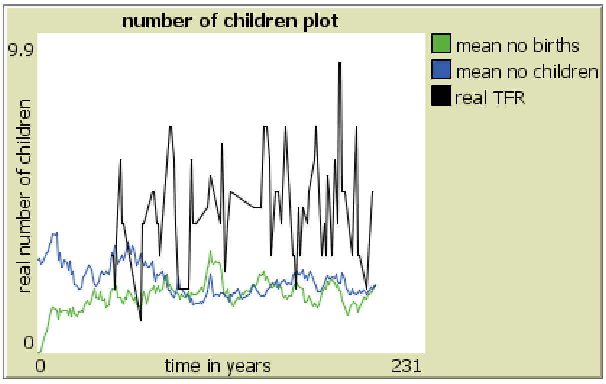


Fig. 66 Population fertility over time with an average TFR of 4.2 children per woman. The model records the fluctuating actual TFR per year ('real TFR', black) as well as the average number of births (green) and the average number of children per woman (blue).

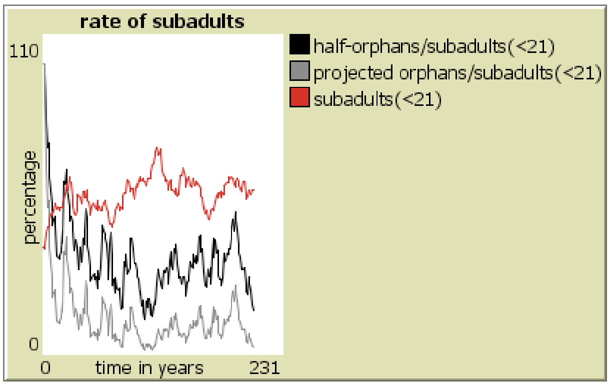


Fig. 67 The percentage of individuals below the age of 21 (red) and the proportion of actual half-orphans (black) and the projected number of orphans (grey).

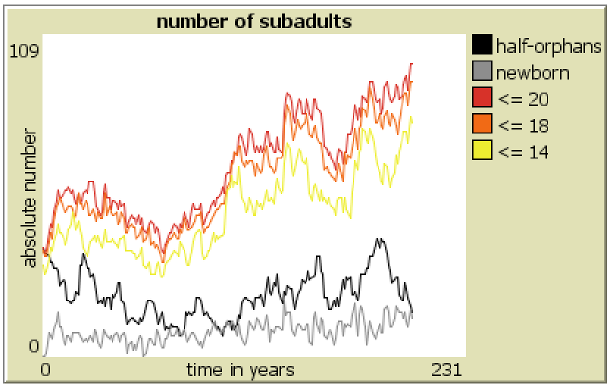


Fig. 68 The number of half-orphans, newborns, and three different sub adult age groups.

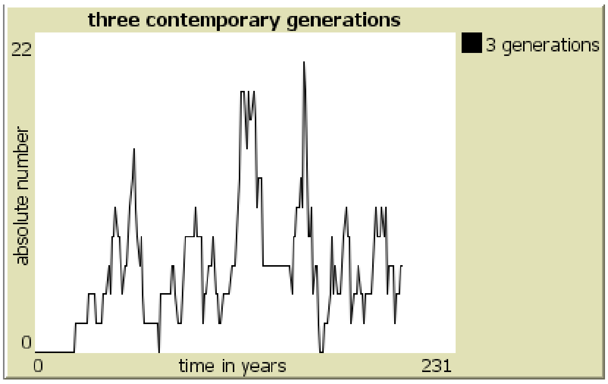


Fig. 69 The number of nuclear families in which individuals of three subsequent generations are alive at the same point in time, i.e. the number of grandparents in nuclear families.

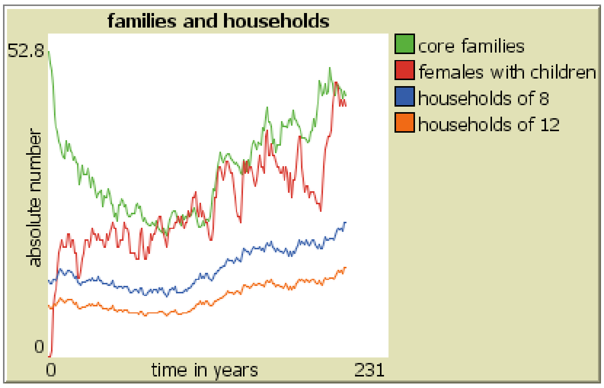


Fig. 70 Here two different methods to capture the number of nuclear family units in the population are plotted in red and green. These values are compared with average household size estimates of 8 and 12 individuals.

Fig. 70 shows the development of approximate numbers of households and the number of nuclear families which would have lived in the dwellings. The general pattern follows the development of the modelled population size with an exponential growth spurt in the second century. The measurement of nuclear families is irregular in the first 50 years of the simulation. The effect of the burn-in period or stabilisation phase is typical (see chapter 5.5). It takes a few generations until the state of the initial starter generation develops into a natural population which follows the trend defined by the parameters in the model. The number of nuclear families grows from c. 20 to c. 40 with an average of approximately 30. If we suppose that households consisted of 8 individuals, the model predicts c. 11 (beginning) to 18 (end of run) households. If 12 individuals existed per household, we can see an increase from c. 7 to 12. However, the published household size of 8 or 12 in the early medieval period (Ausenda 1997; Donat and Ullrich 1971) are not to be confused with household sizes estimates of 4.75 individuals based on Domesday Book data (Hinton 2013, footnote 11). The average number of 8 to 10 posthole buildings published by Hamerow (1993) is generally consistent with the results obtained by the model for households consisting of 12 individuals. If this scenario were true, the extended households would have included individuals of c. three nuclear family units at any point in time, some of which might have been unfree or slaves of the household.

But even complex patchwork families made up of extended family relations, e.g. orphaned children of aunts and uncles, cannot explain the tripling of the individuals per household from the modelled nuclear family size of c. 4 to 4.5 individuals (a number which is consistent with the historical estimate of family sizes in the 11th century) to 12. Separate nuclear families would have to be combined. It is therefore necessary to explore the complexity of the social system and the processes of household formation. If we loosen the primary assumption that every individual buried in the cemeteries also belonged to the community living in the settlement excavated, the results can also be read in a way which reinforces doubts regarding the estimates of Anglo-Saxons per household. It is possible that the cemeteries were used by a community or regional population up to three times larger than attested for in terms of the dwellings found at Mucking. Under these circumstances, the historical Domesday Book household sizes and the modelled nuclear families (including a proportion of orphans, widows etc.) would be almost equal.

Fig. 71 The population development and the growing cemetery for the next 100 years after c. AD 625. The population's exponential growth has the greatest effect just after the 200th year. During the next century, however, this single run develops a stagnating and slightly declining trend. However, it is very unlikely that the population would decline to its initial size or even below that in the next 100 years.

The simulation of the next 100 years (Fig. 71) shows that the population would have grown further in the 7th and 8th centuries, although, the run which was chosen here does not show a continuation of the exponential growth spurt. The stagnation after c. 50 years after the 200th year is based purely on mathematical chance. However, the cemetery (right hand side, Fig. 71) does indeed almost negate the trends of the living population. As 7th century graves are rare in the two cemeteries excavated at Mucking, and as the settlement is given up in the early 8th century (Hamerow 1993; Hirst and Clark 2009), the population must have moved to another place to build their dwellings and bury their deceased. It is unlikely that the population at Mucking declined to zero or went extinct over the course of the 7th century.

Furthermore, and most interestingly, the exponential nature of population growth leads to a growth spurt in the 6th century without any need for large-scale economic and environmental changes, as the presented results were achieved without any parameter changes during the 200(+100) modelled years. The impact of parameters chosen to grow the population were applied from the beginning of the model, but due to the demographic delay and the nature of exponential processes, the population reacted after a delay and grew in the second century to be modelled, but not before. Developments during the 5th and 6th centuries might have led to a growing population of Mucking during the 7th century. Socioeconomic circumstances hypothetically improved relatively early, certainly before the 7th century.

8.4 Discussion

The fertility level, i.e. the Total Fertility Rate and the average number of children per woman per point in time, can be estimated based on the rate of growth and the mortality profile. The TFR, a purely hypothetical value as many of the women will have died before the end of their reproductive phase, is 4.2. This approximates modern values measured for populations in Yemen, Samoa or Iraq which have very different mortality profiles and are growing fast (World Health Organisation 2013). The PCS further reveals that considering the high infant mortality ($q0\text{-}20=0.46$) the average number of living children per female is c. 2.3. While the TFR is useful for demographic comparisons, it is the latter number that tells archaeologists more directly how the families worked in the early medieval period. 4.3 is the average nuclear family size for such populations. Considering that 10% of the children were orphans and some families included widows and widowers, grandparents and other distant relatives, the number increases to a maximum of 4.7. This is actually close to the estimates in Domesday Book (4.75) (Hinton 2013) and for early medieval Scandinavia (4.24) (Benedictow 1996, Tab. 4). For Scandinavia, the additional individuals per household in populations practising slavery do not increase the household size beyond 6 (Benedictow 1996, 176). If we assume complex hierarchies within Anglo-Saxon households, this would still fall short of the necessary 12 or more individuals per household if all the individuals in the virtual population which buried their dead in the two cemeteries also lived in the posthole buildings excavated. Assuming the average life-span of a posthole structure as c. 35 years (Hamerow 1993; Hamerow 2012), "an average of 8-10 posthole buildings and 13-14 Grubenhäuser present at any one time, with an average total of 13 to 19 individuals per household" (Hirst and Clark 2009) can be reconstructed artificially using the PCS by placing 3 nuclear family units within one posthole building/household. A number of posthole buildings might remain unrecorded and it is possible that the cemetery continued to be used in the 7th century, and this interpretation rests on two additional assumptions: (1) a relatively short period of use for posthole buildings of c. one human generation, and (2) that all the individuals buried in the Mucking cemeteries also lived in the dwellings excavated. I will first discuss assumption 1 and then assumption 2 in the following:

Let us suppose a slightly longer period of use of the posthole structures of 50 or even 70 years, although timber in soil decays fast (Fries-Knoblach 2007), the absolute maximum based on studies of the survivability of timber in the soil (Hamerow 2002; Hamerow 2012)), the dwellings might have been inhabited by nuclear family units in a relationship closer to 1 : 1. This scenario cannot be excluded based on the simulation as it rests on observations on the decay rate of timber in soil (Fries-Knoblach 2007).

Even with the average age at death of c. 26 years, it is possible that the 35 years of use of posthole structures can be linked with the length of the life of men who were heads of households as they might generally have had a lower mortality due to better living conditions and as they had survived childhood. Some authors argue a direct relationship between the lifecycle of houses and the lifecycle of their inhabitants (e.g. Brück 1999; cited by Hamerow 2012). This relationship is also consistent with the timeframe of the demographically caused patchwork families described above. The households consisted of more than one person with delayed ages, including nuclear family units and some dependants who would have probably even used a house together for a few years longer on average than the lifespan of a single adult male head of household. Complex “social factors” and “cultural habits” which account for the life-cycle of buildings (Gerritsen 1999) are probably unnecessary or secondary in the light of the demographics described.

As demonstrated above, the proposed high number of individuals per household cannot belong to one nuclear family unit alone. Can we interpret the size offset between ‘households’ and nuclear families with social dynamics typical of pre-modern populations, which practised adoption and placed a high value on godparents and where widows and widowers regularly remarried (Shahar 1991)? The high rate of orphaned and half-orphaned children, the high mortality rates and the high proportion of subadult individuals shown in Figs. 65 to 69 demonstrate that complicated extended family structures around nuclear units existed. The extended families, i.e. the households, would have consisted of relatives who had lost their nuclear families and became reattached to more distantly related other nuclear units. As only c. 6 nuclear families (out of c. 30) had a person of the third generation present (a grandparent) at any one time in the modelled run, the role of grandparents was limited (although this will likely differ in models which include age categories beyond age 60). When the grandchildren were still quite young, there is some overlap of three generations. But the major transmission of knowledge and the social role of the family would be between father and son and mother and daughter. This observation strengthens Sayer’s argument in his generational observations on ‘Death and the family’ that the decision over who became head of the household was sometimes determined by “who was able to fill the role” (2010, 59). The continuity of the social roles between generations was constantly challenged by the harsh demographic state of these populations, which were made up of mainly two coexisting generations instead of three.

But Sayer also argues for complex movements between populations and a complex burial landscape, e.g. that children were often buried in the cemeteries of their mother’s lineage before they came of age (Sayer 2014), and we know that large cremation rite cemeteries were used by extended settlement networks instead of one single community (Hills and Lucy 2013). If we do not fill the c. 50 dwellings excavated at Mucking with the complete population buried, we can create a different picture which is completely consistent with the model – albeit inconsistent with the prevailing interpretation (Ausenda 1997; Hamerow 1993; Hamerow 2012; Härke 1997). If a larger regional group or settlement landscape used the cemeteries, it is possible to fill one posthole structure with one nuclear family, or even an extended nuclear family of c. 5 individuals, consistent with historical estimates of household sizes in later centuries, e.g. in the model of the medieval population of South Oxfordshire (chapter 7) (Benedictow 1996; Hinton 2013). In this case, between one-half and two-thirds of the population buried at the two cemeteries probably came from outside the community represented by the posthole structures. Mucking’s size is further consistent with a regional centre, as it belongs to the larger settlements in the Anglo-Saxon period (Hamerow 1993) and its cemeteries could therefore also attract people from a wider region, comparable with, for instance, Spong Hill, but on a smaller scale (Hills and Lucy 2013). This solves the problem of how to imagine the cohabitation of two to three nuclear families in one dwelling. Exceptions in the form of some slaves or workers per household unit are still allowed for in this hypothetical scenario, raising some households by a few individuals – but not by a factor of 3 as in the household size model of 12 or more. A more complex settlement landscape involving burials from a wider regional population and with smaller household units would, furthermore, be consistent with the historical

Domesday Book estimates and with the system regularly observed in pre-modern patrilocal agricultural systems (Hajnal 1965; Hajnal 1982; Hinton 2013). In such systems social differences are expressed between households, as some families have accumulated more wealth and a higher social position than others – which is a typical trait of pre-Christian cemeteries (Härke 2001; Härke 2005; Härke 2014).

Lastly, due to the exponential nature of population growth the projection of the 7th and 8th centuries for the population of Mucking suggests that the settlement and cemeteries were not given up because the population had collapsed. The population is big enough to have survivability chances of almost 100% over 300 years (Figs. 35 to 37) and only extreme catastrophic events could have led to population extinction. But there is no trace of catastrophic events, especially as the 7th century is already underrepresented in the cemetery. Catastrophes would have caused a visible peak in the burial record. On the contrary, the demographic conditions of the observable 200 years already account for further population growth beyond 140 living individuals. But why was the settlement in transition in the 7th (and 8th) century? Social reorganisation and substantial changes in the settlement landscape are common features of the Middle Saxon Period (Hamerow 2012). Population growth and population pressure seem to be plausible factors in the light of the presented simulation run of the population of Mucking. If archaeologists want to explain the changes in the 7th and 8th centuries, they must study what happened in the centuries before, i.e. the 5th and 6th centuries, for which we have abundant cemetery data. The exponential reactions in the demography of populations are probably delayed.

8.5 Conclusions

The published interpretations of the settlement and cemeteries of Anglo-Saxon Mucking and the results obtained using the PCS are generally consistent. By linking the living and dead population in a dynamic demographic model, we can predict a more complete demographic picture, including a great deal of secondary demographic information, than by using the old static formulas.

But if we suppose that posthole structures had lifespans of c. 20 to 35 years, the data and the models also support an interpretation of early medieval household sizes which is different from published interpretations: using the historical Domesday Book estimate for household size seems at least as plausible as it is consistent with the demographically modelled biological nuclear family sizes. Consequently, early medieval households could very well have been of a size of 4.5 to 5 individuals and a maximum of 6 individuals, including orphans, patchwork family members and probably slaves and workers. The estimates of household sizes of 8 and 12 are not necessary if we assume that the cemeteries were used both by the community/communities settling at Mucking and an extended regional population which considered Mucking a centre of some sorts. In this case, only c. one-half or one-third of the individuals buried in the cemeteries belong to the population which inhabited the settlement(s) excavated.

All in all, the case study of Mucking shows how the PCS can tackle site-specific datasets in a ‘virtual Petri dish’, although the models are mostly hypothetical experiments limited by the data available. The demographic information obtained from burials and the early medieval settlement pattern can be linked. Despite some gaps in the data and despite the necessity of guessing some data, multiple parameters can be estimated and the models can be contextualised with a number of research questions discussed in settlement archaeology.

9 The demographic structure of early medieval Kentish and Alamannic populations

9.1 Introduction

I have described how settlement and cemetery data can be compared in chapter 8 and I have set the scene for analysing the demographics of early medieval populations by validation studies that explore fertility, household size and settlement structures in chapters 6 and 7. The following case studies will focus more on the cemeteries and burials and tries to reconstruct possible living populations based on cemetery data from Kent in South England and the South German Alamannic territories. What can the graves tell us about early medieval demographics if there is no or limited information available of the living population? This chapter first approaches a single site trying to estimate a range of demographic parameters based on the osteological data, then explores regional populations focussing on the reconstruction of population profiles from problematic mortality data and the missing infant problem. In the final section, I will model artefacts in the Kentish population to show that research questions beyond pure demographics can be tackled using the PCS. The advantage of analysing Kentish and Alamannic populations in a comparative approach were described above, but the data are, in a nutshell, complementary. The following case studies represent examples of scenarios and models which could be useful to understand early medieval communities and their demographics. Models with better data, more detailed scenarios and more complex parameter networks will ultimately replace the following preliminary results.

The following section will describe the reconstruction of the living population of the Alamannic cemetery of Bärenthal, Kreis Tuttlingen, by modelling a number of possible scenarios of virtual communities which will each create a virtual cemetery that can then be compared with the actual excavated material. The initial set of parameters for the starter generation, and the reproduction and mortality profile of the population in the following scenarios will primarily be based on the excavated data and their interpretations discussed in the site reports. Although the data might well be biased and problematic, especially as life table mortality estimates are used, the following scenarios are designed to make the most of the material available at this stage to show how the PCS can be used to make the transition from cemetery to living population independent of the actual quality of the data employed. More reliable data will be provided in a second step in which the regional population profiles of the Kentish and Alamannic early medieval populations will be explored in comparison with demographic standards and historical data from different centuries. I will focus on the discussion of a range of demographic scenarios in order to show the spectrum of possible scenarios limited by the archaeological and contextual information available. One problem, for instance, is the incomplete information available on childhood mortality, which can only be tackled by comparison with demographic standard data and historical information on infant death.

Finally, economic change in Kent (Brookes 2007; Harrington and Brookes 2012) will be contextualised with demographic change, using an experiment which models the demographics and change in grave goods of the population in combination. Thus demographic questions will be tackled, first based on a single site and then in relation to bigger regional datasets. To demonstrate how the available limited demographic information can be exploited in archaeological research beyond pure demographics, artefacts and their links with the living and the deceased will be modelled.

9.2 Reconstructing the cemetery of Bärenthal, Kreis Tuttlingen

9.2.1 The site

The early medieval cemetery of Bärenthal is situated in the region of the Upper Danube in Baden-Württemberg, Kreis Tuttlingen, Germany, and was excavated between 2008 and 2010. It has outstandingly good preservation conditions for human remains, and a high proportion of the buried population falls into the subadult age category (age <20 years, 41.24%). According to 20 radiocarbon dates, the cemetery was continuously used between the 7th and 10th century, which means a core period of 250 years. Although further Bayesian modelling might reveal that the burial activity was limited to the 8th and 9th centuries. The 97 excavated individuals are representative of the population which buried their dead at this place for a number of reasons, i.e. the distribution of ages and sexes over the site, several demographic tests of representativity and the estimated size of the complete population. The maximum estimate for the complete number of graves is 250. Parts of the cemetery were truncated by modern roadwork and the 250 graves represent the absolute maximum of graves that can theoretically be placed in that area. Other contextual information suggests that the site belonged to a relatively normal poor population which had to cope with the harsh climatic conditions of the mountain region. The topography of the site (narrow valley) and the fact that a two-phased stone church clearly contemporary with the graves was found in the centre of the cemetery suggests that some kind of nucleated community buried their dead at the place (Duering 2011a; Duering 2011b; Duering 2012; Duering 2014; Duering and Wahl 2010; Duering and Wahl 2015).

9.2.2 Hypothesis

The hypothesis for the following experiment is that the published demographic data of the population of Bärenthal based on standard osteological procedures, e.g. the life table, can be used as parameter input for a simulation which reproduces virtual cemeteries that look exactly like the excavated sample. This checks the internal mathematical consistency and demonstrates one possible scenario of how the site has been formed. Furthermore, the simulations calculate the possible composition of the living population behind the buried population and model the stochastic variability for a fixed set of parameters.

9.2.3 Parameters

To simulate a virtual living population, we must identify the initial set of parameters for the population of Bärenthal.

The *period of time* for which the cemetery was in use is given by the radiocarbon dates as approximately 250 years (Duering 2014). Therefore each simulation consists of 250 subsequent (yearly) ticks.

In this experiment, the *starter generation* of the living population in one year is equal to the average number of individuals living at each point in time. According to the formula by Acsádi and Nemeskéri (Acsádi and Nemeskéri 1970),[9] and adopting a mean life expectancy of c. 27.7 years, a core period of use of 250 years and a maximum of 250 burials, the average size of the living population is 30. The distribution of sexes in the cemetery was slightly skewed towards males, which is very common in early medieval populations of the same region (males 51.5%, females 38.1%, unsexed 10.3%, sexed based on osteology) (Ade et al. 2008; Duering 2014; Wahl et al. 1998). All in all, this adds up to a starter group of 17 males and 13 females of random ages between 0 and 50.

The *fertility* parameters of the population must be levelled out with the mortality of the population in a few preliminary runs, because the growth parameter is 0 in this experiment. This will be discussed in detail in the following chapter on the simulation process. Further, a maximum estimate for the fertile phase utilising a range between age 16 years and age 40 years is used, and a child-spacing value of 2.5 is chosen as this is close to the estimated values for the early medieval period

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[9] $P = 1.1 \times \frac{D \times e0}{t}$; P: average population size, D: number of deceased individuals, e0: average life expectancy at birth, t: period of time the site was is use.

both at Wharram Percy and also at Bärenthal based on observations of enamel linear hypoplasia (Duering 2014; Fuller et al. 2003; Mays et al. 2007).

The *mortality* table of the complete population of Bärenthal is based on the distribution of ages at death of the individuals buried in the excavated sample (Figs. 72 and 73). The life table with the calculated probabilities of dying in each age group is shown in the qx column in Tab. 11. All the caveats using a life table in palaeodemography apply.

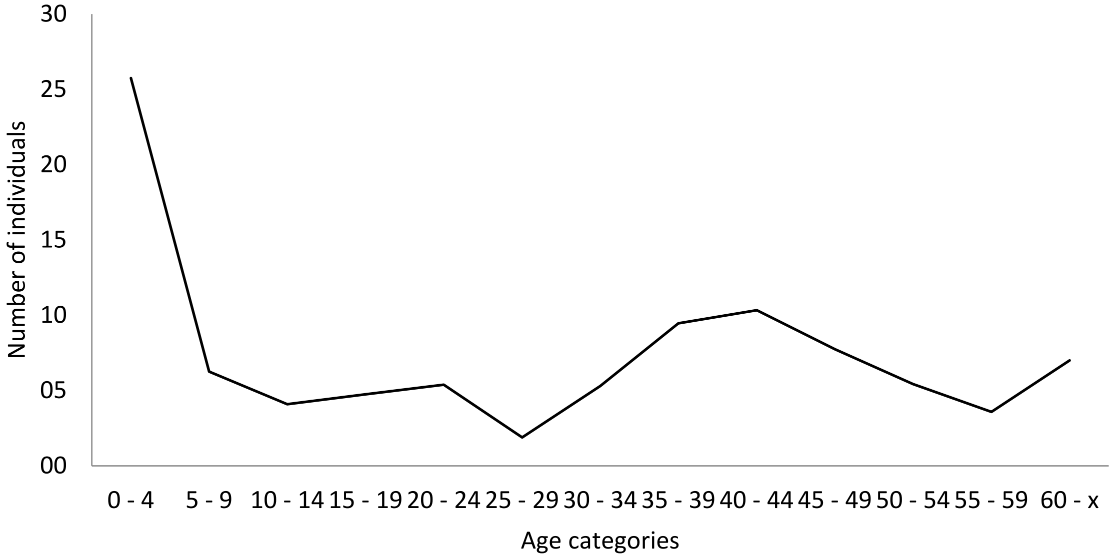


Fig. 72 Number of individuals per age category of the sample excavated at Bärenthal, Germany.

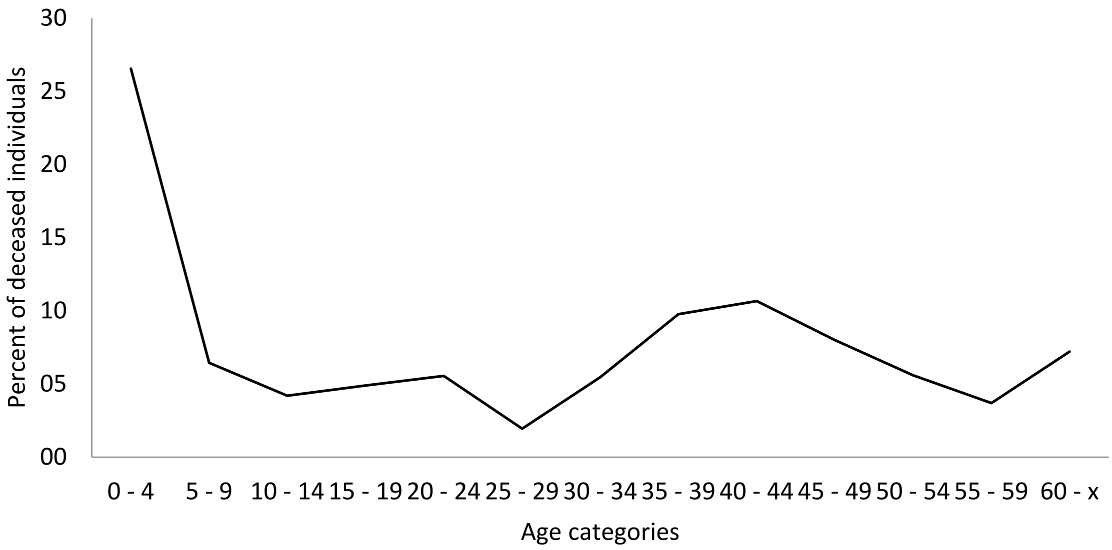


Fig. 73 The age-at-death profile in percent of the sample excavated at Bärenthal, Germany.

Age x	*a*	Number deceased Dx	Percentage Deceased dx	Survivors lx	Mortality qx	Years lived Lx	Years still to live Tx	Life expectancy ex
0 - 4	5	25.8	26.5	100.0	26.5	433.6	2765.9	27.7
5 - 9	5	6.3	6.4	73.5	8.8	351.2	2332.3	31.8
10 - 14	5	4.1	4.2	67.0	6.3	324.5	1981.1	29.6
15 - 19	5	4.7	4.9	62.8	7.8	301.8	1656.6	26.4
20 - 24	5	5.4	5.6	57.9	9.6	275.6	1354.8	23.4
25 - 29	5	1.9	1.9	52.3	3.7	256.9	1079.2	20.6
30 - 34	5	5.3	5.5	50.4	10.9	238.3	822.3	16.3
35 - 39	5	9.5	9.8	44.9	21.7	200.2	584.0	13.0
40 - 44	5	10.3	10.7	35.2	30.3	149.2	383.7	10.9
45 - 49	5	7.8	8.0	24.5	32.6	102.5	234.6	9.6
50 - 54	5	5.4	5.6	16.5	33.9	68.6	132.0	8.0
55 - 59	5	3.6	3.7	10.9	33.9	45.4	63.4	5.8
60 - x	5	7.0	7.2	7.2	100.0	18.1	18.1	2.5
Sum		97	100.000			2765.8904		

Tab. 11 The life table of Bärenthal, which transforms the age-at-death distribution (red, Dx) of the population into the mortality (green, qx).

PCS DATA SHEET VIRTUAL EXPERIMENT NO Bärenthal 1

Research Question	Observed Parameters	Number of Repetitions
Model 100 runs, conduct internal plausibility check and show stochastic variability around one set of parameters.	Whole range of demographic parameters, especially age distributions in living population and cemetery.	100
		Time / Duration of Run
		250

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
13	17	0	50	-	-	-	-

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
16	45	0.5	2.5	0.384

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
-	-	-	-	-	-

Mortality (qx)	
0-4	0.265
5-9	0.088
10-14	0.063
15-19	0.078
20-24	0.096
25-29	0.037
30-34	0.109
35-39	0.217
40-44	0.303
45-49	0.326
50-54	0.339
55-59	0.339
60+	1

Mortality based on:
Duering 2014

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 12 Data sheet for the model of the Bärenthal case study.

9.2.4 Simulation process

As the standard osteological procedures that were used to obtain mortality only work if one assumes that there was no population growth and the population stayed stationary over the complete period of time, there must be a balance of the rates of death and reproduction. Therefore, a few preliminary runs must be conducted to determine an estimate for the rate of reproduction of the population of Bärenthal until a stationary state has been found. In the site report for Bärenthal I have recently conducted a few runs in the NeoLogo interface of the PCS and found that in visual terms the fertility value of TFR 4.1 children per reproductive female was likely to produce stationary signals (Duering 2014). For this chapter, I have improved the search for the most likely fertility value by using NetLogo's BehaviourSpace which helps to automate a parameter sweep over the parameter *the-reprodprobability* and allows the same parameter set to be repeated many times (here: 100 repetitions). For the search, I have also increased the population artificially to 100 individuals per point in time, to avoid the stochastic effect of small numbers affecting the result by decreasing the survival probability of the population (see chapter 5.6). The parameter sweep over *the-reprodprobability* found a stationary population development for 250 years to be the most likely at 0.384, i.e. at this number the population is most likely to be 100 individuals in year 250 (Fig. 74). The standard deviation at this rate is 54.5, which shows the high variability between single simulation runs. With a probability of reproduction of 0.384, the approximate number of children per female in the reproductive period which balances out the mortality to assume a stationary population is 4.5 (a value which is very similar to the one obtained for Wharram Percy in the chapters above). Automating the process clearly improves the reliability of the result, but the complex and precise estimation procedure seems excessive in light of the overall issues of the data and the high variability between single runs.

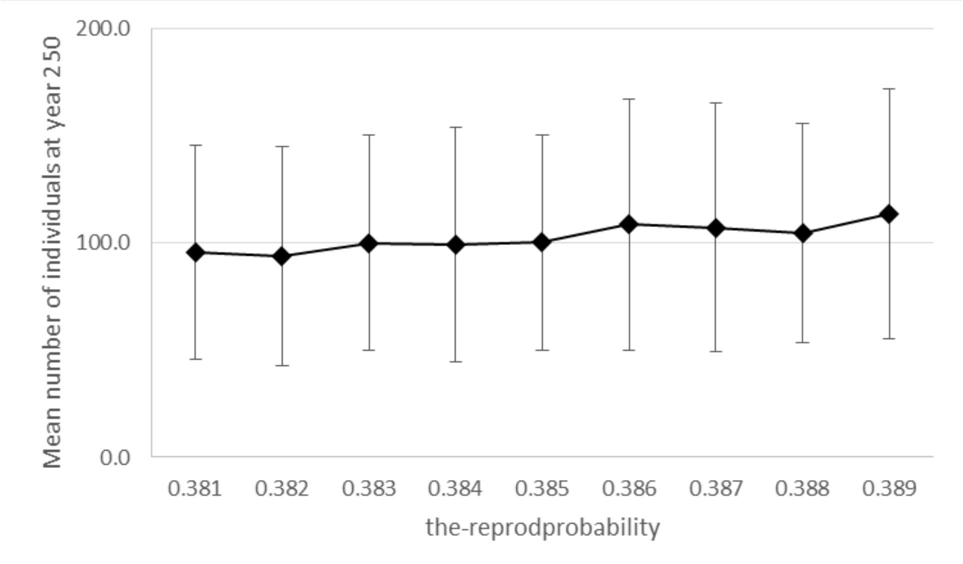


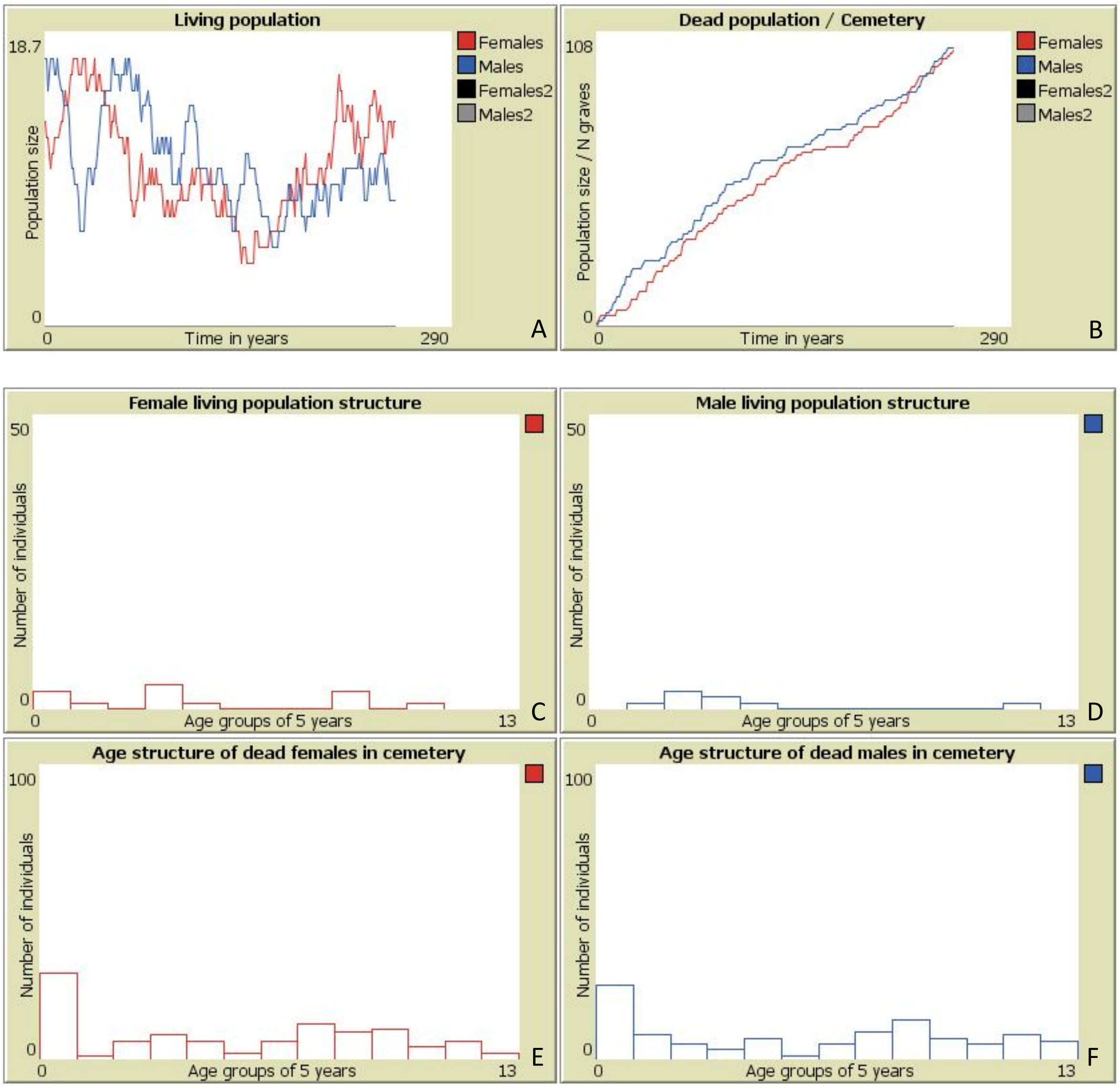
Fig. 74 Parameter sweep with the objective to find the most likely fertility rate which produces stationary populations around the size of 100 individuals after 250 years. Population sizes at different values of *the-reprodprobability* and one standard deviation with 100 repetitions per parameter.

The fertility parameters found are then used in a simulation that records the age profile in both the living population and the cemetery for each yearly step. In the case of Bärenthal, I repeated the model 100 times and collected all the data for 100 x 250 years of the simulation. The following results are, consequently, a mean of 25,000 observed years.

9.2.5 Results

The results of one modelled simulation run that remains relatively stable over the complete period of 250 years can be observed in Fig. 75. At this population size some fluctuations are unavoidable. Using these results it is possible to conduct a few preliminary plausibility checks: for a population to stay stationary, the net fertility has to fluctuate around two children to produce one surviving child per parent. Of the approx. 4.5 children born on average in early medieval Bärenthal, c. 50% died before reaching the age of 20. This is consistent with the modelling run, which produces c. 2.2

surviving children per female at any point in time. The average age at death fluctuates around 28 years after having reached a stable state after the first generation. The low number of individuals in the early years of the cemetery produces an initial random signal. The average age at death of the excavated skeletal sample of Bärenthal is 27.7 years (Duering 2014; Duering and Wahl 2015), which is also consistent with the simulation run. The simulation runs reproduce the excavated data well; which is no validation but shows that the input data can be reproduced. Initially, one can observe that the medieval population is mainly made up of relatively young individuals with an average age of c. 21 years.



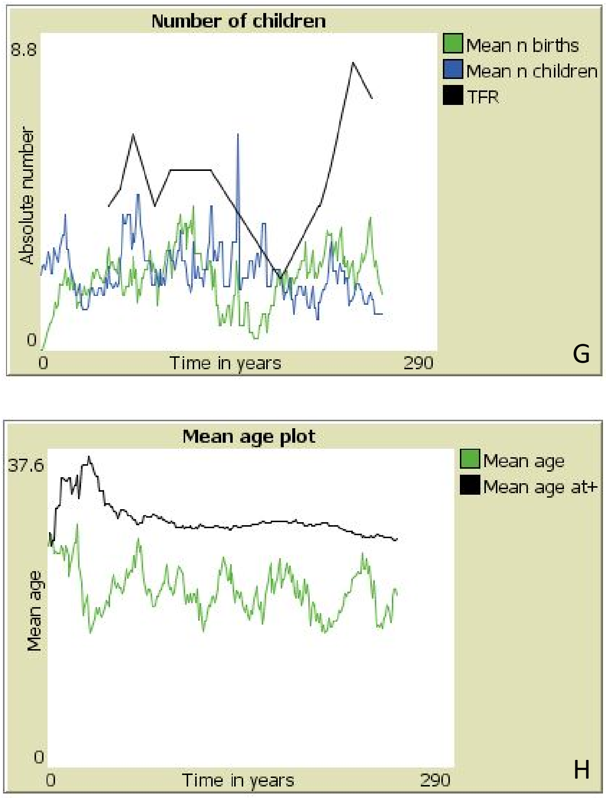


Fig. 75 The results of one single simulation run of a relatively stable population, based on the cemetery of Bärenthal as shown in the NetLogo interface. The two top graphs show the development of the size of the population in the living group (A, left) and the cemetery (B, right) (females: red, males: blue). The living population's composition per age category in year 250 is shown in the second row (C, D). The individuals accumulated in the cemetery up to that point are plotted in the third row (E, F). The population's number of children (mean: 2.2), number of births (mean: 2.0) and TFR over time are plotted below that (G) and in the bottom graph (H) we can observe the development of the mean age at death (black, 27 years at year 250) and the mean age of the living group (green signal, overall average: 21 years).

But because of the random stochastic fluctuations in the small population, it is better to observe the average results of multiple repetitions of the same parameter sets. In Fig. 76 and 77 the average virtual cemeteries, i.e. the mean age structure of the 100 repetitions, can be seen in comparison with the excavated age-at-death structure of the population of Bärenthal. The initial input can be reproduced well. This means that the population structure and parameters are internally consistent and represent a possible scenario of how the site could have been formed. The age group of modelled individuals buried aged 0 to 4 equals the 26.5 percent found at the site (Fig. 76) but the fluctuations between the different modelling runs are very large, which is demonstrated by the high standard deviation of 37.7 years (Fig. 77). In the living population (Fig. 78), the highest variation can be observed in the youngest age group. The number of infants buried in cemeteries is therefore not only strongly influenced by demographic conditions represented by the parameter values, but also by random effects occurring over time. It is particularly hard to estimate a realistic value for infant mortality based on the variable number of children buried in a cemetery. This is consistent with similar studies (Kölbl 2004; Séguy and Buchet 2013).

The chosen parameters further indirectly tell us much about the demographic state of the community that lived in early medieval Bärenthal. Firstly, the population requires approximately 4.5 subadults (individuals aged 0 to 19 years) per reproductive female individual. Of these c. 50% survive. The nuclear family can therefore be estimated at c. 4.2 or 4.3 individuals, a number generally consistent with Domesday Book estimates of household sizes and the results estimated in the case studies above (Benedictow 1996; Hinton 2013). Fig. 78 shows a plot of the average size of the living population per age category. For the medieval population of Bärenthal, the projection of the living group that buried their dead at the site is possible using the PCS. The number of subadults modelled here were actually excavated at Bärenthal and in the light of the results it seems plausible that the site represents the demographics of all age groups in the medieval rural population relatively well (Duering 2014).

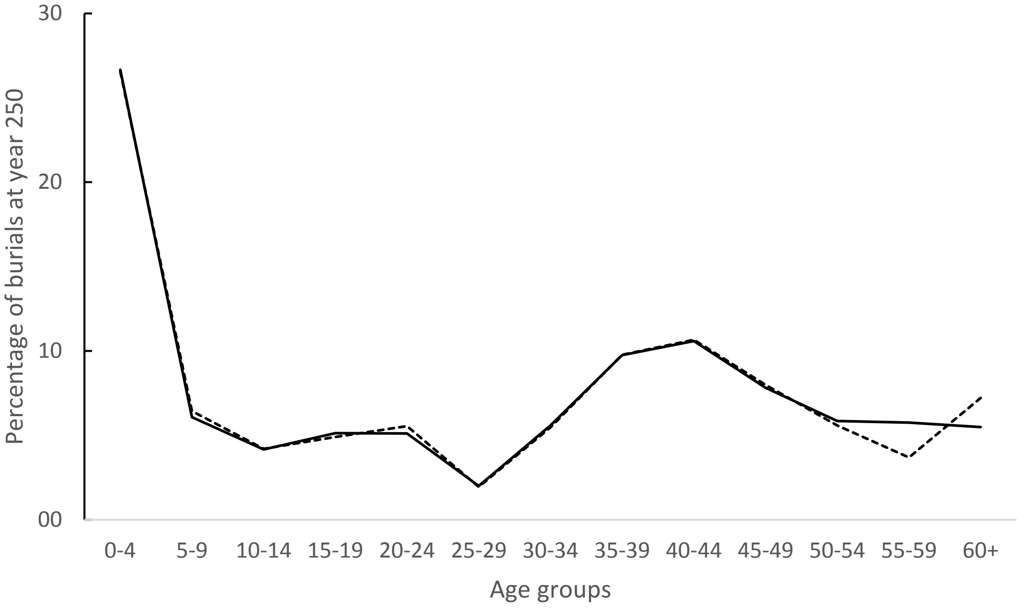


Fig. 76 The excavated relative age profile of the cemetery of Bärenthal (dotted line) and the modelled average population structure in the cemetery after 250 years, 100 repetitions (full line).

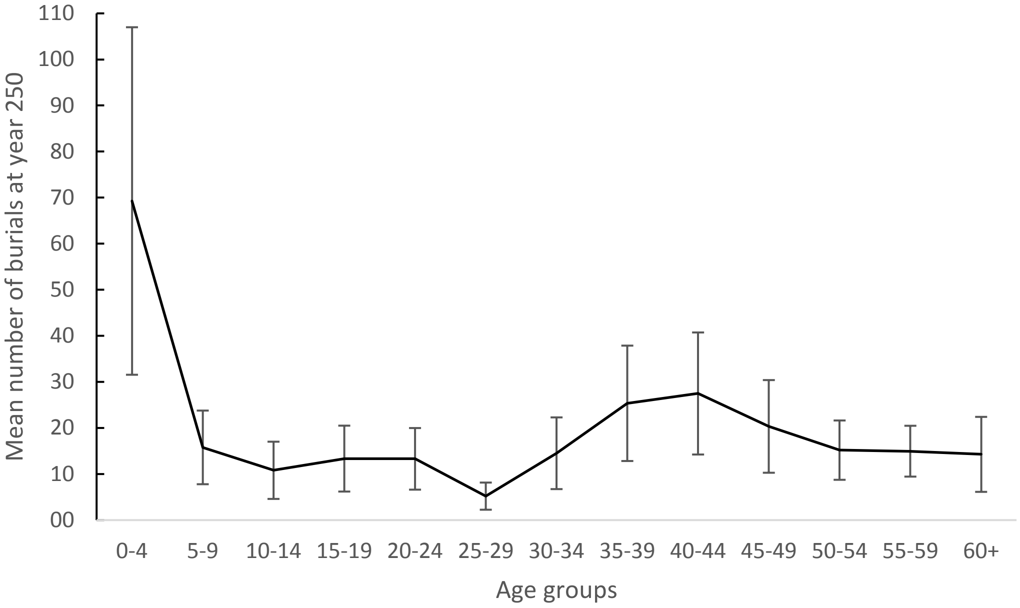


Fig. 77 The modelled mean number of individuals per age category, average of 100 repetitions and 1 standard deviation to show the fluctuations between the runs.

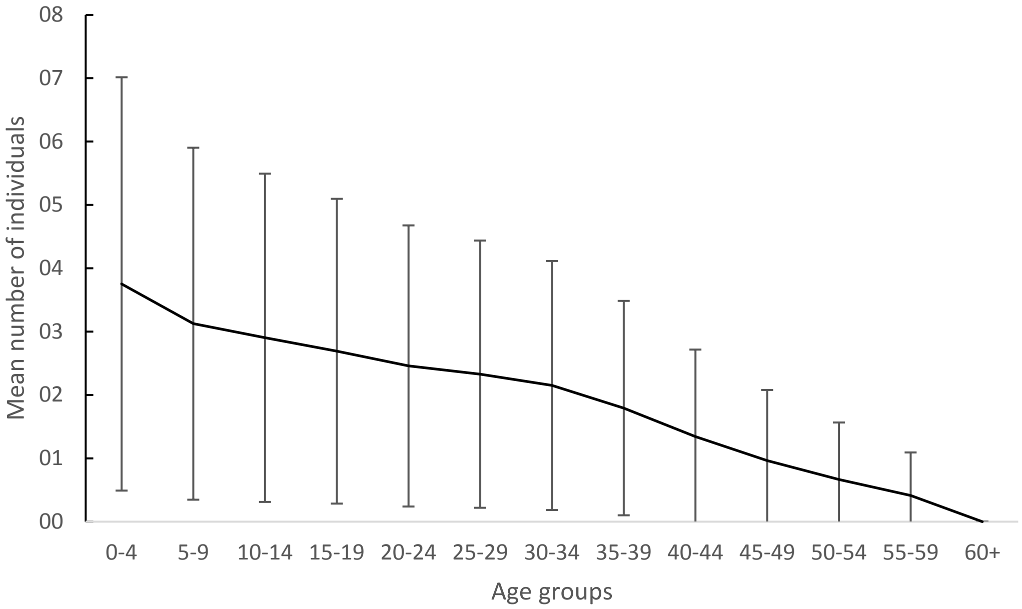


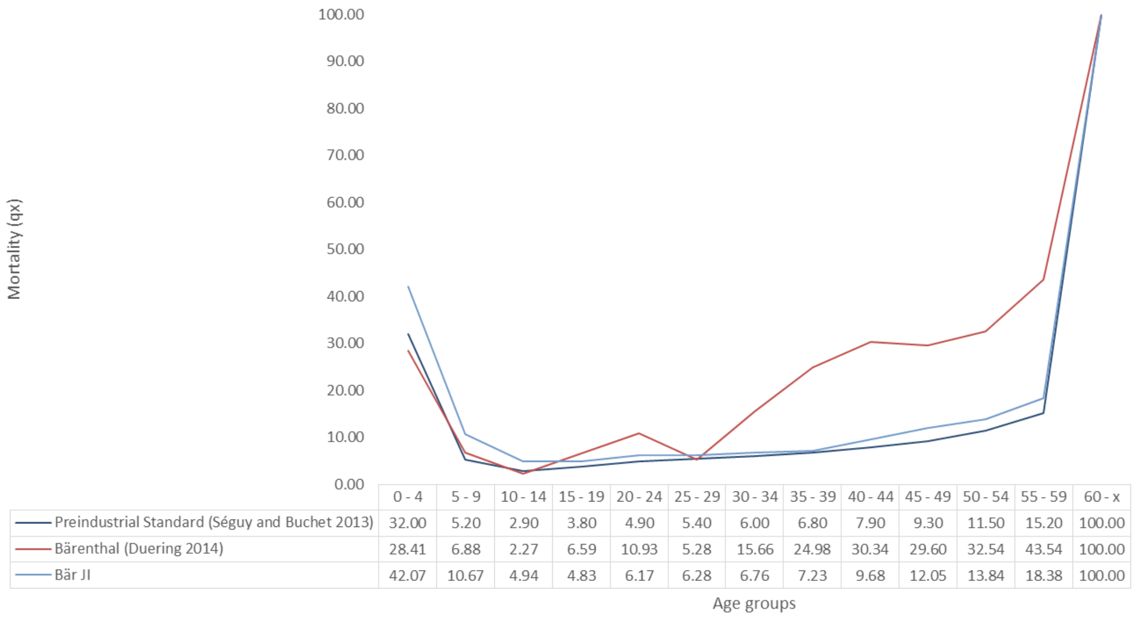
Fig. 78 The modelled average number of living individuals per age category in Bärenthal and one standard deviation showing the fluctuations between the 100 repetitions and over the 250 years.

9.2.6 A different way of estimating mortality

To avoid basing the results on life table data only, and because a mortality pattern calibrated using a new Bayesian procedure does not yet exist for these data, I additionally utilise a different estimation procedure for the mortality of Bärenthal known as *Estimator Method,* which was proposed by French demographers to counter the effect of the unreliability of single age estimates (Bocquet-Appel 2008a; Bocquet-Appel 2011; Bocquet-Appel and Masset 1996; Bocquet and Masset 1977). For this method, the Juvenility Index of Bärenthal (JI = 0.184) is compared with a preindustrial standard curve and taken as the sole basis fof the prediction of the mortality of all age groups. The Juvenility Index excludes the highly problematic infant age group and represents the ratio of individuals aged 5 to 14 years to adults (JI=D_{5-14}/D20+). I have used the estimation method which is published in Séguy and Buchet (2013) to calculate the mortality shown in Fig. 78. The Estimator Method loses all the individuality of the site's data and creates a mortality pattern for adults which has much lower values than the mortality pattern found using the life table. The preindustrial standard is almost completely replicated, and one wonders how much the archaeological data actually influence the Estimator Method's results. Further, the infant mortality of the original life table is much closer to the preindustrial standard than the calibrated curve. The inadequacy of estimating the infant mortality correctly in a population is one of the reported weaknesses of the Estimator Method (Séguy and Buchet 2013, 95). The crucial problem, however, is that the data of D_{5-14}, i.e. the number of individuals at Bärenthal aged 5 to 14 years, are unreliable. The whole result depends on the low, and probably random, number of 10.4 individuals for whom the age might have been misclassified and/or individuals might be missing (Séguy and Buchet 2013, 96). Bigger skeletal datasets are necessary to make the D_{5-14} parameter more reliable. The artificial cut-off point at age 60 and over with a mortality of 1 is necessary in the PCS at this stage to prevent the perpetual survival of individuals that live beyond age 60 (Fig. 79).

A cross-check of the results of the life table model presented above was conducted utilising this alternative way of estimating mortality, which can be regarded as a minimum adult mortality approach (although it is probably a maximum subadult mortality approach, because of the pronounced peak of the probability of dying in the first five years of life). In the following section I will focus on the fertility necessary to produce a stationary population and the estimate of the nuclear family size.

Although the adult mortality is much lower over most of the lives of the modelled individuals, the fertility required to stabilise the population with the JI mortality needs to be higher than in the previous model. Interestingly, the seemingly slight increase in childhood mortality (Fig. 79) has a much stronger effect on the whole population than the difference in adult mortality. A parameter sweep over different values of *the-reprodprobability* between 0.4 and 0.5, using the JI mortality and equal parameter values as in the above experiment (Tab. 12), reveals that *the-reprodprobability* of approximately 0.44 – which is equal to a TFR of 5.1 – is the most likely fertility for stationary populations (Fig. 80). With a probability of dying before age 20 of q_{0-19}=63% the average number of surviving children per female is c. 1.9. Adding two parents, this equals an average nuclear family size of 3.9, which is still roughly within the range of historical estimates of between 4 and 5 individuals per household (Hinton 2013), but still further away from the expected values than the life table data used above or in the Mucking case study. All in all, as the infant mortality is estimated to such a high value and the individual age patterns are lost, the use of the JI Estimator Method unfortunately results in no significant improvement of our demographic knowledge of the site.



	0 - 4	5 - 9	10 - 14	15 - 19	20 - 24	25 - 29	30 - 34	35 - 39	40 - 44	45 - 49	50 - 54	55 - 59	60 - x
Preindustrial Standard (Séguy and Buchet 2013)	32.00	5.20	2.90	3.80	4.90	5.40	6.00	6.80	7.90	9.30	11.50	15.20	100.00
Bärenthal (Duering 2014)	28.41	6.88	2.27	6.59	10.93	5.28	15.66	24.98	30.34	29.60	32.54	43.54	100.00
Bär JI	42.07	10.67	4.94	4.83	6.17	6.28	6.76	7.23	9.68	12.05	13.84	18.38	100.00

Fig. 79 The mortality pattern of Bärenthal based on the traditional life table compared with the preindustrial standard (Séguy and Buchet 2013), and a different method of estimating the mortality at Bärenthal (Bär JI) using the Juvenility Index of Bärenthal, which is 0.184, based on an estimation procedure published in Séguy and Buchet (2013).

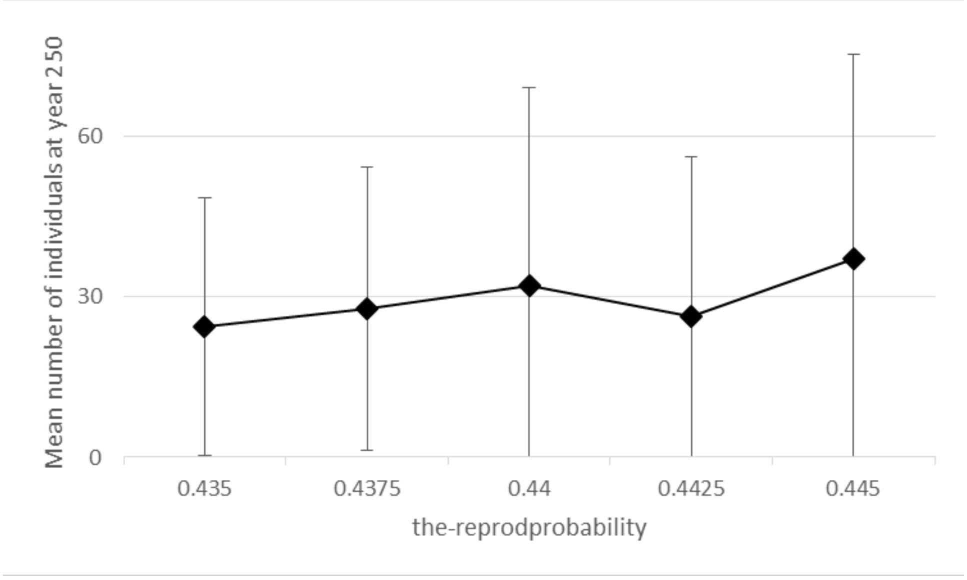


Fig. 80 Parameter sweep with the objective of finding the most likely fertility rate that produces stationary populations around the size of 30 individuals after 250 years. Population sizes at different values of *the-reprodprobability* and one standard deviation with 100 repetitions per parameter.

9.2.7 Discussion and conclusions

For a mortality pattern which rests on both the traditional individual ageing techniques and the much-criticised life table, the results obtained when modelling populations based on the parameters using the PCS are internally consistent, i.e. populations modelled using the estimated parameters actually produce cemeteries which, on average, produce the distribution of ages excavated at early medieval Bärenthal. However, the results obtained in this model depend on the assumption that the population size remained stable over 250 years; this cannot be tested as the few radiocarbon dates obtained from the burials are not enough to trace temporal dynamics. Further, the osteological age estimation conducted for the population at Bärenthal suffers from the inevitable inaccuracy of estimating adult age (Hoppa and Vaupel 2002a; Séguy and Buchet 2013). The check against the Juvenility Index mortality estimate showed that TFR levels at the site might vary c. in the range of 4.5 and 5 children when more accurate ageing methods are employed between those and the traditional methods. As the osteological estimation of subadult age versus adult age is much less problematic, the high ratio of excavated subadult burials is indicative of early medieval demographics although the high standard deviation of the 0 to 4 years age category in Fig. 77 shows that infant burial data from single archaeological sites are often unreliable as they represent relatively unstable parts of human demographics. Bearing these caveats in mind, the site of Bärenthal might still provide decisive information when tackling the issue of missing infants in early medieval sites because of its context, its good bone preservation and its closeness to the infant mortality values observed at Wharram Percy and the preindustrial standard (Fig. 79) (Duering 2011b; Duering 2012; Duering 2014; Duering and Wahl 2015; Séguy and Buchet 2013). In estimating a mortality profile in order to model early medieval populations, the models show that good estimates of infant mortality are crucial and that variability in the adult age categories is much less problematic becasue it is less sensitive regarding the complete system.

9.3 Estimating the demographics of regional populations: Kent and Alamannia

In the following section, more general regional early medieval demographic profiles are discussed and modelled. Single sites are often so small that stochastic effects strongly govern the individual age distributions. Adding multiple sites has the advantage that individual dynamics are levelled out. An alternative would be the use of relatively large sites with high numbers of burials. Sites such as Spong Hill which contain many hundreds of burials unfortunately do not exist in the study regions. Sites in Kent and the Alamannia usually contain a maximum of a few hundred burials which is why the data collected by Kokkotidis (1999) and combining 4,407 burials from AD 450 to 750 as well as the burials collected in the Anglo-Saxon Kent Electronic Database (ASKED), which also date between AD 450 and 750 are used here (Harrington and Brookes 2012).

I will first discuss the Kentish and Alamannic profiles in comparison with demographic standards, and historical demographic data. This will lead to an estimate of the infants missing in the population profiles. Finally, I will use the PCS to simulate a range of scenarios. The goal is to establish a rough idea of the range of possible demographics of the early medieval populations in the regions, e.g. estimation of the mortality of the population and estimation of the infants missing in the osteological data. Although new ageing methods might considerably improve the mortality data for future PCS models, their values per age category will most likely be somewhere in between the osteological and the historical demographical curves presented here.

9.3.1 Mortality data

In Fig. 81, the mortality profiles calculated on the basis of the regional archaeological data are compared with historical data and demographic standards. The mortality data were taken directly from published life tables for the Alamanni, developed on the basis of c. 4,400 aged individuals (Kokkotidis 1999, 304), the French preindustrial standard (Séguy and Buchet 2013) and England in AD 1541 to 1871 (Wrigley and Schofield 1989). I have included the minimum (e10) and maximum (e3) mortality curves estimated by Wrigley and Schofield on the basis of their data. I have calculated new life tables for Wharram Percy and Kent based on the published osteological age data (Harrington and Brookes 2012; Mays et al. 2007) – in full awareness of the limitations of the life table approach discussed in previous chapters (Tab. 14 and 15). While Wharram Percy had a probably realistic or close to ‘natural’ number of infant burials, the complete sample from Kent of 2651 aged individuals only had 79 individuals aged 0 to 4 years. Compared with the mortality for the first five years of life in Séguy and Buchet’s preindustrial standard (q0-4=32.01), the actual number of infants in the static population case should be c. 1211. This means that compared with standard demographic expectations, c. 1132 infants and young children have been ‘lost’.

In both the Wharram Percy and the ASKED samples, adult individuals were aged only roughly using the typical individual ageing technique prevalent in osteoarchaeology. I therefore had to proportionally distribute adult individuals in 5-year intervals beyond age 20 over all the age categories their imprecise age data covered. Only rarely could old adults be differentiated from young adults and separated in the life tables. The data presented here reflects the problems of osteoarchaeological ageing but some general observations can be made:

First, the archaeological data and estimates for the subadult age category of the Alamanni and Wharram Percy samples fall in between the historical estimates. Strong underestimation is possible compared with the maximum mortality profile of the English early modern population (e3). The 79 subadults in the ASKED database therefore do not represent all the individuals who had died in that age category in the populations represented by the burials. As infant mortality is a sensitive demographic parameter, minimum and maximum scenarios need to be tackled in the following in order to get a better understanding of the demographic information available.

Second, the Alamannic and Kentish mortality curves beyond age 0 to 4 years are strikingly similar. Further, the adult mortality in the curves based on historical data is much lower throughout than the mortality data collected from early medieval cemeteries using osteological ageing methods. The effect of strong under-ageing of adults combined with broad age categories beyond age 25 are responsible for the offset. This is to be expected given the problems of palaeodemographic methods already described in detail. The similarities of each of the two groups suggests that the osteological ageing methods either suffer a relatively standard offset, or that similar selective effects which distort the buried populations in the archaeological record affected both the Kentish and the Alamannic early medieval populations.

Age x	a	Number of Deceased Dx	Percentage of Deceased dx	Survivors lx	Mortality qx	Years lived Lx	Years left to live Tx	Life expectancy ex
0 - 4	5	184.00	26.78	100.00	26.78	433.05	2561.98	25.62
5 - 9	5	79.00	11.50	73.22	15.70	337.35	2128.94	29.08
10 - 14	5	46.00	6.70	61.72	10.85	291.86	1791.59	29.03
15 - 19	5	18.00	2.62	55.02	4.76	268.57	1499.73	27.26
20 - 24	5	39.17	5.70	52.40	10.88	247.77	1231.16	23.49
25 - 29	5	39.17	5.70	46.70	12.21	219.26	983.39	21.06
30 - 34	5	35.67	5.19	41.00	12.66	192.03	764.13	18.64
35 - 39	5	35.67	5.19	35.81	14.50	166.07	572.10	15.98
40 - 44	5	35.67	5.19	30.62	16.96	140.11	406.02	13.26
45 - 49	5	35.67	5.19	25.43	20.42	114.15	265.91	10.46
50 - 54	5	46.34	6.74	20.23	33.33	84.31	151.76	7.50
55 - 59	5	46.34	6.74	13.49	50.00	50.59	67.45	5.00
60 - x	5	46.34	6.74	6.74	100.00	16.86	16.86	2.50
		687	100.000			2561.98		

Tab. 13 Life table of the Wharram Percy population with the actual number of excavated infants.

Age x	a	Number of Deceased Dx	Percentage of Deceased dx	Survivors lx	Mortality qx	Years lived Lx	Years left to live Tx	Life expectancy ex
0 - 4	5	1211.00	32.01	100.00	32.01	419.97	2592.02	25.92
5 - 9	5	269.00	7.11	67.99	10.46	322.16	2172.05	31.95
10 - 14	5	114.00	3.01	60.88	4.95	296.85	1849.89	30.39
15 - 19	5	74.00	1.96	57.86	3.38	284.43	1553.03	26.84
20 - 24	5	130.00	3.44	55.91	6.15	270.95	1268.60	22.69
25 - 29	5	304.56	8.05	52.47	15.34	242.23	997.65	19.01
30 - 34	5	270.56	7.15	44.42	16.10	204.22	755.42	17.01
35 - 39	5	264.06	6.98	37.27	18.73	168.89	551.20	14.79
40 - 44	5	257.56	6.81	30.29	22.48	134.42	382.31	12.62
45 - 49	5	220.56	5.83	23.48	24.83	102.82	247.89	10.56
50 - 54	5	193.56	5.12	17.65	28.99	75.46	145.06	8.22
55 - 59	5	184.56	4.88	12.53	38.93	50.47	69.60	5.55
60 - x	5	289.56	7.65	7.65	100.00	19.14	19.14	2.50
		3783	100.000			2592.0235		

Tab. 14 Life table for all aged individuals in the ASKED database, AD 450 to 750. The missing infants were corrected using the preindustrial standard.

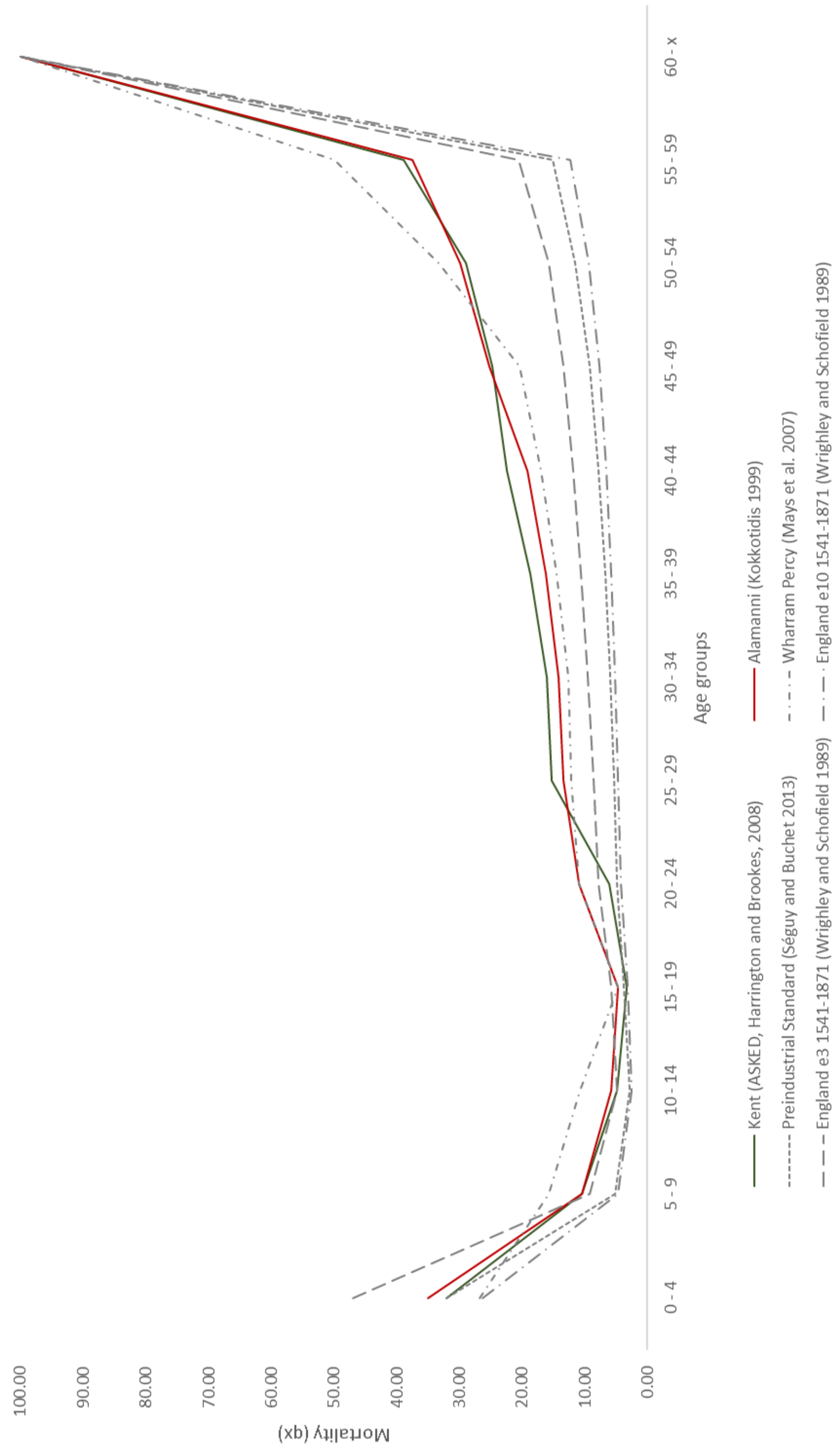
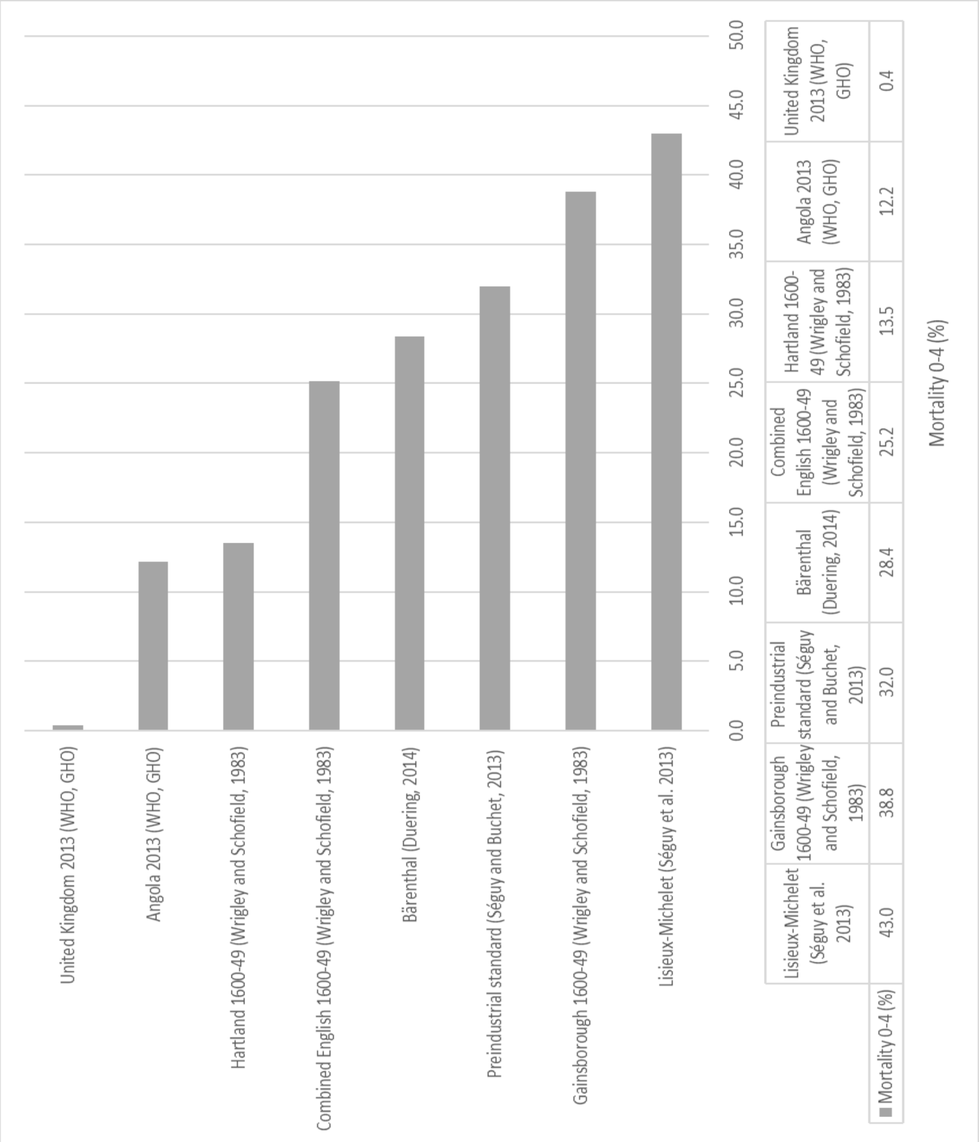


Fig. 81 Comparison between archaeological and historical/standard mortality profiles. Mortality is cut off at age 60 and over because of the limited osteological information available for those age categories and as this is also the cut-off point in the PCS.

9.3.2 Estimating the missing infants

In the early medieval burial record, infant burials are regularly reported as ‘missing’ or less numerous than expected, and many have studied the phenomenon (see chapter 5.1.3) (Crawford 2007; Kölbl 2004; Lohrke 2004; Sayer 2013; Sayer 2014). The incomplete burial record is especially vexing as it leaves us with little information on childhood mortality, which is one of the most sensitive demographic parameters when populations are modelled. Some limited information on childhood mortality can be glimpsed from a few cemeteries such as Wharram Percy and Bärenthal which prove that values comparable with demographic expectations and historical data are seen in burial sites where infants were interred regularly (Duering 2014; Duering and Wahl 2015; Lewis and Gowland 2007). While historical demographers mainly subscribe to relatively high values for infant mortality (Coale and Demeny 1983; Séguy and Buchet 2013; Wrigley and Schofield 1983; Wrigley and Schofield 1989), archaeologists explain lower numbers of infants found in cemeteries by claiming selective effects in the burial ritual and social behaviour of the burying population (Sayer 2014).

At this point it is important to remember that cemeteries are no direct reflection of demographically stationary populations. It is further imperative to make a distinction between childhood mortality and the number or percentage of deceased infants in a cemetery (see chapter 5.1.3). In addition to selective processes, preservation and migration, the number of infants in a cemetery is dependent on the combination of the available infants and the probability of dying for that age group, i.e. fertility determines how many individuals are available and mortality determines how many of these die during infancy. If parameters such as fertility and growth rates are unknown, the number or percentage of deceased subadult individuals in a cemetery is insufficient for accurately estimating childhood mortality (Kölbl 2004). It is however possible to tackle the problem under the model condition of a stationary population and zero population growth. Because of the diversity of opinions and the differences between samples, it is prudent to look at minimum and maximum estimates. Tab. 15 shows a range of data available for the probability of dying between age 0 and 4 years. Séguy and Buchet’s preindustrial standard estimates a 6.8% higher infant mortality than the combined ‘modern’ pre-industrial English data collected by Wrigley and Schofield. The Bärenthal estimate lies between the two. But instead of deciding which of these middle range estimates is the most likely, it is helpful to consider the 17th-century English parishes with the highest and lowest historically attested rates of infant death. The rural parish of Hartland, Devon, yielded the lowest rate of infant death, at 13.5%, while the more urban Gainsborough, Lincolnshire, had the highest recorded probability of dying in the first five years of life, at 38.3% (Wrigley and Schofield 1983; Wrigley and Schofield 1989).



	Lisieux-Michelet (Séguy et al. 2013)	Gainsborough 1600-49 (Wrigley and Schofield, 1983)	Preindustrial standard (Séguy and Buchet, 2013)	Bärenthal (Duering, 2014)	Combined English 1600-49 (Wrigley and Schofield, 1983)	Hartland 1600-49 (Wrigley and Schofield, 1983)	Angola 2013 (WHO, GHO)	United Kingdom 2013 (WHO, GHO)
■ Mortality 0-4 (%)	43.0	38.8	32.0	28.4	25.2	13.5	12.2	0.4

Tab. 15 A comparison of childhood mortality estimates in percent.

The higher mortality of crowded urban environments is probably unrealistic in an early medieval context, but will define the upper end of the expected range in the following. Rural Hartland might more closely reflect conditions of dispersed, small early medieval settlements although it must be noted that the historical data itself can be distorted by selective recording or demographic non-stationarity (Wrigley 1997; Wrigley and Schofield 1989).

If the values of 13.5% and 38.8% are used in life tables calculated for the early medieval Kentish population collected in the ASKED database, between 7.7% and 52.2% of individuals need to be added to the archaeologically recorded populations, i.e. in absolute numbers, between 323 and 1551 infants need to be added to the 79 recorded infants. Using the infant mortality recorded for the combined English population (25.2%), 787 infants would have to be added to the sample in order to equal demographic expectations. Tabs. 16 to 18 represent the life tables used to calculate these three scenarios.

Age x	***a***	**Number of Deceased Dx**	**Percentage of Deceased dx**	**Survivors lx**	**Mortality qx**	**Years lived Lx**	**Years left to live Tx**	**Life expectancy ex**
0 - 4	5	402.00	13.52	100.00	13.52	466.21	3229.11	32.29
5 - 9	5	269.00	9.05	86.48	10.46	409.80	2762.90	31.95
10 - 14	5	114.00	3.83	77.44	4.95	377.61	2353.10	30.39
15 - 19	5	74.00	2.49	73.60	3.38	361.80	1975.50	26.84
20 - 24	5	130.00	4.37	71.12	6.15	344.65	1613.69	22.69
25 - 29	5	304.56	10.24	66.75	15.34	308.12	1269.04	19.01
30 - 34	5	270.56	9.10	56.50	16.10	259.78	960.92	17.01
35 - 39	5	264.06	8.88	47.41	18.73	214.84	701.14	14.79
40 - 44	5	257.56	8.66	38.53	22.48	170.99	486.30	12.62
45 - 49	5	220.56	7.42	29.87	24.83	130.80	315.32	10.56
50 - 54	5	193.56	6.51	22.45	28.99	95.98	184.52	8.22
55 - 59	5	184.56	6.21	15.94	38.93	64.20	88.54	5.55
60 - x	5	289.56	9.74	9.74	100.00	24.34	24.34	2.50
		2974	100.000			3229.1106		

Tab. 16 Minimum estimate. The ASKED population using the Hartland infant mortality value of 13.5%.

Age x	a	Number of Deceased Dx	Percentage of Deceased dx	Survivors lx	Mortality qx	Years lived Lx	Years left to live Tx	Life expectancy ex
0 - 4	5	1631.00	38.81	100.00	38.81	402.99	2357.99	23.58
5 - 9	5	269.00	6.40	61.19	10.46	289.97	1955.00	31.95
10 - 14	5	114.00	2.71	54.79	4.95	267.19	1665.03	30.39
15 - 19	5	74.00	1.76	52.08	3.38	256.01	1397.84	26.84
20 - 24	5	130.00	3.09	50.32	6.15	243.87	1141.83	22.69
25 - 29	5	304.56	7.25	47.23	15.34	218.03	897.96	19.01
30 - 34	5	270.56	6.44	39.98	16.10	183.82	679.93	17.01
35 - 39	5	264.06	6.28	33.54	18.73	152.02	496.12	14.79
40 - 44	5	257.56	6.13	27.26	22.48	120.99	344.10	12.62
45 - 49	5	220.56	5.25	21.13	24.83	92.55	223.11	10.56
50 - 54	5	193.56	4.61	15.89	28.99	67.92	130.57	8.22
55 - 59	5	184.56	4.39	11.28	38.93	45.43	62.65	5.55
60 - x	5	289.56	6.89	6.89	100.00	17.22	17.22	2.50
		4203	100.000			2357.9883		

Tab. 17 Maximum estimate. The ASKED population using the Gainsborough infant mortality value of 38.8%.

Age x	a	Number of Deceased Dx	Percentage of Deceased dx	Survivors lx	Mortality qx	Years lived Lx	Years left to live Tx	Life expectancy ex
0 - 4	5	866.00	25.20	100.00	25.20	437.01	2827.65	28.28
5 - 9	5	268.00	7.80	74.80	10.42	354.52	2390.64	31.96
10 - 14	5	114.00	3.32	67.01	4.95	326.74	2036.11	30.39
15 - 19	5	74.00	2.15	63.69	3.38	313.06	1709.38	26.84
20 - 24	5	130.00	3.78	61.54	6.15	298.23	1396.31	22.69
25 - 29	5	304.56	8.86	57.75	15.34	266.62	1098.09	19.01
30 - 34	5	270.56	7.87	48.89	16.10	224.78	831.47	17.01
35 - 39	5	264.06	7.68	41.02	18.73	185.90	606.69	14.79
40 - 44	5	257.56	7.49	33.34	22.48	147.95	420.79	12.62
45 - 49	5	220.56	6.42	25.84	24.83	113.18	272.84	10.56
50 - 54	5	193.56	5.63	19.43	28.99	83.05	159.66	8.22
55 - 59	5	184.56	5.37	13.79	38.93	55.55	76.61	5.55
60 - x	5	289.56	8.42	8.42	100.00	21.06	21.06	2.50
		3437	100.000			2827.6477		

Tab. 18 Mid-range estimate. The ASKED population using the combined English mortality value of 25.2%.

This leaves us with a wide range of possible demographic scenarios but illustrates the range of possible populations. Most of the early medieval populations in Kent and Alamannia could very well fall within the lower ‘rural’ spectrum, with the Hartland number as an absolute minimum. Sayer has observed that smaller Anglo-Saxon cemetery sites (below 100 burials) have proportionately fewer infant burials than sites with more than 100 buried individuals (Sayer 2014). This might give an indication that infant mortality at values that are slightly lower than the historical average estimates based on a combination of rural and urban sites is possible. However, even the minimum value of infant mortality taken from the Hartland case, legitimates the addition of a few hundred individuals to the ASKED sample in order to represent demographic expectations under standard conditions. That infant burials are lacking from the early medieval regional samples studied here must be regarded as a fact, especially as more missing infants are to be expected in growing populations than in static populations where more young individuals are available in the living population, and, consequently, more of those young individuals die.

One important caveat remains: the influence of population growth and decline in the number of buried infants in small single sites is much stronger than in the regional populations studied here, in which the abnormal developments of individual sites are levelled out by the dynamics of their neighbours. Cemeteries of failed villages, rapidly growing hubs for migrating people and the like will show wide differences between the selective parameter of childhood mortality and the actual number of deceased and buried infants (see chapter 5) (Kölbl 2004).

Instead of opting for one of these scenarios, in the following section, I will use the minimum and maximum values to explore their influence on fertility estimates and estimates of the average size of nuclear families under such demographic conditions. What useful information can we recover about the demographics of early medieval Kent and Alamannia, from the highly problematic information available?

9.3.3 Modelling Kentish and Alamannic fertility, AD 450 to 750

The mortality data described in chapter 9.3.2 can be used to infer the fertility necessary in order to produce stationary populations with zero population growth by modelling such populations over a few hundred years with the PCS. The mortality data for the Kentish and Alamannic populations discussed in chapters 9.3.1 and 9.3.2 are used in the following experiments in combination with the minimum and maximum childhood mortality estimates from the English population based on historical data (Wrigley and Schofield 1983; Wrigley and Schofield 1989). The populations were each modelled over a 200-year period and every parameter setup was repeated 100 times. Tabs. 19 to 22 contain the data sheets for the input information for each experiment. The results of the experiments are presented in Figs. 82 to 85 in which the population size is recorded over different levels of the parameter the-reprodprobability. The child-spacing is stable at a value of 2.5 years for all the modelling runs. For each parameter combination of the fertility parameters, the PCS interface shows the corresponding value of the Total Fertility Rate (TFR).

The results give an absolute minimum and maximum range for the TFR of both the Kentish and the Alamannic populations:

The ASKED population with the minimum infant mortality estimate (q0-4=0.14) remains stationary at TFR 3.4 (Fig. 82). The ASKED population with the maximum infant mortality estimate (q0-4=0.39) remains stationary at TFR 4.8 (Fig. 83).

The Alamannic population with the minimum infant mortality estimate (q0-4=0.14) remains stationary at TFR 3.6 (Fig. 84). The Alamannic population with the maximum infant mortality estimate (q0-4=0.39) remains stationary at TFR 5 (Fig. 85).

This means that an Anglo-Saxon woman in Kent had between 3.4 and 4.8 children if she survived until the end of her fertile phase (taken to be age 40 years) under these model conditions (including life table issues and 0 growth). In Alamannia, women had slightly more children – between 3.6 and 5 – if they reached the end of their reproductive phase.

In comparison with the fertility values published for the English population AD 1541 to 1871 (Wrigley and Schofield 1983) the results of the PCS models yield similar values; this is not surprising, as I have used their early modern child mortality data.

However, the English population is reported to have grown to 280% of its original size between 1541 and 1871 (Wrigley and Schofield 1983), whereas the growth rate of the early medieval populations in Kent and the Alamannia is unknown. The growth rates during the early medieval period were certainly not as high as in late medieval urban populations and during the Industrial Revolution. A growth rate equal to or exceeding 280% is entirely possible but improbable between AD 450 to 750. As a comparison, it took Scandinavian populations the much longer 550-year period between AD 750 and 1300 to triple their size (Benedictow 1996, 181-182). If the development of the settlement of Mucking, which grows by c. 22% from the 5th to the 6th century (Hamerow 1993), is taken as a rough indicator for population growth in the early medieval period, populations would grow to c. 140% to 150% of their size over the modelled 200 years. The 22% can only be a crude estimate as it depends on the accuracy of the dating evidence and the difficulty of dating graves of the earliest and latest phases. The models provide information on the TFR necessary to achieve population growth of this level: in order to grow the modelled ASKED population to c. 140 to 150 individuals, the TFR would have to be increased by c. 0.2. And to grow the Alamannic population to 200% of its original size, an increase in TFR from 3.6 to 3.9 would be necessary in the case of the minimum childhood mortality scenario (Fig. 84).

Even moderately growing populations would have TFR values close to the range modelled in the four scenarios, presented above, and as long as there is no better data for childhood mortality, population growth and migration rates, the minimum and maximum range presented here can be used as estimates of early medieval demographics of populations living in Kent and Alamannia.

The modelled scenarios also allow for an estimate of the size of the average nuclear family units, because the actual number of surviving children is recorded for each female of reproductive age. The results fluctuate between 2 and 3 surviving children, which results in c. 4 to 5 individuals per nuclear family unit. This is consistent with estimates used for the interpretation of Domesday Book (Hinton 2013), the 4.24 individuals estimated for the average Scandinavian family unit around 1300 (Benedictow 1996, 175 Tab. 4) and the family size estimated for the English population between 1541 and 1871 (Wrigley and Schofield 1983).

Despite the problematic nature of the data employed (individual age estimates, life table calculations) and all the estimates necessary (infant mortality, 0 growth and migration), the PCS provides researchers with a tool able to model historical and archaeological populations to a degree of accuracy depending on the input data. The issue of the missing infants in early medieval cemeteries can be tackled by using data from historical demographic research, although regional, period-specific behaviour and individual populations' fates are lost in that process. Finally, the under-ageing problem in osteoarchaeology does not prevent us from modelling functioning and roughly realistic populations. The sensitivity of the probably too-high mortality rates in the adult age categories in the Kentish and Alamannic life tables leads to errors small enough that fertility rates close to historical expectations can still be modelled. If models need not be broken down into individuals with individual ages corresponding with the archaeological and osteological data available in the literature, it is advisable to use standard demographic curves such as the West mortality tables collected by Coale and Demeny (1983), the preindustrial standard (Séguy and Buchet 2013) and the English 1541 to 1871 mortality data (Wrigley and Schofield 1989). However, models using site-specific archaeological and osteological data collected in the traditional way can still be used for roughly realistic experiments; these have the advantage that they work with virtual populations consisting of individual agents with individual ages and sexes, pathologies and grave goods.

PCS DATA SHEET VIRTUAL EXPERIMENT NO ASKED 1

Research Question	Observed Parameters	Number of Repetitions
Estimate TFR value for a population which is stationary for 200 years.	Number of individuals at year 200, probability of reproduction, TFR	100
		Time / Duration of Run
		200

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
50	50	0	40	-	-	-	-

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
15	40	0.5	2.5	0.334 to 0.354

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Mortality (qx)	
0-4	0.140374332
5-9	0.104587869
10-14	0.049500651
15-19	0.033805391
20-24	0.061465721
25-29	0.153431990
30-34	0.161007178
35-39	0.187294973
40-44	0.224785905
45-49	0.248311286
50-54	0.289899841
55-59	0.389269707
60+	1

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
-	-	-	-	-	-

Mortality based on:
Calculated based on: (Harrington and Brookes 2012; Wrigley and Schofield 1989)

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 19 Data sheet for ASKED population with minimum infant mortality estimate.

PCS DATA SHEET VIRTUAL EXPERIMENT NO ASKED 2

Research Question	Observed Parameters	Number of Repetitions
Estimate TFR value for a population which is stationary for 200 years.	Number of individuals at year 200, probability of reproduction, TFR	100
		Time / Duration of Run
		200

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
50	50	0	40	-	-	-	-

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
15	40	0.5	2.5	0.48 to 0.49

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Mortality (qx)	
0-4	0.390810043
5-9	0.104587869
10-14	0.049500651
15-19	0.033805391
20-24	0.061465721
25-29	0.153431990
30-34	0.161007178
35-39	0.187294973
40-44	0.224785905
45-49	0.248311286
50-54	0.289899841
55-59	0.389269707
60+	1

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
-	-	-	-	-	-

Mortality based on:
Calculated based on: (Harrington and Brookes 2012; Wrigley and Schofield 1989)

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 20 Data sheet for ASKED population with maximum infant mortality estimate.

PCS DATA SHEET VIRTUAL EXPERIMENT NO Alamanni 1

Research Question	Observed Parameters	Number of Repetitions
Estimate TFR value for a population which is stationary for 200 years.	Number of individuals at year 200, probability of reproduction, TFR	100
		Time / Duration of Run
		200

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
50	50	0	40	-	-	-	-

Mortality (qx)	
0-4	0.140
5-9	0.104
10-14	0.058
15-19	0.047
20-24	0.109
25-29	0.135
30-34	0.142
35-39	0.162
40-44	0.191
45-49	0.253
50-54	0.299
55-59	0.375
60+	1

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
15	40	0.5	2.5	0.34 to 0.4

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
-	-	-	-	-	-

Mortality based on:
Calculated based on: (Kokkotidis 1999; Wrigley and Schofield 1989)

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 21 Data sheet for Alamannic population with minimum infant mortality estimate.

PCS DATA SHEET VIRTUAL EXPERIMENT NO Alamanni 1

Research Question	**Observed Parameters**	**Number of Repetitions**
Estimate TFR value for a population which is stationary for 200 years.	Number of individuals at year 200, probability of reproduction, TFR	100
		Time / Duration of Run
		200

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
50	50	0	40	-	-	-	-

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
15	40	0.5	2.5	0.43 to 0.55

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

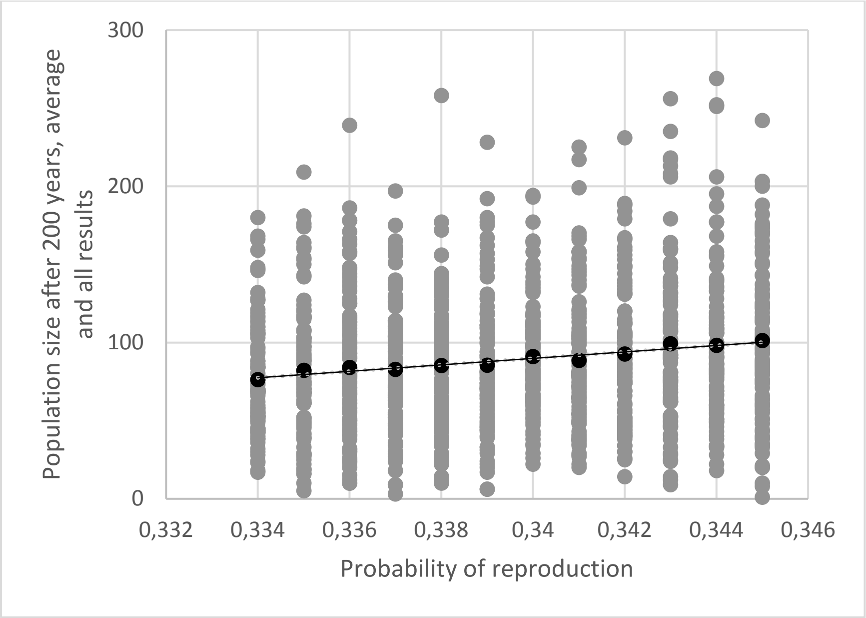
Mortality (qx)	
0-4	0.390
5-9	0.104
10-14	0.058
15-19	0.047
20-24	0.109
25-29	0.135
30-34	0.142
35-39	0.162
40-44	0.191
45-49	0.253
50-54	0.299
55-59	0.375
60+	1

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
-	-	-	-	-	-

Mortality based on:
Calculated based on: (Kokkotidis 1999; Wrigley and Schofield 1989)

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 22 Data sheet for Alamannic population with maximum infant mortality estimate.



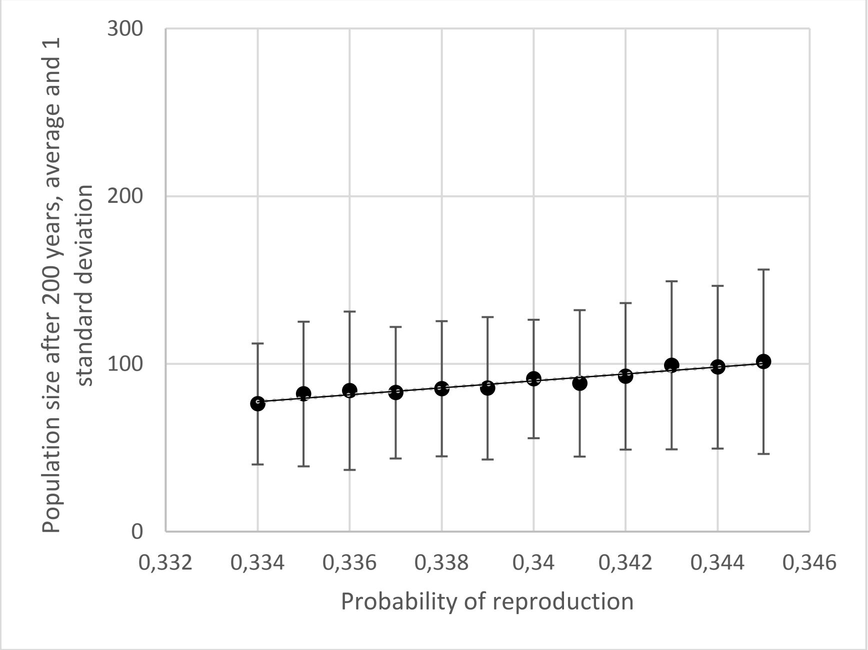
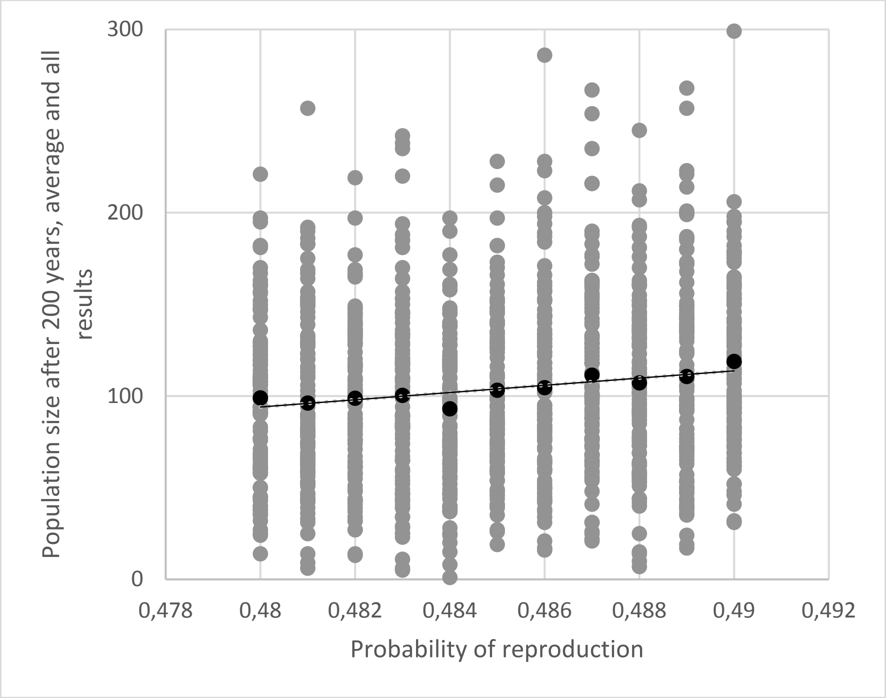


Fig. 82 ASKED population, low infant mortality (q0-4=0.14) scenario. Population size after 200 years over probability of reproduction with constant child-spacing of 2.5 years and a starter generation of 100 individuals. Zero population growth is reached at the-reprodprobability=0.344, which equals TFR 3.4. Each parameter value is modelled 100 times and the range of results is shown as grey dots. The black dots represent the average over 100 repetitions. The line is the linear regression of the results.



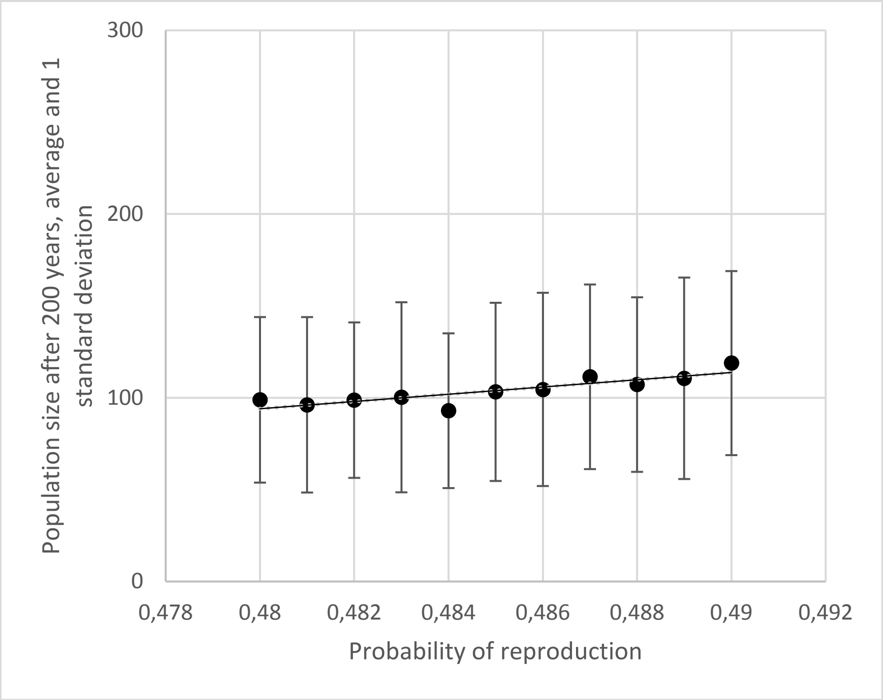
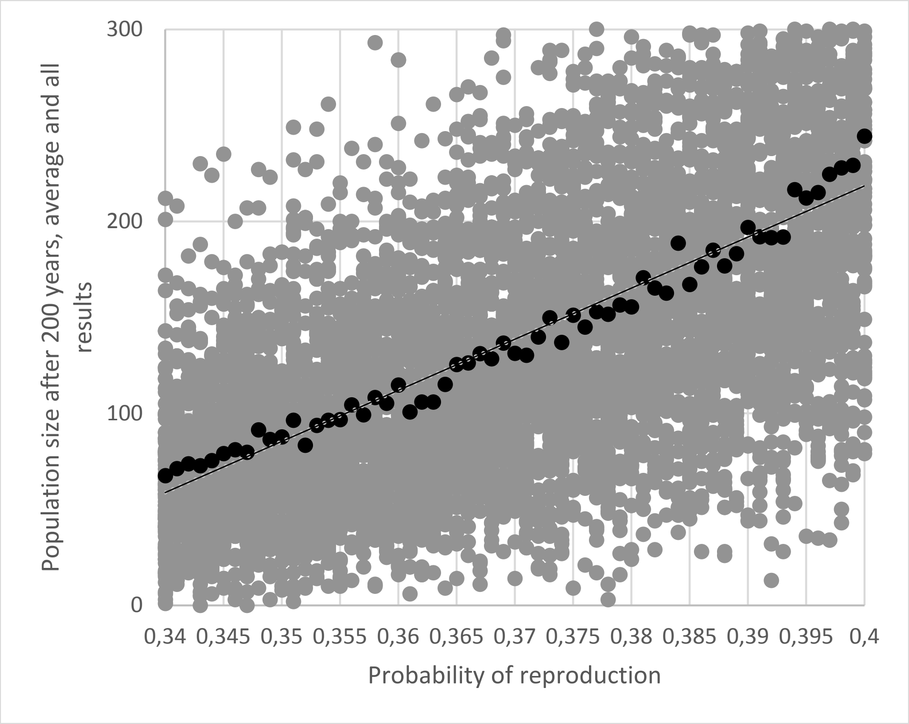


Fig. 83 ASKED population, high infant mortality (q0-4=0.39) scenario. Population size after 200 years over probability of reproduction with constant child-spacing of 2.5 years and a starter generation of 100 individuals. Zero population growth is reached at the-reprodprobability=0.483, which equals TFR 4.8. Each parameter value is modelled 100 times and the range of results is shown as grey dots. The black dots represent the average over 100 repetitions. The line is the linear regression of the results.



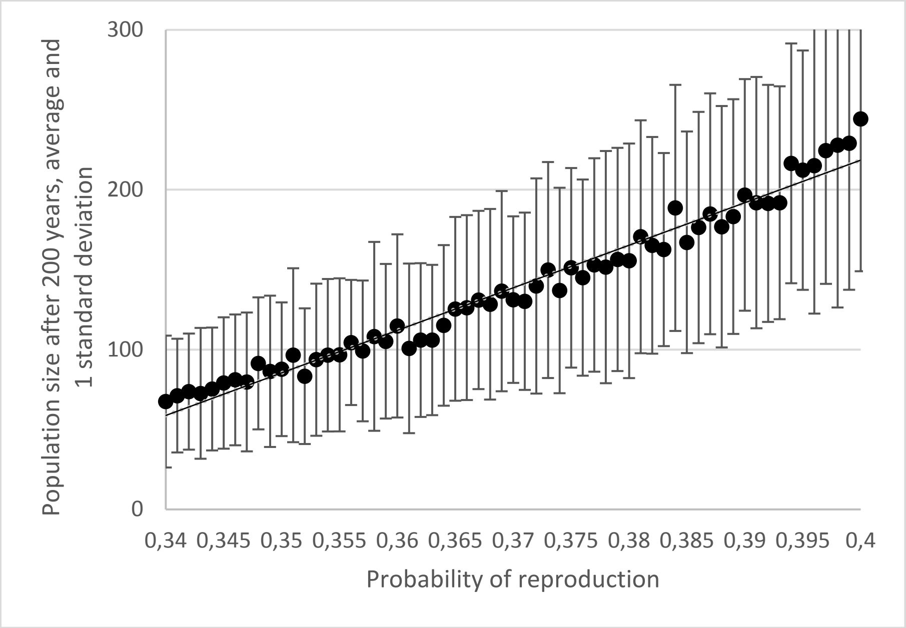
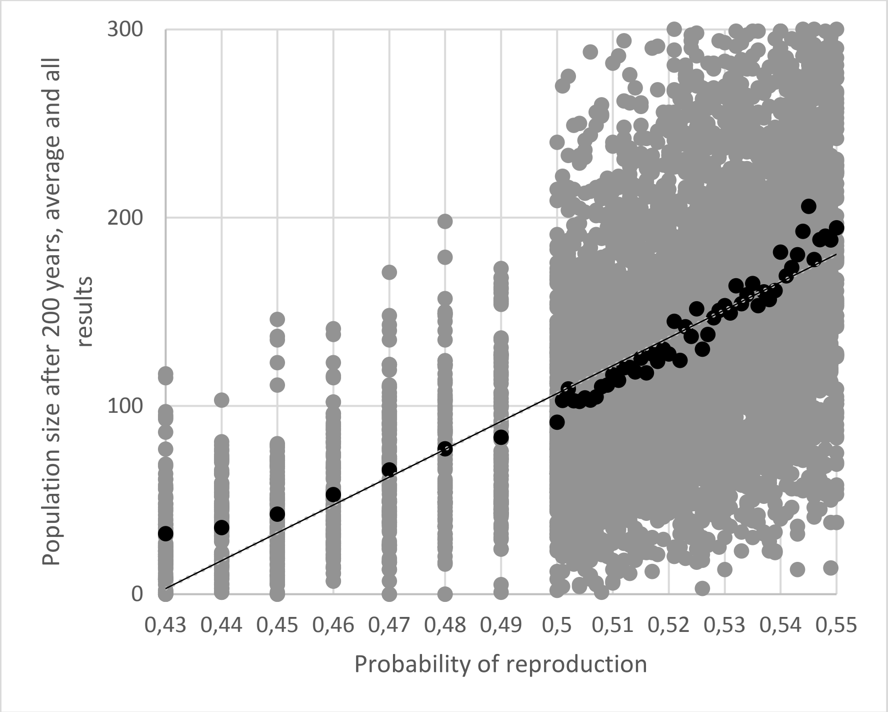


Fig. 84 Alamannic population, low infant mortality (q0-4=0.14) scenario. Population size after 200 years over probability of reproduction with constant child-spacing of 2.5 years and a starter generation of 100 individuals. Zero population growth is reached at the-reprodprobability=0.357, which equals TFR 3.6. Each parameter value is modelled 100 times and the range of results is shown as grey dots. The black dots represent the average over 100 repetitions. The line is the linear regression of the results. At c. TFR 3.9 the population size doubles within the 200-year period (the-reprodprobability=0.393).



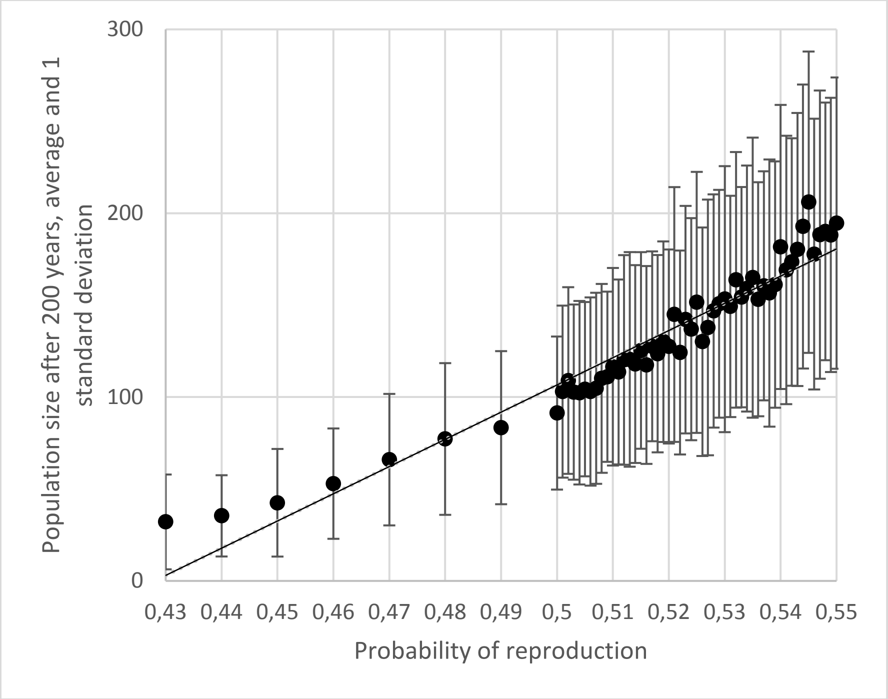


Fig. 85 Alamannic population, high infant mortality (q0-4=0.39) scenario. Population size after 200 years over probability of reproduction with constant child-spacing of 2.5 years and a starter generation of 100 individuals. Zero population growth is reached at the-reprodprobability=0.495, which equals TFR 5. Each parameter value is modelled 100 times and the range of results is shown as grey dots. The black dots represent the average over 100 repetitions. The line is the linear regression of the results.

9.4 Beyond Demographics – Artefacts, economy and power

In the final section, the regional population of Anglo-Saxon Kent will be modelled using the PCS in order to demonstrate how questions beyond demographics can be tackled. This chapter is not designed to provide definite answers, but to show the potential of demographic modelling to address central themes of archaeological research.

As grave goods are traditionally used in early medieval archaeology to study the relationship between economy, power and social structure, the following example will employ the PCS to model differential access to the material culture of the living group(s) as reflected in the grave goods found in their cemeteries. In his study of the artefacts in Kentish cemeteries from AD 450 to 750, Stuart Brookes reports an economic and/or social change shortly before AD 600, based on the observation that metal objects were more common in graves dated to the 5th and 6th centuries than in graves dated to the 7th century. Iron objects, found in c. 80% of graves before AD 600, drop to c. 60% after that period. More markedly, copper-alloy object abundance drops from c. 50% to less than 20% in the short phase between 550 and 600. Rare artefacts made from silver and gold similarly become less numerous over the course of the 7th century, with less than 8% of individuals interred with silver after AD 675 (Brookes 2007, 138-143). Brookes interprets this “impression of the demographic use of raw materials” as indicating “that the seventh century witnessed a hardening of social-group identification” (Brookes 2007, 142). Copper-alloy, silver and gold in particular, had become reserved for elite display in grave assemblages by the c. 600 (*ibid.*). The ASKED database and Stuart Brookes’ research into the region are used as data input (Brookes 2007; Harrington and Brookes 2012).

The first part of this section will analyse representativeness and bias of the data employed by Brookes. Who is represented demographically by the burials and their grave goods, and does this affect Brookes findings?

Secondly, I will model the population with changing artefact abundances in the cemetery in order to assess how quickly social changes in the living population affected the buried population and the delayed response of cemetery data. The differences between living and dead populations described in previous chapters of this thesis are important factors in this case study.

Thirdly, it will be estimated which part of the living population had access to artefacts made of various different metals and alloys, taking into account the biases of missing infants, females and population growth.

9.4.1 Population and sample size

The number of aged individuals in the ASKED database is 2651. As established in the previous chapter, hundreds of infant burials are missing from this sample. If the average child mortality level estimated for the English population from AD 1541 to 1871 ($q_{0\text{-}4}$=25.2%) is taken as a proxy, c. 787 children would have to be added in the case of a stationary population with zero growth (see life table, Tab. 23). The resulting cemetery sample would therefore increase to slightly less than 3500 individuals deceased between AD 450 and 750. Despite all the issues with ageing in osteology, despite all the mathematical and demographic problems, in the following experiments I will assume that the sample is roughly representative of the demographics of the population of Kent. The life table calculated forms the basis for the mortality estimates used in the PCS simulations. Using a rough estimate of a generation length of 30 years, the average living population in a static population burying c. 3500 individuals in a period of 450 to 750 years is c. 342. A PCS model run of a community consisting of 171 females and 171 males would bury roughly 3500 individuals over the period of 300 years (see test run, Fig. 86). The living group represented by the sample is therefore small compared to the size of Kent. And as the sample is made up of 28 individual cemeteries, the average population represented per point in time is c. 12 per site, 6 female and 6 male individuals, c. 50% of whom are below the age of 21 years. This equates to 3 adult males and 3 adult females existing together at each point in time in the average site, and c. 170 adults in the complete regional sample.

Age x	*a*	Number of Deceased Dx	Percentage of Deceased dx	Survivors lx	Mortality qx	Years lived Lx	Years left to live Tx	Life expectancy ex
0 - 4	5	866.00	25.20	100.00	25.20	437.01	2827.65	28.28
5 - 9	5	268.00	7.80	74.80	10.42	354.52	2390.64	31.96
10 - 14	5	114.00	3.32	67.01	4.95	326.74	2036.11	30.39
15 - 19	5	74.00	2.15	63.69	3.38	313.06	1709.38	26.84
20 - 24	5	130.00	3.78	61.54	6.15	298.23	1396.31	22.69
25 - 29	5	304.56	8.86	57.75	15.34	266.62	1098.09	19.01
30 - 34	5	270.56	7.87	48.89	16.10	224.78	831.47	17.01
35 - 39	5	264.06	7.68	41.02	18.73	185.90	606.69	14.79
40 - 44	5	257.56	7.49	33.34	22.48	147.95	420.79	12.62
45 - 49	5	220.56	6.42	25.84	24.83	113.18	272.84	10.56
50 - 54	5	193.56	5.63	19.43	28.99	83.05	159.66	8.22
55 - 59	5	184.56	5.37	13.79	38.93	55.55	76.61	5.55
60 - x	5	289.56	8.42	8.42	100.00	21.06	21.06	2.50
		3437	100.000			2827.6477		

Tab. 23 Life table with corrected infant mortality, mid-range estimate taken from the English Population AD 1541 to 1871.

Fig. 86 One test run of a population which remains stationary at slightly more than 171 males and 171 females, and its cemetery formed over 300 modelled years. 3597 individuals are buried in this test run.

Further, instead of dividing up the sexes equally, we can examine the proportion of sexed individuals. Of the 699 sexed individuals in the sample, only 304 were females, which means that there are c. 30% more males than females in the cemetery sample. The 30% difference exceeds the sex ratio commonly observed by demographers in modern living populations. While slightly more male babies are born to humans, the mortality of embryos after conception and newborn babies is complex, sex-dependent and changes over time (Orzack et al. 2015). Differential mortalities during life, most importantly the lower life expectancy of old adult males compared with old adult females, lead to further alterations of the sex ratio (Chamberlain 2006; Grupe et al. 2005; Waldron 1983). Modern countries such as China, India or Armenia have ratios of c. 1.2 at most, i.e. c. 20% more males than females (World Bank 2016). However, as the cemetery sample does not represent a living population, the mortality effect could lead to the inverse picture for the living population, i.e. a higher number of surviving females. After World War II, the German population had roughly 40% more females than males because of the high number of fallen soldiers, even more when POWs were considered (Bethmann and Kvasnicka 2013). In the case of a similar 'war effect', the bodies of the fallen Anglo-Saxons would have to be taken home or at least been buried in a cemetery closeby. Under such theoretical circumstances, the actual living population which formed the early medieval sample would have an excess of women of up to 30%. But is early medieval warfare really comparable with the effects of a world war waged using modern technologies of killing? And why are the children missing from the cemetery sample as well?

As established in the previous chapter, hundreds of children are missing from the cemetery sample (see, for instance, the above mid-range estimate of c. 787), which indicates that we must look for reasons beyond demographics to explain the age compositions observed. Archaeological cemetery populations can be affected by selective preservation and selective excavation. For instance, infant bones are less likely to survive in adverse soil conditions and could regularly be overlooked during the excavation process because of their small size. As they will have rested in much shallower graves than their adult counterparts (Duering 2014), it is likely that a proportion of the offset can be explained by differential preservation. But as both infants and women are missing, it is even more likely that the selection is based on a bias during the burial ritual or a combination of all the mentioned effects. The Anglo-Saxons probably chose not to bury a part of the population which happens to represent the ‘weaker’ part of the population, in both physical power and socio-economic influence, in their cemeteries. The sample must therefore not be regarded as a complete cross-section of Anglo-Saxon society and demographics. And if the population represented by the few thousand individuals in the sample selected against their own women and young children, who else might be missing from the sample? Combined with the low total number of living individuals represented by the sample, it is quite possible that a large proportion of individuals with low levels of wealth, influence and power are entirely missing from the study sample – men, women and their children. But how large is the missing part of the population? Is it 20% of slaves or the majority of 80% of ordinary people? Are these cemeteries of almost entire settlement populations, or burial places restricted to local elites and their retinues? Even if we do not know the answers to these questions at this point, it becomes clear that the base population and its demographics are potentially heavily biased towards the socio-economic elites of Anglo-Saxon Kent and that Stuart Brookes’ percentage estimates of material frequencies (see above) might need to be moderately, or even drastically reduced.

9.4.2 Modelling change during the 6th century

The question to be explored in the following is how long it takes for a change in the socioeconomic setup of the living population to manifest itself in the cemetery. Before modelling an instant change scenario versus a long-term change scenario, a few further thoughts regarding the cemetery data available are necessary. For change to register in the record, we need to identify two things. First, the changing parameter itself, i.e. the change of one regime of object availability to another. Second, the material and graves need to be dated in order to sort them into the phase before or after the change.

Theoretically, two effects directly following this are possible. If the objects are independent of the dating evidence, for instance if the objects are not themselves used for dating the grave, and if the dating evidence available has wide margins of error (and all dating efforts by early medieval archaeologists have proved to be accompanied by wide margins of error, mostly much wider than generation lengths (Bayliss et al. 2013)), the actual change will be hidden behind the imprecise dates/broad date ranges assigned to graves in the cemetery which transition gradually between one phase and the next. Therefore, a gradual change in the cemetery might actually hide a relatively abrupt socioeconomic event causing fast change in the living population because of the problems of dating.

On the other hand, if the objects showing the socioeconomic (or ritual etc.) change are themselves used during the dating procedure, e.g. as part of the objects sorted in archaeological typologies, changes in artefact deposition in graves are used directly to sort graves into phases. In such cases, sharp phase differences can arise purely because of the sorting procedure used when dating the artefacts, as they then either fall into the earlier or the later phase in a binary procedure that possibly hides the actual gradual transition over time. Dating of Anglo-Saxon graves mostly merges all the available data, i.e. all the available artefacts which have typologies and if radiocarbon dates are available, they are combined with the merged date as well. The dates in the ASKED sample used here are combined dates which partly or exclusively use the artefacts for dating which are also the basis for Brookes' socioeconomic observations (Brookes 2007; Harrington and Brookes 2012).

Combined with the bias and size of the sample, the two scenarios described show that any observation of change in cemetery data must be taken with a pinch of salt. A degree of humility is warranted, but the issues with the primary information available also allows for a more playful approach to modelling various scenarios until the graves and artefacts in the sample are better dated than they are at present. In one such interpretative 'game', I will assume that the dates given in the ASKED are more or less correct and that the artefact typologies of the objects used in Brookes' socioeconomic observation of change in the 6th century have not affected the phasing of the graves very much.

The change in the sample happens relatively quickly between AD 550 and 650; i.e. within c. 100 years the cemetery population is affected by the change in the living population (Brookes 2007, 138-143). This situation can be modelled using the PCS. A stationary population is modelled for 100 years in which every adult male and female (from age 20) receives a copper-alloy artefact in 50% of cases in modelled year 0. From modelled year 1 onwards, however, only 20% of adult males and females receive a copper-alloy artefact. This equals a drastic change in the socioeconomic regime of 'artefact distribution'. Every individual buried receives his or her artefact as a grave good when buried. In the model (Figs. 87 to 88) one can see that an abrupt change in the artefact distribution routine in the living population can reproduce the drop in raw material frequencies (copper-alloy example) in the adult population (from c. 50% to c. 20%) within a 100-year period. The living population needs c. 40 years to react to the sudden change in artefact frequency. The cemetery reacts with a slight delay to the changes in the living population, as the individuals buried under the new artefact frequency regime must first accumulate against the individuals buried under the old regime. Especially if graves cannot be dated to the accuracy of generation lengths, the smooth reaction in the cemetery hides drastic changes in the system which governs the accessibility of artefacts. We can further observe in the lower right-hand graph of Fig. 87 that the actual frequency of artefacts in the total population (adults and children) drops from roughly 30% to 17% in the cemetery, and from c. 26% to 10% in the living population.

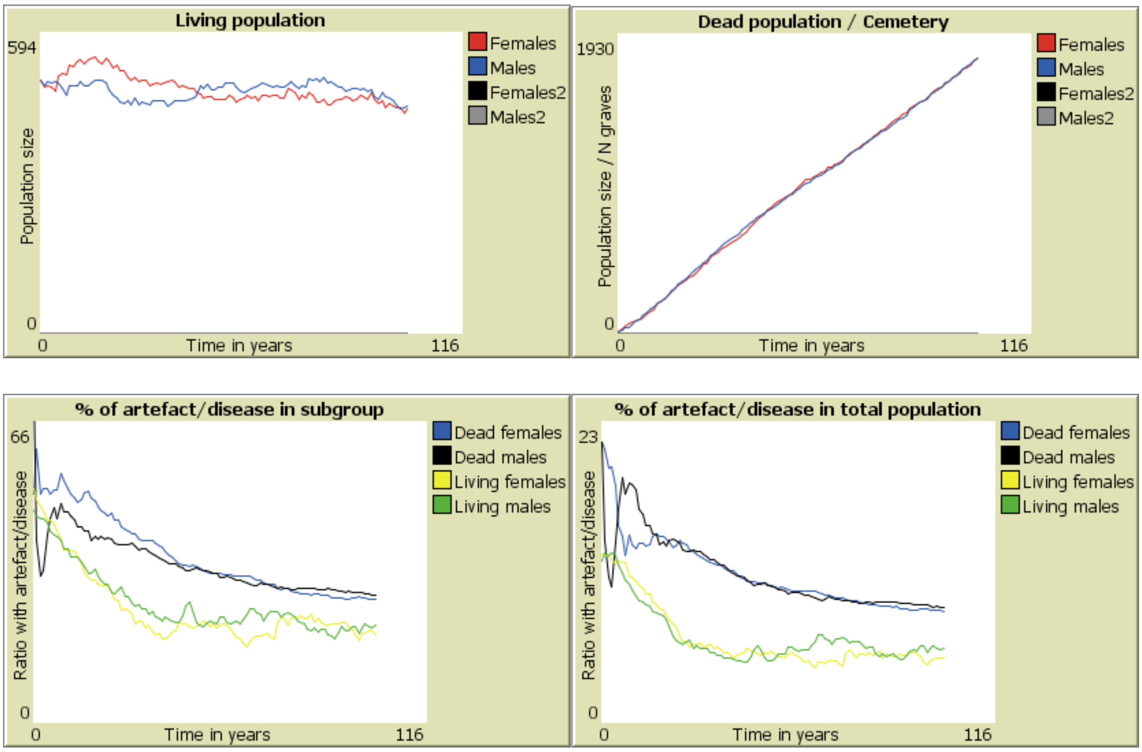


Fig. 87 Model of a stationary population for 100 years, between AD 550 and 650. Upper left-hand corner: living population size over time. Upper right-hand corner: cemetery population over time. Lower left-hand corner: percentage of adult population (males and females) living with access to copper alloy and buried with copper-alloy artefacts over time. Lower right-hand corner: frequency of individuals with copper-alloy artefacts in total living and total cemetery populations over time.

PCS DATA SHEET VIRTUAL EXPERIMENT NO Frequency 1

Research Question	Observed Parameters	Number of Repetitions
Observe artefact frequency change over time.	Population size, artefact frequencies in adults (20 years and over) and total population.	1
		Time / Duration of Run
		100

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
500	500	0	40	-	-	-	-

Mortality (qx)	
0-4	0.25
5-9	0.104587869
10-14	0.049500651
15-19	0.033805391
20-24	0.061465721
25-29	0.153431990
30-34	0.161007178
35-39	0.187294973
40-44	0.224785905
45-49	0.248311286
50-54	0.289899841
55-59	0.389269707
60+	1

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
15	40	0.5	2.5	0.383

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
20	0.5 at year 0, then 0.2	1	20	0.5 at year 0, then 0.2	1

Mortality based on:
Calculated based on: (Harrington and Brookes 2012; Wrigley and Schofield 1989)

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 24 Data sheet for experiment of abrupt change in artefact frequencies.

For comparison, a model with a longer period of change in the living population – for instance an incremental change from 50% to 20% in 5% increments every 10 years (see Fig. 88) – results in a drawn-out signal change in the cemetery. In this theoretical scenario, the cemetery signal remains at c. 35% after 100 years. The living population declines faster than the cemetery and adjusts relatively quickly to the smooth change in frequency. Because of the small scale of the frequency change over time, the generational delay, i.e. the reaction time, is not as long as in the case of the abrupt change scenario.

As a result of the comparison between the model of abrupt change and the model of incremental change over 60 years, we are faced with the fact that the data do not contain the information required to distinguish between abrupt and relatively long term change regarding the living population. However, if the change in the living population is drawn out beyond one or two human generation lengths it becomes unlikely that the cemetery data have time to react within the 100-year period, from AD 550 and 650. Because of the demographic delay effect, the socioeconomic changes must have happened before AD 600 and are likely to have had the most impact on the living population around AD 550.

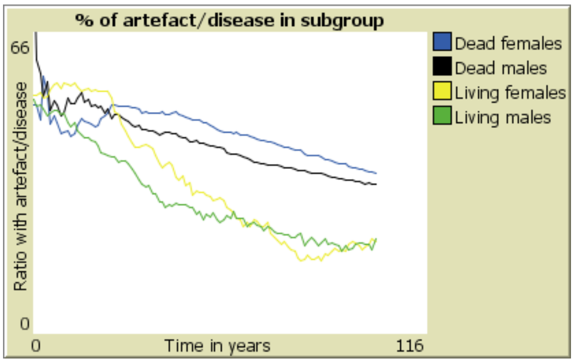


Fig. 88 Model of a stationary population for 150 years, between AD 550 and 700. Percentage of adult population (males and females) living with access to copper alloy and buried with copper-alloy artefacts over time.

PCS DATA SHEET VIRTUAL EXPERIMENT NO Frequency 2

Research Question	Observed Parameters	Number of Repetitions
Observe artefact frequency change over time.	Population size, artefact frequencies in adults (20 years and over) and total population.	1

Time / Duration of Run
100

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
500	500	0	40	-	-	-	-

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
15	40	0.5	2.5	0.383

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Mortality (qx)	
0-4	0.25
5-9	0.104587869
10-14	0.049500651
15-19	0.033805391
20-24	0.061465721
25-29	0.153431990
30-34	0.161007178
35-39	0.187294973
40-44	0.224785905
45-49	0.248311286
50-54	0.289899841
55-59	0.389269707
60+	1

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
20	0.5 - 0.05 every 10 years, stop at 0.2	1	20	0.5 - 0.05 every 10 years, stop at 0.2	1

Mortality based on:
Calculated based on: (Harrington and Brookes 2012; Wrigley and Schofield 1989)

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 25 Data sheet for experiment of long-term change in artefact frequencies.

9.4.3 Modelling the wealth of the living population

The following experiment represents a scenario which takes the bias of the missing infants into account, although men and women are treated as equally likely to receive an artefact in this model. I will also model a moderately growing population in order to account for the fact that c. 45% more individuals were buried after AD 600 than before AD 600 (data taken from the ages ASKED sample). I therefore estimate that the population grows from c. 266 to c. 418 individuals within a 300-year period. The mortality regime of the first set of models is taken from the life table of the ASKED population (Tab. 26). The results are then compared with the same models using the mortality taken from a demographic standard curve.

The raw-material frequencies (copper-alloy) for a living population which does not bury over 90% of children can be observed in Fig. 89 compared with the frequencies in the population's cemetery. From AD 450, i.e. in modelled year zero, 50% of adult males and females receive an artefact. At year AD 550, i.e. in the 100th modelled year, only 20% of adult males and females receive an artefact.

The results are that the artefact distribution change modelled can be seen to impact the living population after AD 550, i.e. after modelled year 100. The adult living population starts off with 50% having access to copper alloy and ends up with just below 20% having access to copper alloy. The accumulated cemetery signal (i.e. the data for each year includes the data for all previous years) drops from 50% to 30% in the 300-year period. The data for the complete population represent a drop from roughly 36% to 18% in the cemetery and from c. 30% to 8% in the living population. If demographic growth and subadult individuals are modelled in order to understand the actual frequencies in the living population that formed the cemeteries of Kent, access to copper alloy becomes more and more limited until a maximum of only 8% of the total living population had access to copper alloys in the 7th century AD, based on the cemetery data and the demographic estimates employed here.

A simplified version of this model is conducted for silver, modelling a drop from 20% to 8% in the cemeteries in the period between AD 450 and 750 (Tab. 27, Fig. 90). For the total living population, this corresponds with a drop in access to silver from c. 12% to a maximum of 4%.

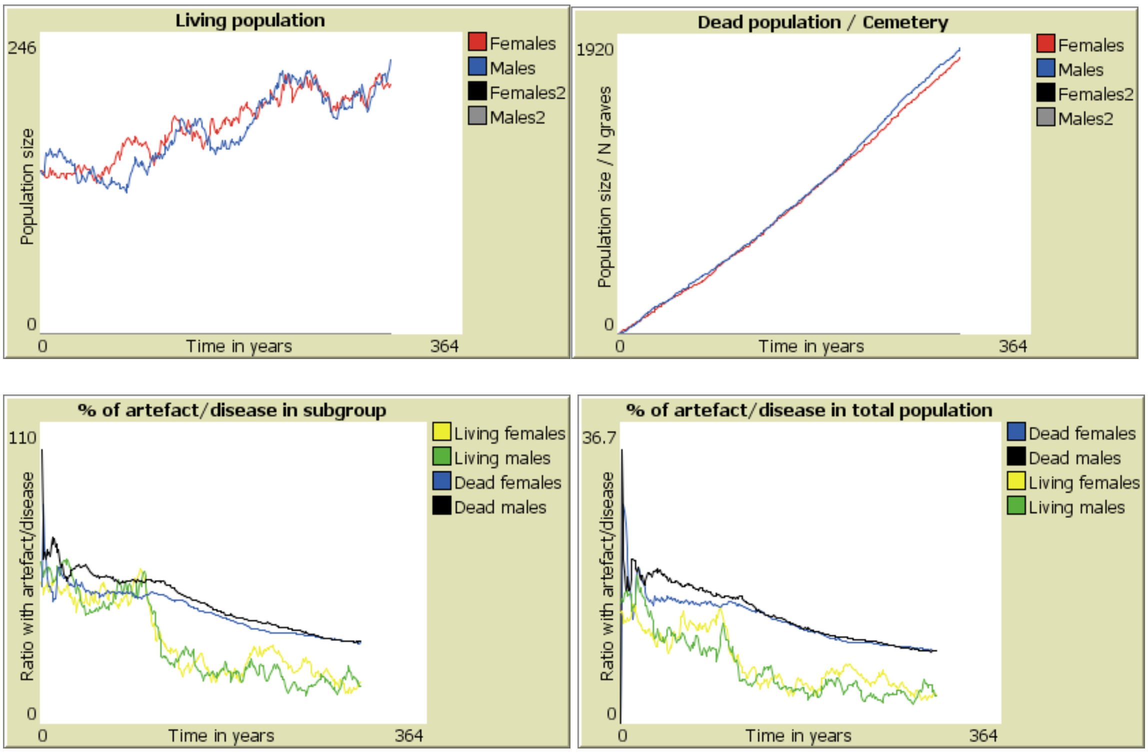


Fig. 89 Model of a growing population simulated for 300 years, between AD 450 and 750. Upper left-hand corner: living population size over time. Upper right-hand corner: cemetery population over time. Lower left-hand corner: percentage of adult population (males and females) living with access to copper alloy and buried with copper-alloy artefacts over time. Lower right hand corner: frequency of individuals with copper-alloy artefacts in total living and total cemetery populations over time.

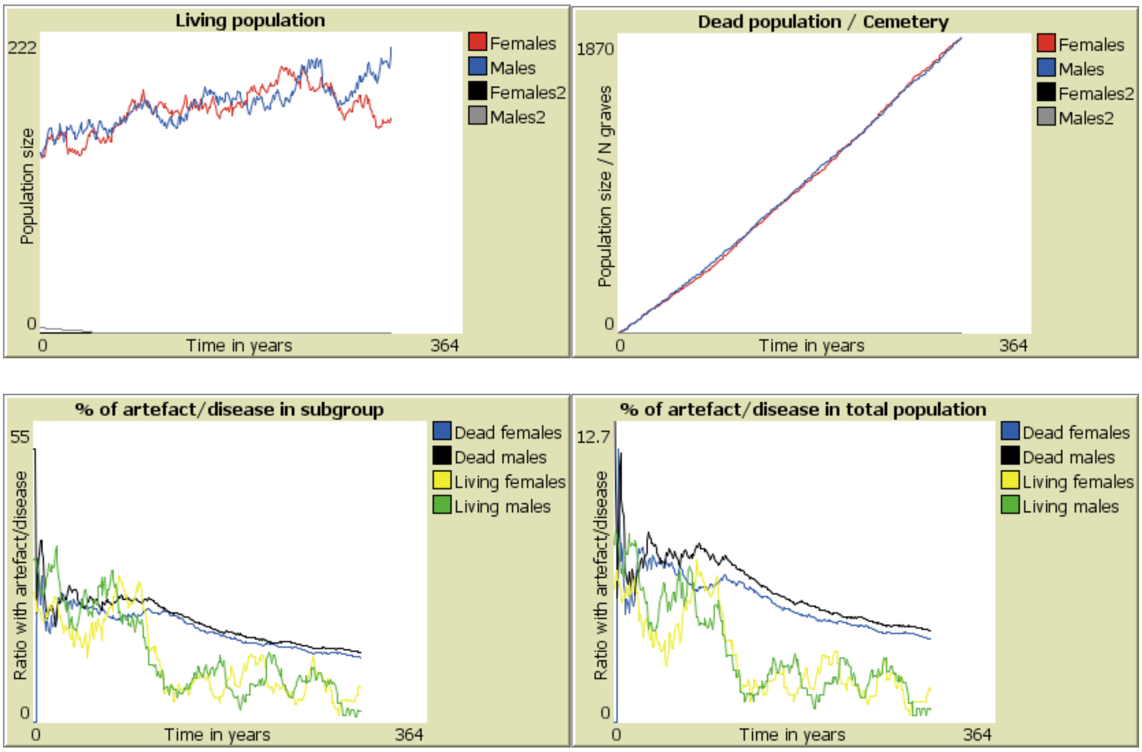


Fig. 90 Model of a growing population simulated for 300 years, between AD 450 and 750. Upper left-hand corner: living population size over time. Upper right-hand corner: cemetery population over time. Lower left-hand corner: percentage of adult population (males and females) living with access to silver and buried with silver artefacts over time. Lower right-hand corner: frequency of individuals with silver artefacts in total living and total cemetery populations over time.

PCS DATA SHEET VIRTUAL EXPERIMENT NO Frequency 3

Research Question	Observed Parameters	Number of Repetitions
Observe artefact frequency change over time.	Population size, artefact frequencies in adults (20 years and over) and total population.	1
		Time / Duration of Run
		100

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
133	133	0	40	-	-	-	-

Mortality (qx)	
0-4	0.25
5-9	0.104587869
10-14	0.049500651
15-19	0.033805391
20-24	0.061465721
25-29	0.153431990
30-34	0.161007178
35-39	0.187294973
40-44	0.224785905
45-49	0.248311286
50-54	0.289899841
55-59	0.389269707
60+	1

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
15	40	0.5	2.5	0.413

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
20	0.5, 0.2 after year 100	1	20	0.5, 0.2 after year 100	1

Mortality based on:
Calculated based on: (Harrington and Brookes 2012; Wrigley and Schofield 1989)

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 26 Data sheet for frequency experiment number three, copper alloy.

PCS DATA SHEET VIRTUAL EXPERIMENT NO Frequency 4

Research Question	Observed Parameters	Number of Repetitions
Observe artefact frequency change over time.	Population size, artefact frequencies in adults (20 years and over) and total population.	1
		Time / Duration of Run
		100

Initial Population / Starter Generation							
P1				**P2**			
Nf	Nm	Lage	Uage	Nf	Nm	Lage	Uage
133	133	0	40	-	-	-	-

Reproduction / Fertility				
Minrage	Maxrage	Fbratio	Childsp	Reproprob
15	40	0.5	2.5	0.413

Selective Data Loss in Cemetery		
Chance	Min Age	Max Age
0	-	-

Catastrophes		
On/Off	Delay	X Mort
Off	-	-

Mortality (qx)	
0-4	0.25
5-9	0.104587869
10-14	0.049500651
15-19	0.033805391
20-24	0.061465721
25-29	0.153431990
30-34	0.161007178
35-39	0.187294973
40-44	0.224785905
45-49	0.248311286
50-54	0.289899841
55-59	0.389269707
60+	1

Artefacts / Diseases					
Male			**Female**		
Iniage	Prob	X Mort	Iniage	Prob	X Mort
20	0.2, 0.08 after year 100	1	20	0.2, 0.08 after year 100	1

Mortality based on:
Calculated based on: (Harrington and Brookes 2012; Wrigley and Schofield 1989)

Exogamy / Migration				
Probabilities	**Female**		**Male**	
P2 to P1	-		-	
P1 to P2	-		-	
Migrant Age	Min	Max	Min	Max
	-	-	-	-

Tab. 27 Data sheet for frequency experiment number four, silver.

Instead of using raw data from cemeteries, the frequencies in the total living populations should be used for comparisons with behavioural and economic models, e.g. those which show wealth regimes in human populations utilising Game Theory approaches and Pareto's Law (Brookes 2007, 138). Such economic models are based on living instead of cemetery populations and their subdivision of populations into strata according to their access to wealth use percentages of the living and not percentages of the deceased. Judging from raw material frequency data, a very small part of the population alive at each point in time had access to copper alloy and silver objects. In absolute numbers, a maximum of c. 27.4 (8% of the c. 243 individuals) individuals had access to copper alloys and fewer than 13.7 (4% of the c. 243 individuals) had access to silver objects in the population represented by the sample after AD 600 at each point in time. Broken down into the hypothetical value of individuals per average site, the number of individuals equates to c. one for copper-alloy and roughly half a person for silver.

9.4.4 Conclusions

Demographic models were used used to recreate the economic and social changes of the Kentish population between AD 550 and 650 described by Brookes. The cemetery population collected in the ASKED database must be regarded as a subpopulation with hundreds of infants missing, as well as in all probability, other elements of the complete early medieval population of Kent. All the graves gathered only represent a couple of hundred individuals existing at the same point in time, and it is highly likely that the material is biased towards the higher echelons of society. The percentage of individuals associated with artefacts during their life is probably lower than in the cemetery record.

The relatively short-term change of the artefact numbers in cemeteries, especially the objects made from copper-alloys, can be described either by the abrupt appearance of restriction in the access to such materials for some parts of the population, or by a process probably in the range of one to two generation-lengths in the middle of the 6th century. A long-term decline in furnished burial seems to be a less likely cause of the cemetery signal. But with regard to new material uncovered and published in Kent since ASKED went online and new dating evidence (Bayliss et al. 2013), a review of Brookes' results would be very interesting, and with it a repetition of the above models with the new data. It is likely that the strong AD 600 marker is an artefact of typological dating routines. Further, individual cemeteries need to be modelled in a fine-grained approach to validate the general results. Exceptionally rich sites such as Dover Buckland, Eastry Updown and Broadstairs Bradstow School should be separated from the rest in a more detailed study of this kind (Brookes 2007).

All in all, the PCS models provide more demographic information. The percentages in Brookes' research are likely to represent a small sub-population biased towards the rich and influential; because of the lack of infants in the original data, the access to copper alloy and silver seems to be fairly restricted from the start in relation to the three tiers of self-organised value proposed for the Anglo-Saxon population of Kent by Brookes (2007, 138): (1) 80% of a product available = little differential access / (2) 20% = restricted access / (3) 1% = very rare luxury goods, restricted to the 'inner élite'. The restrictions increase at c. AD 550 and one to two generations later, at c. AD 600, a pattern of highly restricted access to wealth can be observed. With regard to the absolute numbers of the sample, only 27.4 individuals controlled access to the raw material of copper alloy in the whole region, and only half that number had access to silver after AD 550. By AD 550, only a handful of families, or even only one single extended family, form the élite class of Kent. As Kent furthermore represents the 'richest' region within the Anglo-Saxon spheres of influence, the data available suggest that the population of early medieval England was highly stratified as early as the middle of the 6th century AD if not before, and that the 6th century is a time of intensification of the power of social elites which make up a maximum of 8% of the population, probably far less.

10 General Conclusions

This thesis has described and contextualised the Population & Cemetery Simulator (PCS), which is an agent-based demographic modelling software that can be used to model living populations based on archaeological and historical data as well as their cemeteries. The basic data used by the PCS are demographic in nature, e.g. age and sex data generated by osteoarchaeologists from excavated cemeteries or historical demographic data. The case studies in the thesis use data from early medieval Anglo-Saxon (South England) and Alamannic (South Germany) cemeteries although excursions into neighbouring periods and regions were necessary because of the incompleteness of archaeological data. These excursions represent validation studies.

In the first part of the thesis, I focus on archaeological applications and the demographic basis of most cemetery analysis in archaeology. The most common parameters encountered, from mortality to fertility and migration, and their complex interactions are first set out theoretically, and then evaluated in a series of validation and case studies. The problems of palaeodemography and archaeological demography cannot be completely overcome using the PCS, as the software is also dependent on good demographic data. But experiments using the PCS can lead to a greater understanding of the interplay between the parameters, of which parameters are most important, and of insights regarding the limitations of the data. The modelling software itself is described in conjunction with general tests against demographic standards.

The demographic differences between living populations and cemetery populations lead to a number of complications, which need to result in a more informed way of doing cemetery archaeology that constantly extrapolates conditions of the living from cemetery data. The PCS provides archaeologists with a tool to tackle these complications, especially those described in the seminal “Osteological Paradox” article (Wood et al. 1992). I demonstrate in the thesis using the PCS that the problems described by Wood et al. in relation to skeletal pathologies and skeletal palaeodemographics are also present when dealing with artefacts in the archaeological record. The core database for the early medieval period, the graves, need demographic modelling approaches to be deciphered successfully.

In the second part of the thesis, various examples taken from early medieval archaeology and historical demography are presented which demonstrate a variety of useful applications of the PCS, but also the limitations of the information about medieval, Anglo-Saxon Kentish and Alamannic, demographics, e.g. the dependence on historical and ethnographic parallels whenever data are missing or demographic parameters cannot be measured.

Chapter 6, ‘The Costs of Late Marriage’, tackles the complexity of archaeo-demographic fertility estimation and analyses the sensitivity of some of the fertility parameters in the demographic system. Historical data for the late medieval and early modern period suggest that females in England married very late. The analysis of bio-archaeological data of medieval England using the PCS demonstrate that late marriage leads to low survival rates of populations if the estimate of a minimum weaning age of 2 years, and therefore a long period between births (i.e. min. 2.5 years of child-spacing) is correct. Our results suggest that an average marriage age for women of 25 years is incompatible with the stable isotope analysis of weaning patterns for the population buried in the cemetery of Wharram Percy, and suggest that early medieval women possibly married earlier than women alive in AD 1540 to 1871.

Chapter 7 provides a model of the population dynamics of a medieval parish in south Oxfordshire and demonstrates that historical data can be modelled with the PCS. The results concern household sizes and the development of the parish over time, with some villages failing and others growing villages. The population dynamics observed in the parish data exceed the power of intrinsic population dynamics, e.g. growth and decline in and out of the population itself. The population size fluctuations are strong enough to show that extrinsic factors were at work such as migration and interaction between settlements. High rates of migration between settlements in the later medieval and early modern phase therefore warrant caution when single sites are analysed on their own.

Chapter 8 focuses on the only Anglo-Saxon site which has both an almost complete cemetery and settlement record, Mucking in Essex. The developments and dynamics of the settlement at Mucking are used to inform the study of the cemetery population and vice versa by modelling the living population represented by the cemeteries and linking its development with the changes in the settlement. A range of possible settlement sizes and household sizes are discussed, including a scenario in which a wider population buried their dead in the cemeteries than attested for by the posthole structures excavated. The PCS allows for a range of scenarios of dynamic populations to be modelled, and therefore proves to be much better suited for understanding the complex system and limitations of the data than static formula calculations.

Chapter 9 makes use of databases in which information pertaining to hundreds of South German Alamannic cemeteries and Kentish Anglo-Saxon graves have been gathered. Single sites and regional patterns are analysed, and it is shown how the PCS can be used to extract demographic information about the living communities behind the cemeteries. The general quality of the demographic data is analysed by comparing the archaeological skeletal samples with demographic standards and data from historical demography. The sensitivity of the parameter of child mortality warranted a focus on the ‘missing infant’ problem. Different scenarios for the number of missing infants in the cemeteries are analysed and compared with fertility and growth estimates. Early medieval populations clearly did not bury a substantial proportion of their infants in the cemeteries excavated both in the Alamannic and Kentish region.

Finally, the data for the Kentish population of the 5th to 7th century gathered in ASKED are used to go beyond pure demographics, and to inform key archaeological questions. Combined with data on raw material frequencies in cemeteries published by Brookes (2007), access to materials by the living populations represented by the cemeteries is modelled, shedding new light on the Kentish sample when transformed into living population data with the PCS. Copper-alloy and silver artefact frequencies in the living population are extremely low, especially after AD 550. If the cemetery data are representative of the socioeconomic structure of the population, the models show that the population was strictly stratified and that the frequencies calculated directly from the cemetery data overestimate the number of individuals who had access to the raw materials for copper- alloy and silver.

This thesis can only be a first step towards archaeological interpretative population modelling. Many more models are necessary to decode the complex interplay between parameters in specific regional populations and single cemeteries. Demographic standard curves and traditional life table data must be reconciled in the future, especially if early medieval populations are re-analysed using more advanced skeletal and statistical ageing methods (Séguy and Buchet 2013). The quality of demographic data is continually improving, for example when imaging, molecular, microscopic and biochemical methods are employed more regularly and the PCS can be used repeatedly to take into account new information and advanced data collection (Henderson et al. 2014; Milner and Boldsen 2011; Milner and Boldsen 2012a; Skoglund et al. 2013; Temple 2014; Truesdell and Duering forthcoming; Wittwer-Backofen 2012).

It is further possible to enlarge the samples by increasing the geographic or temporal scope, as well as to focus on the small-scale, i.e. on sub-populations such as specific horizontal or vertical strata identified by artefacts and living conditions, in single cemeteries. Migrating populations and the interplay between more than one population, e.g. intermarriage and mass-movement of people, warrant further hope for interesting applications for the PCS.

The PCS code will see improvements in three key functions, i.e. the fertility parameters, the starter generation generator and the catastrophic events simulator. Female fertility will be modelled in more detail by adding an age-dependent fertility parameter. The structure of the initial population will be controllable in more detail to simplify the reconstruction of specific historical events; and catastrophes will soon include a chooser with more options of modelling the mortality increase. Different kinds of catastrophic events can be represented when an additive variable is available in addition to the mortality multiplier.

Another direction is the use of the PCS in modelling complex interactions between mortality and disease and the impact of selective mortality on artefact frequencies, which I describe as a general ‘Archaeological Paradox’ that looms as an unsolved and probably unsolvable mystery whenever graves are analysed in archaeology. I hope that the new methodology will be applied by future researchers, in an increasingly digital world: to illustrate, reconstruct and analyse populations in archaeology, to facilitate interdisciplinarity and communicate between archaeologists and the public and, finally, in order to encourage a more demographic and experimental mindset in archaeological research.

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Programming Code of the NetLogo-version of the PCS

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;; This file was generated by the Behaviour Composer at modelling4all.org on Mon Jun 29 10:11:15 UTC 2015
;; The model can be found at http://m.modelling4all.org/m/?frozen=w35nLK5uvZKNRdUZ9WXT44


breed [objects object]


patches-own [pzcor ]


turtles-own [
 scheduled-behaviours  behaviours-at-tick-start  current-behaviours  current-behaviour  behaviour-removals rules
 kind dead dirty
 my-age
 my-ftrait
 my-exotraitf2
 my-fline
 my-next-fline my-next-fline-set
 my-number_of_children
 my-exotraitf
 my-mtrait
 my-exotraitm2
 my-mline
 my-exotraitm
 my-f2trait
 my-f2line
 my-next-f2line my-next-f2line-set
 my-m2trait
 my-m2line
 my-z zcor pitch roll
]


breed [pens pen]


globals [
 the-mortmult
```

```
 the-f2trait_age

 the-f2trait_probability

 the-m2trait_age

 the-m2trait_probability


; The following are needed by the Behaviour Composer

 time cycle-finish-time behind-schedule times-scheduled frame-duration delta-t stop-running

 world-geometry mean-x mean-y mean-z plotting-commands histogram-plotting-commands

 behaviour-procedure-numbers behaviour-names internal-the-other

 button-command radian need-to-clear-drawing

 observer-commands

 objects-with-something-to-do

 maximum-plot-generations plot-generation

 prototypes total-time

 update-patch-attributes-needed

 state-restored-after-setup

 temp

]


;; Other global variables:


;; the-disaster_generator is a global variable control by a switch

;; Define a parameter whose value is either true or false (optionally controlled by a switch to toggle the value
at run time).


to the-model [ globals-not-to-be-initialised ]

   initialise-globals globals-not-to-be-initialised

   create-objects 1

               [ set kind

                   "interface"

                 initialise-object

                 set hidden? true ]

   create-objects 1

               [ set kind

                   "starter generation generator"
```

```
            initialise-object
            set hidden? true ]
create-objects 1
           [ set kind
               "linked agents spring"
            initialise-object
            set hidden? true ]
create-objects 1
           [ set kind
               "disaster generator"
            initialise-object
            set hidden? true ]
create-objects 1
           [ set kind
               "starter generation generator pop2"
            initialise-object
            set hidden? true ]
create-objects 1
           [ set kind
               "Selective data loss"
            initialise-object
            set hidden? true ]
ask all-of-kind "interface"
   [ -STOP-SIMULATION-AT-POPULATION-SIZE-0-59
    -HISTOGRAM-MORTALITY-24
    STARTER-GENERATION-SLIDERS-00001
    -REPRODUCTION-SLIDERS-8
    -DISASTER-GENERATOR-SLIDERS-29
    -MALE-ARTEFACT-DISEASES-SLIDERS-10
    -FEMALE-ARTEFACT-DISEASES-SLIDERS-16
    -FEMALE-EXOGAMY-SLIDERS-10
    -MALE-EXOGAMY-SLIDERS-8
    -PLOTS-148
    -MONITORS-9
    -LABELS-21 ]
```

```
  ask all-of-kind "starter generation generator"
     [ -CREATE-FEMALES-5
      -GP6UWEDZIHWEEKRZYLCL6- ]
  ask all-of-kind "linked agents spring"
     [ -LAY-OUT-LINKED-MALES-00003-1
      -LAY-OUT-LINKED-FEMALES-00002-1
      -LAY-OUT-LINKED-MALES2-1
      -LAY-OUT-LINKED-FEMALES2-1 ]
  ask all-of-kind "disaster generator"
     [ -RAISE-AND-RESET-MORTALITY-5
      -RESET-MULTIPLY-MORTALITY-6 ]
  ask all-of-kind "starter generation generator pop2"
     [ -CREATE-FEMALES2-5
      -CREATE-MALES2-5
      -STARTER-GENERATION-2-SLIDERS-3 ]
  ask all-of-kind "Selective data loss" [ ]
end

to kind-initialisation [ kind-name ]
  if-else ( kind-name = "females" )
       [ -F-AGE-DEPENDENT-APPEARANCE-10
        -STAND-UPRIGHT-1
        -BPBIF0AMCVKMON8YQ-OK59
        -FEMALE-ARTEFACTS-DISEASES-7
        -FEMALE-DEATH-CYCLE-9
        -SETUP-FEMALE-LINE-9
        -MENOPAUSE-80
        CHILDREN-COUNTER-00007
        -FEMALE-REPRODUCTION-190
        -FEMALE2-EXOGAMY-7
        -EXOTRAITF2TO0-3
        -EXOTRAITF0TO2-6 ]
       [ if-else ( kind-name = "males" )
             [ -M-AGE-DEPENDENT-APPEARANCE-3
              -STAND-UPRIGHT-1
```

```
  -MB-34YTCUHXT-OAKTU-BZOL6-
  -MALE-ARTEFACTS-DISEASES-8
  -MALE-DEATH-CYCLE-12
  -MALE1-EXOGAMY-1
  -EXOTRAITM2TO0-2
  -EXOTRAITM0TO2-3 ]
[ if-else ( kind-name = "deadfemales" )
    [ -APPEARANCE-DEAD-FEMALES-4 ]
    [ if-else ( kind-name = "deadmales" )
        [ -APPEARANCE-DEAD-MALES-3 ]
        [ if-else ( kind-name = "interface" )
            [ -STOP-SIMULATION-AT-POPULATION-SIZE-0-59
              -HISTOGRAM-MORTALITY-24
              STARTER-GENERATION-SLIDERS-00001
              -REPRODUCTION-SLIDERS-8
              -DISASTER-GENERATOR-SLIDERS-29
              -MALE-ARTEFACT-DISEASES-SLIDERS-10
              -FEMALE-ARTEFACT-DISEASES-SLIDERS-16
              -FEMALE-EXOGAMY-SLIDERS-10
              -MALE-EXOGAMY-SLIDERS-8
              -PLOTS-148
              -MONITORS-9
              -LABELS-21 ]
            [ if-else ( kind-name = "starter generation generator" )
                [ -CREATE-FEMALES-5
                  -GP6UWEDZIHWEEKRZYLCL6- ]
                [ if-else ( kind-name = "linked agents spring" )
                    [ -LAY-OUT-LINKED-MALES-00003-1
                      -LAY-OUT-LINKED-FEMALES-00002-1
                      -LAY-OUT-LINKED-MALES2-1
                      -LAY-OUT-LINKED-FEMALES2-1 ]
                    [ if-else ( kind-name = "disaster generator" )
                        [ -RAISE-AND-RESET-MORTALITY-5
                          -RESET-MULTIPLY-MORTALITY-6 ]
                        [ if-else ( kind-name = "females2" )
```

```
[ -F2-AGE-DEPENDENT-APPEARANCE-2
  -STAND-UPRIGHT-2
  -AGEING-145
  -FEMALE2-DEATH-CYCLE-3
  -FEMALE2-ARTEFACTS-DISEASES-2
  -SETUP-FEMALE2-LINE-1
  -MENOPAUSE-79
  -CHILDREN-COUNTER-59
  -FEMALE2-REPRODUCTION-6
  -FEMALE2-EXOGAMY-6
  -EXOTRAITF2TO0-2
  -EXOTRAITF0TO2-5 ]
[ if-else ( kind-name = "males2" )
        [ -M2-AGE-DEPENDENT-APPEARANCE-2
          -STAND-UPRIGHT-3
          -AGEING-146
          -MALE2-DEATH-CYCLE-1
          -MALE2-ARTEFACTS-DISEASES-1
          -MALE2-EXOGAMY-2
          -EXOTRAITM2TO0-3
          -EXOTRAITM0TO2-2 ]
        [ if-else ( kind-name = "deadfemales2" )
                [ -APPEARANCE-DEAD-FEMALES2-4 ]
                [ if-else ( kind-name = "deadmales2" )
                        [ -APPEARANCE-DEAD-MALES2-4 ]
                        [ if-else ( kind-name = "starter generation
generator pop2" )
                                [ -CREATE-FEMALES2-5
                                  -CREATE-MALES2-5
                                  -STARTER-GENERATION-2-
SLIDERS-3 ]
                                [ if-else ( kind-name
                                        = "Selective data loss" ) [ ]
                                        [ output-print ( word
                                                    "create-agent   called
with an unknown kind: " kind-name
```

```
                                                                                          ) ] ] ] ] ] ] ] ] ] ] ] ] ] ]
end


 ; Add any NetLogo command including those that define a new reporter or command to NetLogo.
to-report probability-death [ x
                    ]
  if x >= 0 and x <= 4
    [ report ( ( 1 - ( 1 - the-mortality_0to4 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 9
    [ report ( ( 1 - ( 1 - the-mortality_5to9 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 14
    [ report ( ( 1 - ( 1 - the-mortality_10to14 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 19
    [ report ( ( 1 - ( 1 - the-mortality_15to19 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 24
    [ report ( ( 1 - ( 1 - the-mortality_20to24 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 29
    [ report ( ( 1 - ( 1 - the-mortality_25to29 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 34
    [ report ( ( 1 - ( 1 - the-mortality_30to34 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 39
    [ report ( ( 1 - ( 1 - the-mortality_35to39 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 44
    [ report ( ( 1 - ( 1 - the-mortality_40to44 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 49
    [ report ( ( 1 - ( 1 - the-mortality_45to49 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  if x <= 54
    [ report ( ( 1 - ( 1 - the-mortality_50to54 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
  ifelse x <= 59
       [ report ( ( 1 - ( 1 - the-mortality_55to59 ) ^ ( 1 / 5 ) ) * the-mortmult ) ]
       [ report ( 1 - ( 1 - the-mortality_60plus ) ^ ( 1 / 5 ) ) ]
end


to -FEMALE-COLOR-CHILD-2
                ; Change the color of this agent.
```

```
  set color
     127
end

to -FEMALE-SHAPE-CHILD-1
                    ; Change the appearance to one of the defined shapes.
  set shape
     "person"
end

to -F-CH-SIZE-1
             ; Change size of this agent.
  set size
     3
end

to -F-APPEARANCE-CHILD-10
                     ; Add a list of behaviours
                     ; (a way to package up several behaviours into a single unit).
  -FEMALE-COLOR-CHILD-2
  -FEMALE-SHAPE-CHILD-1
  -F-CH-SIZE-1
end

to -FEMALE-COLOR-2
               ; Change the color of this agent.
  set color
     red
end

to -FEMALE-SHAPE-2
               ; Change the appearance to one of the defined shapes.
  set shape
     "person"
end
```

```
to -SIZE-F-1
          ; Change size of this agent.
  set size
     4
end

to -F-APPEARANCE-7
               ; Add a list of behaviours
               ; (a way to package up several behaviours into a single unit).
  -FEMALE-COLOR-2
  -FEMALE-SHAPE-2
  -SIZE-F-1
end

to -F-AGE-DEPENDENT-APPEARANCE-10
                          ; Conditionally adds one of two lists of micro-behaviours.
  do-every ( 1 )
         task [ if-else ( my-age < 20 )
                    [ -F-APPEARANCE-CHILD-10 ]
                    [ -F-APPEARANCE-7 ] ]
end

to -STAND-UPRIGHT-1
               ; Set heading to a random angle.
  do-every ( 1 )
         task [ set heading
                  0 ]
end

to -BPBIF0AMCVKMON8YQ-OK59
                     ; Increase the age attribute on every tick.
  do-every ( 1 )
         task [ set my-age
                  my-age + 1 ]
```

```
end


to -FEMALE-TRAIT0-1
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-ftrait
               0 ]
end


to -FEMALE-TRAITGIVER-3
                   ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age >= the-ftrait_age ]
      task [ if random-float 1.0 <= ( the-ftrait_probability )
              [ set my-ftrait
                   1 ] ]
end


to -FEMALE-ARTEFACTS-DISEASES-7
                         ; Add a list of behaviours
                         ; (a way to package up several behaviours into a single unit).
  -FEMALE-TRAIT0-1
  -FEMALE-TRAITGIVER-3
end


to -DIE-F-31
          ; Remove this agent from the model.
  set dead
     true
end


to -AGETRANSFER-64
               ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
end
```

```
to -EXOTRAITF2TRANSFER-26
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitf2
     [ my-exotraitf2 ] of myself
end

to -F-TRAITTRANSFER-45
                  ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-ftrait
     [ my-ftrait ] of myself
end

to -LINE-NUMBER-TRANSFER-F-25
                       ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-fline
     [ my-fline ] of myself
end

to -CREATE-DEADFEMALES-OR-NOT-4
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
  if random-float 1.0 <= ( 1 - the-chance_of_losing_burials )
    [
    ; The following code was generated by a call to create-agent.
 set just-created-agents
         nobody
      ask patch pxcor pycor
         [ sprout-objects 1 [
                         set just-created-agents
                            ( turtle-set self just-created-agents )
                         set kind
                            "deadfemales" ] ]
      ask just-created-agents
```

```
          [ set xcor
               xcor
            set ycor
               ycor
            initialise-object
            initialise-previous-state ]
       ask just-created-agents
          [ kind-initialisation "deadfemales" ]
       ask just-created-agents
          [ -AGETRANSFER-64
            -EXOTRAITF2TRANSFER-26
            -F-TRAITTRANSFER-45
            -LINE-NUMBER-TRANSFER-F-25 ] ]
end

to -AGETRANSFER-66
               ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
end

to -EXOTRAITF2TRANSFER-28
                     ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitf2
     [ my-exotraitf2 ] of myself
end

to -F-TRAITTRANSFER-47
                  ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-ftrait
     [ my-ftrait ] of myself
end

to -LINE-NUMBER-TRANSFER-F-27
                        ; Set an attribute, parameter, or Netlogo variable to a new value.
```

```
  set my-fline
     [ my-fline ] of myself
end

to -CREATE-DEADFEMALES-39
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                    set just-created-agents
                       ( turtle-set self just-created-agents )
                    set kind
                       "deadfemales" ] ]
  ask just-created-agents
     [ set xcor
          xcor
       set ycor
          ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "deadfemales" ]
  ask just-created-agents
     [ -AGETRANSFER-66
       -EXOTRAITF2TRANSFER-28
       -F-TRAITTRANSFER-47
       -LINE-NUMBER-TRANSFER-F-27 ]
end

to -CREATE-DEADFEMALE-OR-LOOSE-BURIAL-1
                              ; Conditionally adds one of two lists of micro-behaviours.
```

```
  if-else ( the-max_age_of_lost_dead >= the-min_age_of_lost_dead and my-age >= the-min_age_of_lost_dead and my-age <= the-max_age_of_lost_dead )
       [ -CREATE-DEADFEMALES-OR-NOT-4 ]
       [ -CREATE-DEADFEMALES-39 ]
end


to -PROB-DEATH-F-WITH-TRAIT-5
                ; Notes<br>; <br>; <br>; <br>;
  if random-float 1.0 <= ( probability-death my-age ) * the-ftrait_mortchange
    [ -DIE-F-31
     -CREATE-DEADFEMALE-OR-LOOSE-BURIAL-1 ]
end


to -DIE-F-29
       ; Remove this agent from the model.
  set dead
     true
end


to -AGETRANSFER-69
          ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
end


to -EXOTRAITF2TRANSFER-31
               ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitf2
     [ my-exotraitf2 ] of myself
end


to -F-TRAITTRANSFER-50
             ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-ftrait
     [ my-ftrait ] of myself
```

```
end


to -LINE-NUMBER-TRANSFER-F-30
                        ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-fline
     [ my-fline ] of myself
end


to -CONDITIONALLY-CREATE-DEADFEMALES-3
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
  if random-float 1.0 <= ( 1 - the-chance_of_losing_burials )
    [
    ; The following code was generated by a call to create-agent.
 set just-created-agents
        nobody
      ask patch pxcor pycor
         [ sprout-objects 1 [
                         set just-created-agents
                            ( turtle-set self just-created-agents )
                         set kind
                            "deadfemales" ] ]
      ask just-created-agents
         [ set xcor
              xcor
           set ycor
              ycor
           initialise-object
           initialise-previous-state ]
      ask just-created-agents
         [ kind-initialisation "deadfemales" ]
      ask just-created-agents
         [ -AGETRANSFER-69
           -EXOTRAITF2TRANSFER-31
```

```
          -F-TRAITTRANSFER-50
          -LINE-NUMBER-TRANSFER-F-30 ] ]
end

to -AGETRANSFER-68
              ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
end

to -EXOTRAITF2TRANSFER-30
                   ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitf2
     [ my-exotraitf2 ] of myself
end

to -F-TRAITTRANSFER-49
                 ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-ftrait
     [ my-ftrait ] of myself
end

to -LINE-NUMBER-TRANSFER-F-29
                      ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-fline
     [ my-fline ] of myself
end

to -CREATE-DEADFEMALES-44
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
```

```
  ask patch pxcor pycor
     [ sprout-objects 1 [
                    set just-created-agents
                       ( turtle-set self just-created-agents )
                    set kind
                       "deadfemales" ] ]
  ask just-created-agents
     [ set xcor
          xcor
       set ycor
          ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "deadfemales" ]
  ask just-created-agents
     [ -AGETRANSFER-68
       -EXOTRAITF2TRANSFER-30
       -F-TRAITTRANSFER-49
       -LINE-NUMBER-TRANSFER-F-29 ]
end

to -CREATE-DEADFEMALE-OR-NOT-2
                      ; Conditionally adds one of two lists of micro-behaviours.
  if-else ( the-max_age_of_lost_dead >= the-min_age_of_lost_dead and my-age >= the-min_age_of_lost_dead and my-age <= the-max_age_of_lost_dead )
        [ -CONDITIONALLY-CREATE-DEADFEMALES-3 ]
        [ -CREATE-DEADFEMALES-44 ]
end

to -PROB-DEATH-F-22
               ; Notes<br>; <br>; <br>; <br>;
  if random-float 1.0 <= probability-death my-age
    [ -DIE-F-29
      -CREATE-DEADFEMALE-OR-NOT-2 ]
end
```

```
to -CONDITION-WITH-OR-WITHOUT-TRAIT-F-6

                                ; Conditionally adds one of two lists of micro-behaviours.

  if-else ( my-ftrait = 1 )

        [ -PROB-DEATH-F-WITH-TRAIT-5 ]

        [ -PROB-DEATH-F-22 ]

end


to -FEMALE-DEATH-CYCLE-9

  do-every 1

          task [ -CONDITION-WITH-OR-WITHOUT-TRAIT-F-6 ]

                                            ; Notes <br>; <br>; <br>; <br>;

end


to -SETUP-FEMALE-LINE-9

                  ; Set an attribute, parameter, or Netlogo variable to a new value.

  do-at-time ( 0 )

           task [ set my-fline

                    list who 0 ]

end


to -MENOPAUSE-80

             ; Remove behaviours from a specified agent or set of agents.

  when task [ my-age >= the-maxreprodage ]

      task [ remove-behaviours-from self [ "-FEMALE-REPRODUCTION-191" ] ]

end


to CHILDREN-COUNTER-00007

                    ; Set an attribute, parameter, or Netlogo variable to a new value.

  when task [ my-age = 0 ]

      task [ set my-number_of_children

              0 ]

end


to -CHANGE-NUMBER-OF-CHILDREN-F-3
```

```
                         ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-number_of_children
     my-number_of_children + 1
end

to -BIRTHAGE-15
            ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     0
end

to -ADD-LINK-FROM-MOTHER-F-23
                       ; Add a directed link from another.
  create-link-from myself
end

to -FEMALE-LINE-38
              ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-next-fline-set
     true
  set my-next-fline
     [ lput my-number_of_children my-fline ] of myself
end

to -CREATE-FEMALE-OFFSPRING-70
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                     set just-created-agents
                        ( turtle-set self just-created-agents )
```

```
                    set kind
                      "females" ] ]
  ask just-created-agents
     [ set xcor
         xcor
       set ycor
         ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "females" ]
  ask just-created-agents
     [ -BIRTHAGE-15
       -ADD-LINK-FROM-MOTHER-F-23
       -FEMALE-LINE-38 ]
end

to -CHANGE-NUMBER-OF-CHILDREN-M-3
                        ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-number_of_children
     my-number_of_children + 1
end

to -BIRTHAGE-M-8
            ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     0
end

to -ADD-LINK-FROM-MOTHER-M-9
                     ; Add a directed link from another.
  create-link-from myself
end

to -FEMALE-LINE-M-4
```

```
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-next-fline-set
     true
  set my-next-fline
     [ lput my-number_of_children my-fline ] of myself
end

to -CREATE-MALE-OFFSPRING-195
  let just-created-agents
     nobody
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                    set just-created-agents
                       ( turtle-set self just-created-agents )
                    set kind
                       "males" ] ]
  ask just-created-agents
     [ set xcor
          xcor
       set ycor
          ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "males" ]
  ask just-created-agents
     [ -BIRTHAGE-M-8
       -ADD-LINK-FROM-MOTHER-M-9
       -FEMALE-LINE-M-4 ]
end

to -FEMALE-REPRODUCTION-190
```

```
  when task [ time > 0 ]
      task [ when task [ my-age >= the-minreprodage ]
              task [ if ( ( count ( all-of-kind "males" ) with [ my-age >= 16 and my-age <= 50 ] ) > 0 )
                    [ do-after ( random-integer-between 0 the-childspacing )
                          task [ do-every ( the-childspacing )
                                    task [ if random-float 1.0 <= ( the-reprodprobability )
                                         [ if-else ( random-number-between 0 1 <= the-fbirthratio )
                                               [ -CHANGE-NUMBER-OF-CHILDREN-F-3
                                                -CREATE-FEMALE-OFFSPRING-70 ]
                                               [ -CHANGE-NUMBER-OF-CHILDREN-M-3
                                                -CREATE-MALE-OFFSPRING-195 ]
                                                                ; Notes <br>; <br>; <br>; <br>;
 ] ] ] ] ] ]
end

to -AGETRANSFER-84
            ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
end

to -F-TRAITTRANSFER-54
               ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-ftrait
     [ my-ftrait ] of myself
end

to -LINE-NUMBER-TRANSFER-F-33
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-fline
     [ my-fline ] of myself
end

to -EXOTRAITF-1
          ; Set an attribute, parameter, or Netlogo variable to a new value.
```

```
  set my-exotraitf
     1
end

to -CREATE-FEMALE2-1
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                     set just-created-agents
                        ( turtle-set self just-created-agents )
                     set kind
                        "females2" ] ]
  ask just-created-agents
     [ set xcor
          xcor
       set ycor
          ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "females2" ]
  ask just-created-agents
     [ -AGETRANSFER-84
       -F-TRAITTRANSFER-54
       -LINE-NUMBER-TRANSFER-F-33
       -EXOTRAITF-1 ]
end

to -DIE-F-54
  set dead
```

```
     true
end


to -PROB-REMOVE-F-AND-CREATE-F2-1
  if ( my-age >= the-fexoage and my-age <= the-fexoagemax )
     [
     ; conditionally removes a female from the females group depending on her age;
 if random-float 1.0 <= the-fexoprob1to2
         [ -CREATE-FEMALE2-1
          -DIE-F-54 ] ]
end


to -FEMALE2-EXOGAMY-7
  do-every 1
         task [ -PROB-REMOVE-F-AND-CREATE-F2-1 ]
                                        ; Notes <br>; <br>; <br>; <br>;
end


to -EXOTRAITF2TO0-3
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-exotraitf2
               0 ]
end


to -EXOTRAITF0TO2-6
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-exotraitf
               0 ]
end


to -MALE-COLOR-CHILD-1
                  ; Change the color of this agent.
  set color
```

```
     96
end

to -MALE-SHAPE-CH-1
              ; Change the appearance to one of the defined shapes.
  set shape
     "person"
end

to -SIZE-M-CHILD-1
             ; Change size of this agent.
  set size
     3
end

to -M-APPEARANCE-CHILD-3
                 ; Add a list of behaviours
                 ; (a way to package up several behaviours into a single unit).
  -MALE-COLOR-CHILD-1
  -MALE-SHAPE-CH-1
  -SIZE-M-CHILD-1
end

to -MALE-COLOR-2
            ; Change the color of this agent.
  set color
     blue
end

to -MALE-SHAPE-2
            ; Change the appearance to one of the defined shapes.
  set shape
     "person"
end
```

```
to -SIZE-M-1
          ; Change size of this agent.
  set size
     4
end

to -M-APPEARANCE-6
               ; Add a list of behaviours
               ; (a way to package up several behaviours into a single unit).
  -MALE-COLOR-2
  -MALE-SHAPE-2
  -SIZE-M-1
end

to -M-AGE-DEPENDENT-APPEARANCE-3
                      ; Conditionally adds one of two lists of micro-behaviours.
  do-every ( 1 )
         task [ if-else ( my-age < 20 )
                    [ -M-APPEARANCE-CHILD-3 ]
                    [ -M-APPEARANCE-6 ] ]
end

to -MB-34YTCUHXT-OAKTU-BZOL6-
                      ; Increase the age attribute on every tick.
  do-every ( 1 )
         task [ set my-age
                  my-age + 1 ]
end

to -MALE-TRAIT0-2
               ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-mtrait
               0 ]
end
```

```
to -MALE-TRAITGIVER-7
                  ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age >= the-mtrait_age ]
      task [ if random-float 1.0 <= ( the-mtrait_probability )
              [ set my-mtrait
                  1 ] ]
end

to -MALE-ARTEFACTS-DISEASES-8
                        ; Add a list of behaviours
                        ; (a way to package up several behaviours into a single unit).
  -MALE-TRAIT0-2
  -MALE-TRAITGIVER-7
end

to -DIE-M-4
          ; Remove this agent from the model.
  set dead
     true
end

to -AGETRANSFER-74
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
end

to -EXOTRAITM2TRANSFER-11
                     ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitm2
     [ my-exotraitm2 ] of myself
end

to -M-TRAITTRANSFER-46
```

```
                   ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-mtrait
     [ my-mtrait ] of myself
end

to -LINE-NUMBER-TRANSFER-M-77
                        ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-fline
     [ my-fline ] of myself
end

to -CREATE-DEADMALES-OR-NOT-8
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
  if random-float 1.0 <= ( 1 - the-chance_of_losing_burials )
    [
    ; The following code was generated by a call to create-agent.
 set just-created-agents
         nobody
      ask patch pxcor pycor
         [ sprout-objects 1 [
                          set just-created-agents
                             ( turtle-set self just-created-agents )
                          set kind
                             "deadmales" ] ]
      ask just-created-agents
         [ set xcor
              xcor
           set ycor
              ycor
           initialise-object
           initialise-previous-state ]
      ask just-created-agents
         [ kind-initialisation "deadmales" ]
```

```
    ask just-created-agents
      [ -AGETRANSFER-74
        -EXOTRAITM2TRANSFER-11
        -M-TRAITTRANSFER-46
        -LINE-NUMBER-TRANSFER-M-77 ] ]
end

to -AGETRANSFER-72
          ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
    [ my-age ] of myself
end

to -EXOTRAITM2TRANSFER-10
              ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitm2
    [ my-exotraitm2 ] of myself
end

to -M-TRAITTRANSFER-44
             ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-mtrait
    [ my-mtrait ] of myself
end

to -LINE-NUMBER-TRANSFER-M-75
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-fline
    [ my-fline ] of myself
end

to -CREATE-DEADMALES-42
  let just-created-agents
    nobody
    ; Create additional agents initialising them as if at set up time.
```

```
    ; The following code was generated by a call to create-agent.
  set just-created-agents
    nobody
  ask patch pxcor pycor
    [ sprout-objects 1 [
                    set just-created-agents
                      ( turtle-set self just-created-agents )
                    set kind
                      "deadmales" ] ]
  ask just-created-agents
    [ set xcor
        xcor
     set ycor
        ycor
     initialise-object
     initialise-previous-state ]
  ask just-created-agents
    [ kind-initialisation "deadmales" ]
  ask just-created-agents
    [ -AGETRANSFER-72
     -EXOTRAITM2TRANSFER-10
     -M-TRAITTRANSFER-44
     -LINE-NUMBER-TRANSFER-M-75 ]
end

to -CONDITIONALLY-PRODUCE-DEADMALES-1
                          ; Conditionally adds one of two lists of micro-behaviours.
  if-else ( the-max_age_of_lost_dead >= the-min_age_of_lost_dead and my-age >= the-min_age_of_lost_dead and my-age <= the-max_age_of_lost_dead )
       [ -CREATE-DEADMALES-OR-NOT-8 ]
       [ -CREATE-DEADMALES-42 ]
end

to -PROB-DEATH-M-WITH-TRAIT-5
                     ; Notes<br>; <br>; <br>; <br>;
```

```
  if random-float 1.0 <= ( probability-death my-age ) * the-mtrait_mortchange
    [ -DIE-M-4
      -CONDITIONALLY-PRODUCE-DEADMALES-1 ]
end

to -DIE-M-6
        ; Remove this agent from the model.
  set dead
     true
end

to -AGETRANSFER-77
             ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
end

to -EXOTRAITM2TRANSFER-13
                  ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitm2
     [ my-exotraitm2 ] of myself
end

to -M-TRAITTRANSFER-53
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-mtrait
     [ my-mtrait ] of myself
end

to -LINE-NUMBER-TRANSFER-M-84
                     ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-fline
     [ my-fline ] of myself
end
```

```
to -CREATE-DEADMALES-OR-NOT-7
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
  if random-float 1.0 <= ( 1 - the-chance_of_losing_burials )
    [
    ; The following code was generated by a call to create-agent.
 set just-created-agents
         nobody
      ask patch pxcor pycor
         [ sprout-objects 1 [
                        set just-created-agents
                           ( turtle-set self just-created-agents )
                        set kind
                           "deadmales" ] ]
      ask just-created-agents
         [ set xcor
              xcor
          set ycor
              ycor
          initialise-object
          initialise-previous-state ]
      ask just-created-agents
         [ kind-initialisation "deadmales" ]
      ask just-created-agents
         [ -AGETRANSFER-77
          -EXOTRAITM2TRANSFER-13
          -M-TRAITTRANSFER-53
          -LINE-NUMBER-TRANSFER-M-84 ] ]
end


to -AGETRANSFER-79
              ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
```

```
end

to -EXOTRAITM2TRANSFER-14
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitm2
     [ my-exotraitm2 ] of myself
end

to -M-TRAITTRANSFER-55
                  ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-mtrait
     [ my-mtrait ] of myself
end

to -LINE-NUMBER-TRANSFER-M-86
                       ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-fline
     [ my-fline ] of myself
end

to -CREATE-DEADMALES-56
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                     set just-created-agents
                        ( turtle-set self just-created-agents )
                     set kind
                        "deadmales" ] ]
  ask just-created-agents
     [ set xcor
```

```
        xcor
      set ycor
        ycor
      initialise-object
      initialise-previous-state ]
  ask just-created-agents
    [ kind-initialisation "deadmales" ]
  ask just-created-agents
    [ -AGETRANSFER-79
      -EXOTRAITM2TRANSFER-14
      -M-TRAITTRANSFER-55
      -LINE-NUMBER-TRANSFER-M-86 ]
end

to -CONDITIOANLLY-CREATE-DEADMALES-3
                    ; Conditionally adds one of two lists of micro-behaviours.
  if-else ( the-max_age_of_lost_dead >= the-min_age_of_lost_dead and my-age >= the-min_age_of_lost_dead and my-age <= the-max_age_of_lost_dead )
      [ -CREATE-DEADMALES-OR-NOT-7 ]
      [ -CREATE-DEADMALES-56 ]
end

to -PROB-DEATH-M-29
          ; Notes<br>; <br>; <br>; <br>;
  if random-float 1.0 <= probability-death my-age
    [ -DIE-M-6
     -CONDITIOANLLY-CREATE-DEADMALES-3 ]
end

to -CONDITIONAL-MALE-MORTALITY-WITH-OR-WITHOUT-TRAIT-6
                              ; Conditionally adds one of two lists of micro-behaviours.
  if-else ( my-mtrait = 1 )
      [ -PROB-DEATH-M-WITH-TRAIT-5 ]
      [ -PROB-DEATH-M-29 ]
end
```

```
to -MALE-DEATH-CYCLE-12

  do-every 1

         task [ -CONDITIONAL-MALE-MORTALITY-WITH-OR-WITHOUT-TRAIT-6 ]

                                                   ; Notes <br>; <br>; <br>; <br>;

end


to -AGETRANSFER-87

              ; Set an attribute, parameter, or Netlogo variable to a new value.

  set my-age

     [ my-age ] of myself

end


to -M-TRAITTRANSFER-77

                 ; Set an attribute, parameter, or Netlogo variable to a new value.

  set my-mtrait

     [ my-mtrait ] of myself

end


to -LINE-NUMBER-TRANSFER-M-120

                       ; Set an attribute, parameter, or Netlogo variable to a new value.

  set my-mline

     [ my-mline ] of myself

end


to -EXOTRAITM-1

            ; Set an attribute, parameter, or Netlogo variable to a new value.

  set my-exotraitm

     1

end


to -CREATE-MALE2-2

  let just-created-agents

     nobody

     ; Create additional agents initialising them as if at set up time.
```

```
    ; The following code was generated by a call to create-agent.
  set just-created-agents
    nobody
  ask patch pxcor pycor
    [ sprout-objects 1 [
                set just-created-agents
                  ( turtle-set self just-created-agents )
                set kind
                  "males2" ] ]
  ask just-created-agents
    [ set xcor
        xcor
     set ycor
        ycor
     initialise-object
     initialise-previous-state ]
  ask just-created-agents
    [ kind-initialisation "males2" ]
  ask just-created-agents
    [ -AGETRANSFER-87
     -M-TRAITTRANSFER-77
     -LINE-NUMBER-TRANSFER-M-120
     -EXOTRAITM-1 ]
end

to -DIE-M2-6
  set dead
    true
end

to -PROB-REMOVE-M-AND-CREATE-M2-2
  if ( my-age >= the-mexoage and my-age <= the-mexoagemax )
   [
   ; conditionally removes a male from the males2 group depending on her age;
 if random-float 1.0 <= the-mexoprob1to2
```

```
          [ -CREATE-MALE2-2
            -DIE-M2-6 ] ]
end


to -MALE1-EXOGAMY-1
  do-every 1
        task [ -PROB-REMOVE-M-AND-CREATE-M2-2 ]
                                    ; Notes <br>; <br>; <br>; <br>;
end


to -EXOTRAITM2TO0-2
              ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-exotraitm2
             0 ]
end


to -EXOTRAITM0TO2-3
              ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-exotraitm
             0 ]
end


to -FEMALE-COLOR-DEAD-1
                ; Change the color of this agent.
  set color
     12
end


to -DEADFEMALES-SHAPE-1
                ; Change the appearance to one of the defined shapes.
  set shape
     "ghost"
end
```

```
to -SIZE-F-D-1
            ; Change size of this agent.
  set size
     3
end

to -APPEARANCE-DEAD-FEMALES-4
                        ; Add a list of behaviours
                        ; (a way to package up several behaviours into a single unit).
  -FEMALE-COLOR-DEAD-1
  -DEADFEMALES-SHAPE-1
  -SIZE-F-D-1
end

to -MALE-COLOR-D-1
               ; Change the color of this agent.
  set color
     102
end

to DEADMALES-SHAPE-00001
                    ; Change the appearance to one of the defined shapes.
  set shape
     "ghost"
end

to -SIZE-D-M-1
            ; Change size of this agent.
  set size
     3
end

to -APPEARANCE-DEAD-MALES-3
                      ; Add a list of behaviours
```

```
                  ; (a way to package up several behaviours into a single unit).
  -MALE-COLOR-D-1
  DEADMALES-SHAPE-00001
  -SIZE-D-M-1
end

to -STOP-SIMULATION-AT-POPULATION-SIZE-0-59
                            ; Pause the execution of the simulation.
  when task [ ( count all-of-kind "females" + count all-of-kind "males" ) + ( count all-of-kind "females2" + count all-of-kind "males2" ) = 0 ]
     task [ set stop-running
            true ]
end

to -HISTOGRAM-MORTALITY-24
                 ; Add a list of behaviours
                 ; (a way to package up several behaviours into a single unit).
end

to STARTER-GENERATION-SLIDERS-00001
                      ; Add a list of behaviours
                      ; (a way to package up several behaviours into a single unit).
end

to -REPRODUCTION-SLIDERS-8
                 ; Add a list of behaviours
                 ; (a way to package up several behaviours into a single unit).
end

to -DISASTER-GENERATOR-SLIDERS-29
                     ; Add a list of behaviours
                     ; (a way to package up several behaviours into a single unit).
end

to -MALE-ARTEFACT-DISEASES-SLIDERS-10
                       ; Add a list of behaviours
```

```
                            ; (a way to package up several behaviours into a single unit).
end

to -FEMALE-ARTEFACT-DISEASES-SLIDERS-16
                             ; Add a list of behaviours
                             ; (a way to package up several behaviours into a single unit).
end

to -FEMALE-EXOGAMY-SLIDERS-10
                      ; Add a list of behaviours
                      ; (a way to package up several behaviours into a single unit).
end

to -MALE-EXOGAMY-SLIDERS-8
                    ; Add a list of behaviours
                    ; (a way to package up several behaviours into a single unit).
end

to -PLOT-MALES-ON-GRAPH-74
                    ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ set-current-plot "Living population"
             create-temporary-plot-pen "Males"
                                ; this name will be used in the legend if enabled
             set-plot-pen-color blue
             set-plot-pen-mode 0
                          ; 0 for line, 1 for bar, 2 for point
                          ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
             add-to-plot time count all-of-kind "males" ]
end

to -PLOT-MALES2-ON-GRAPH-30
                     ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ set-current-plot "Living population"
```

```
            create-temporary-plot-pen "Males2"
                            ; this name will be used in the legend if enabled
            set-plot-pen-color gray
            set-plot-pen-mode 0
                       ; 0 for line, 1 for bar, 2 for point
                       ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
            add-to-plot time count all-of-kind "males2" ]
end

to -PLOT-FEMALES-ON-GRAPH-72
                 ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ set-current-plot "Living population"
            create-temporary-plot-pen "Females"
                            ; this name will be used in the legend if enabled
            set-plot-pen-color red
            set-plot-pen-mode 0
                       ; 0 for line, 1 for bar, 2 for point
                       ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
            add-to-plot time count all-of-kind "females" ]
end

to -PLOT-FEMALES2-ON-GRAPH-31
                 ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ set-current-plot "Living population"
            create-temporary-plot-pen "Females2"
                            ; this name will be used in the legend if enabled
            set-plot-pen-color black
            set-plot-pen-mode 0
                       ; 0 for line, 1 for bar, 2 for point
                       ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
            add-to-plot time count all-of-kind "females2" ]
end
```

```
to -PLOT-DEADFEMALES-ON-GRAPH-78
                        ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
         task [ set-current-plot "Dead population / Cemetery"
              create-temporary-plot-pen "Females"
                                  ; this name will be used in the legend if enabled
              set-plot-pen-color red
              set-plot-pen-mode 0
                            ; 0 for line, 1 for bar, 2 for point
                            ; remove the ';' in the box to erase everything drawn by this pen
              add-to-plot time count all-of-kind "deadfemales" ]
end

to -PLOT-DEADFEMALES2-ON-GRAPH-30
                         ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
         task [ set-current-plot "Dead population / Cemetery"
              create-temporary-plot-pen "Females2"
                                  ; this name will be used in the legend if enabled
              set-plot-pen-color black
              set-plot-pen-mode 0
                            ; 0 for line, 1 for bar, 2 for point
                            ; remove the ';' in the box to erase everything drawn by this pen
              add-to-plot time count all-of-kind "deadfemales2" ]
end

to -PLOT-DEADMALES-ON-GRAPH-75
                       ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
         task [ set-current-plot "Dead population / Cemetery"
              create-temporary-plot-pen "Males"
                                  ; this name will be used in the legend if enabled
              set-plot-pen-color blue
              set-plot-pen-mode 0
                            ; 0 for line, 1 for bar, 2 for point
```

```
                                ; remove the ';' in the box to erase everything drawn by this pen
                add-to-plot time count all-of-kind "deadmales" ]
end

to -PLOT-DEADMALES2-ON-GRAPH-34
                            ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
          task [ set-current-plot "Dead population / Cemetery"
                create-temporary-plot-pen "Males2"
                                      ; this name will be used in the legend if enabled
                set-plot-pen-color gray
                set-plot-pen-mode 0
                                ; 0 for line, 1 for bar, 2 for point
                                ; remove the ';' in the box to erase everything drawn by this pen
                add-to-plot time count all-of-kind "deadmales2" ]
end

to-report living-females-histogram-11
  report all-of-kind "females"
end

to-report living-females-histogram-12
  report my-age / 5
end

to -LIVING-FEMALES-HISTOGRAM-73
                            ; Set up and maintain a histogram.
  create-histogram "Female living population structure" "Age groups of 5 years" "Number of individuals" task
[ living-females-histogram-11 ] task [ living-females-histogram-12 ]
end

to -AUTO-PLOT-HIST-F-33
  set-current-plot "Female living population structure"


  auto-plot-on
end
```

```
to-report living-males-histogram-13

  report all-of-kind "males"

end


to-report living-males-histogram-14

  report my-age / 5

end


to -LIVING-MALES-HISTOGRAM-68

                    ; Set up and maintain a histogram.

  create-histogram "Male living population structure" "Age groups of 5 years" "Number of individuals" task [
living-males-histogram-13 ] task [ living-males-histogram-14 ]

end


to -AUTO-PLOT-HIST-M-32

  set-current-plot "Male living population structure"


  auto-plot-on

end


to-report deadfemales-histogram-15

  report all-of-kind "deadfemales"

end


to-report deadfemales-histogram-16

  report my-age / 5

end


to -DEADFEMALES-HISTOGRAM-69

                   ; Set up and maintain a histogram.

  create-histogram "Age structure of dead females in cemetery" "Age groups of 5 years" "Number of
individuals" task [ deadfemales-histogram-15 ] task [ deadfemales-histogram-16 ]

end


to -AUTO-PLOT-HIST-DF-32
```

```
  set-current-plot "Age structure of dead females in cemetery"


  auto-plot-on
end


to-report deadmales-histogram-17
  report all-of-kind "deadmales"
end


to-report deadmales-histogram-18
  report my-age / 5
end


to -DEADMALES-HISTOGRAM-69
                  ; Set up and maintain a histogram.
  create-histogram "Age structure of dead males in cemetery" "Age groups of 5 years" "Number of individuals" task [ deadmales-histogram-17 ] task [ deadmales-histogram-18 ]
end


to -AUTO-PLOT-HIST-DM-31
  set-current-plot "Age structure of dead males in cemetery"


  auto-plot-on
end


to-report plot-input-mortality-19
  report time
end


to-report plot-input-mortality-20
  report probability-death time
end


to -PLOT-INPUT-MORTALITY-68
                  ; Set up and maintain a plot of two variables, e.g. hunger versus time.
                  ; The location, size, minimum, and maximum values are all specified.
```

```
  create-plot "Input mortality profile" "Age in years" "Mortality" task [ plot-input-mortality-19 ] task [ plot-input-mortality-20 ]
end


to -MALES-WITH-TRAIT-PEN-39
                    ; Graph data on top of a plot with a fresh pen.   Typically you'll want to enhance this to happen repeatedly.
  do-every ( 1 )
        task [ when task [ ( count ( all-of-kind "males" ) with [ my-age >= the-mtrait_age ] ) > 0 ]
                task [ set-current-plot "% of artefact/disease in subgroup"
                     create-temporary-plot-pen "Living males"
                                      ; this name will be used in the legend if enabled
                     set-plot-pen-color green
                     set-plot-pen-mode 0
                                 ; 0 for line, 1 for bar, 2 for point
                                 ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                     add-to-plot time ( 100 * ( count ( all-of-kind "males" ) with [ my-mtrait = 1 ] ) ) / ( count ( all-of-kind "males" ) with [ my-age >=
                             the-mtrait_age ] ) ) ] ]
end


to -PEN-FEMALES-WITH-TRAIT-43
                     ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ when task [ ( count ( all-of-kind "females" ) with [ my-age >= the-ftrait_age ] ) > 0 ]
                task [ set-current-plot "% of artefact/disease in subgroup"
                     create-temporary-plot-pen "Living females"
                                      ; this name will be used in the legend if enabled
                     set-plot-pen-color yellow
                     set-plot-pen-mode 0
                                 ; 0 for line, 1 for bar, 2 for point
                                 ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                     add-to-plot time 100 * count ( all-of-kind "females" ) with [ my-ftrait = 1 ] / count ( all-of-kind "females" ) with [ my-age >= the-ftrait_age ] ] ]
end


to -PEN-DEADMALES-WITH-TRAIT-46
```

```
                    ; Graph data on top of a plot with a fresh pen.
  do-every ( 1
        )
        task [ when task [ ( count ( all-of-kind "deadmales" ) with [ my-age >= the-mtrait_age ] ) > 0 ]
                task [ set-current-plot "% of artefact/disease in subgroup"
                    create-temporary-plot-pen "Dead males"
                                    ; this name will be used in the legend if enabled
                    set-plot-pen-color black
                    set-plot-pen-mode 0
                               ; 0 for line, 1 for bar, 2 for point
                               ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                    add-to-plot time 100 * count ( all-of-kind "deadmales" ) with [ my-mtrait = 1 ] / count ( all-
of-kind "deadmales" ) with [ my-age >=
                            the-mtrait_age ] ] ]
end

to -PEN-DEADFEMALES-WITH-TRAIT-45
                     ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ when task [ ( count ( all-of-kind "deadfemales" ) with [ my-age >= the-ftrait_age ] ) > 0 ]
                task [ set-current-plot "% of artefact/disease in subgroup"
                    create-temporary-plot-pen "Dead females"
                                    ; this name will be used in the legend if enabled
                    set-plot-pen-color blue
                    set-plot-pen-mode 0
                               ; 0 for line, 1 for bar, 2 for point
                               ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                    add-to-plot time 100 * count ( all-of-kind "deadfemales" ) with [ my-ftrait = 1 ] / count ( all-
of-kind "deadfemales" ) with [ my-age >=
                            the-ftrait_age ] ] ]
end

to -M-PLOT-TRAIT-IN-LIVING-POPULATION-68
                         ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ when task [ ( count all-of-kind "males" + count all-of-kind "females" ) > 0 ]
```

```
                task [ set-current-plot "% of artefact/disease in total population"

                    create-temporary-plot-pen "Living males"

                                    ; this name will be used in the legend if enabled

                    set-plot-pen-color green

                    set-plot-pen-mode 0

                              ; 0 for line, 1 for bar, 2 for point

                              ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen

                    add-to-plot time 100 * count ( all-of-kind "males" ) with [ my-mtrait = 1 ] / ( count all-of-kind "males" + count all-of-kind "females" ) ] ]

end


to -F-PLOT-TRAIT-IN-LIVING-POPULATION-69

                         ; Graph data on top of a plot with a fresh pen.

  do-every ( 1

        )

        task [ when task [ ( count all-of-kind "females" + count all-of-kind "males" ) > 0 ]

                task [ set-current-plot "% of artefact/disease in total population"

                    create-temporary-plot-pen "Living females"

                                    ; this name will be used in the legend if enabled

                    set-plot-pen-color yellow

                    set-plot-pen-mode 0

                              ; 0 for line, 1 for bar, 2 for point

                              ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen

                    add-to-plot time 100 * count ( all-of-kind "females" ) with [ my-ftrait = 1 ] / ( count all-of-kind "males" + count all-of-kind "females" ) ] ]

end


to -M-PLOT-TRAIT-IN-DEAD-POPULATION-49

                        ; Graph data on top of a plot with a fresh pen.

  do-every ( 1

        )

        task [ when task [ ( count all-of-kind "deadmales" + count all-of-kind "deadfemales" ) > 0 ]

                task [ set-current-plot "% of artefact/disease in total population"

                    create-temporary-plot-pen "Dead males"

                                    ; this name will be used in the legend if enabled

                    set-plot-pen-color black
```

```
                    set-plot-pen-mode 0
                               ; 0 for line, 1 for bar, 2 for point
                               ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                    add-to-plot time 100 * count ( all-of-kind "deadmales" ) with [ my-mtrait = 1 ] / ( count all-of-kind "deadmales" + count all-of-kind "deadfemales"
                          ) ] ]
end

to -F-PLOT-TRAIT-IN-DEAD-POPULATION-70
                        ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ when task [ ( count all-of-kind "deadmales" + count all-of-kind "deadfemales" ) > 0 ]
                task [ set-current-plot "% of artefact/disease in total population"
                    create-temporary-plot-pen "Dead females"
                                    ; this name will be used in the legend if enabled
                    set-plot-pen-color blue
                    set-plot-pen-mode 0
                               ; 0 for line, 1 for bar, 2 for point
                               ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                    add-to-plot time 100 * count ( all-of-kind "deadfemales" ) with [ my-ftrait = 1 ] / ( count all-of-kind "deadmales" + count all-of-kind "deadfemales"
                          ) ] ]
end

to -MEAN-AGE-PEN-138
              ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ if ( count all-of-kind "deadmales" > 0 and count all-of-kind "deadfemales" > 0 )
              [ set-current-plot "Mean age plot"
                create-temporary-plot-pen "Mean age at+"
                                ; this name will be used in the legend if enabled
                set-plot-pen-color black
                set-plot-pen-mode 0
                          ; 0 for line, 1 for bar, 2 for point
                          ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
```

```
                add-to-plot time ( mean [ my-age ] of all-of-kind "deadmales" + mean [ my-age ] of all-of-kind "deadfemales" ) / 2 ] ]
end


to -MEAN-AGE-PEN-133
             ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
       task [ if ( ( count all-of-kind "males" ) > 0 and ( count all-of-kind "females" > 0 ) )
               [ set-current-plot "Mean age plot"
                create-temporary-plot-pen "Mean age"
                            ; this name will be used in the legend if enabled
                set-plot-pen-color green
                set-plot-pen-mode 0
                        ; 0 for line, 1 for bar, 2 for point
                        ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                add-to-plot time ( mean [ my-age ] of all-of-kind "males" + mean [ my-age ] of all-of-kind "females" ) / 2 ] ]
end


to -AVERAGE-NUMBER-OF-BIRTHS-PEN-48
                    ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
       task [ if ( ( count ( all-of-kind "females" ) with [ my-age >= the-minreprodage and my-age <= the-maxreprodage ] ) > 0 )
               [ set-current-plot "Number of children"
                create-temporary-plot-pen "Mean n births"
                            ; this name will be used in the legend if enabled
                set-plot-pen-color green
                set-plot-pen-mode 0
                        ; 0 for line, 1 for bar, 2 for point
                        ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                add-to-plot time mean [ my-number_of_children ] of ( all-of-kind "females" ) with [ my-age >= the-minreprodage and my-age <= the-maxreprodage ] ] ]
end


to -AVERAGE-OF-LIVING-CHILDREN-PER-REPROD-FEMALE-PEN-69
                               ; Graph data on top of a plot with a fresh pen.
```

```
  do-every ( 1
        )
        task [ if ( ( count ( all-of-kind "females" ) with [ my-age >= the-minreprodage ] - count ( all-of-kind "females" ) with [ my-age >= the-maxreprodage ] ) >
              0 )
              [ set-current-plot "Number of children"
                create-temporary-plot-pen "Mean n children"
                                ; this name will be used in the legend if enabled
                set-plot-pen-color blue
                set-plot-pen-mode 0
                           ; 0 for line, 1 for bar, 2 for point
                           ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                add-to-plot time ( count ( all-of-kind "males" ) with [ my-age >= 20 ] + count ( all-of-kind "females" ) with [ my-age >= 20 ] ) / ( count ( all-of-kind
                       "females" ) with [ my-age >= the-minreprodage ] - count ( all-of-kind "females" ) with [ my-age >= the-maxreprodage ] ) ) ] ]
end


to -REAL-TFR-PEN-38
             ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ if ( ( count ( all-of-kind "females" ) with [ my-age = the-maxreprodage ] ) > 0 )
              [ set-current-plot "Number of children"
                create-temporary-plot-pen "TFR"
                                ; this name will be used in the legend if enabled
                set-plot-pen-color black
                set-plot-pen-mode 0
                           ; 0 for line, 1 for bar, 2 for point
                           ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                add-to-plot time mean [ my-number_of_children ] of ( all-of-kind "females" ) with [ my-age = the-maxreprodage ] ] ]
end


to -PERCENTAGE-OF-EXOGAMOUS-WOMEN-PEN-FEMALES-67
                                ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ if ( count all-of-kind "females" > 0 )
```

```
            [ set-current-plot "Exogamy / Migration"
             create-temporary-plot-pen "Living immigrant females"
                          ; this name will be used in the legend if enabled
             set-plot-pen-color green
             set-plot-pen-mode 0
                      ; 0 for line, 1 for bar, 2 for point
                      ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
             add-to-plot time 100 * count ( all-of-kind "females" ) with [ my-exotraitf2 = 1 ] / ( count all-of-kind "females" ) ] ]
end

to -PERCENTAGE-OF-EXOGAMOUS-WOMEN-PEN-DEADFEMALES-27
                              ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
       task [ if ( count all-of-kind "deadfemales" > 0 )
            [ set-current-plot "Exogamy / Migration"
             create-temporary-plot-pen "Dead immigrant females"
                          ; this name will be used in the legend if enabled
             set-plot-pen-color black
             set-plot-pen-mode 0
                      ; 0 for line, 1 for bar, 2 for point
                      ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
             add-to-plot time 100 * count ( all-of-kind "deadfemales" ) with [ my-exotraitf2 = 1 ] / ( count all-of-kind "deadfemales" ) ] ]
end

to -PERCENTAGE-OF-EXOGAMOUS-MEN-PEN-MALES-23
                          ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
       task [ if ( count all-of-kind "males" > 0 )
            [ set-current-plot "Exogamy / Migration"
             create-temporary-plot-pen "Living immigrant men"
                          ; this name will be used in the legend if enabled
             set-plot-pen-color blue
             set-plot-pen-mode 0
                      ; 0 for line, 1 for bar, 2 for point
```

```
                              ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                    add-to-plot time 100 * count ( all-of-kind "males" ) with [ my-exotraitm2 = 1 ] / ( count all-of-kind "males" ) ] ]
end


to -PERCENTAGE-OF-EXOGAMOUS-MEN-PEN-DEADMALES-34
                                   ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ if ( count all-of-kind "deadmales" > 0 )
                   [ set-current-plot "Exogamy / Migration"
                    create-temporary-plot-pen "Dead immigrant men"
                                    ; this name will be used in the legend if enabled
                    set-plot-pen-color gray
                    set-plot-pen-mode 0
                              ; 0 for line, 1 for bar, 2 for point
                              ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                    add-to-plot time 100 * count ( all-of-kind "deadmales" ) with [ my-exotraitm2 = 1 ] / ( count all-of-kind "deadmales" ) ] ]
end


to -NUMBER-OF-NUCLEAR-FAMILIES-PEN-5
                          ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ if ( count ( all-of-kind "females" ) with [ my-age >= the-minreprodage and my-age <= the-maxreprodage ] > 0 )
                   [ set-current-plot "Families / Households"
                    create-temporary-plot-pen "Nuclear families"
                                    ; this name will be used in the legend if enabled
                    set-plot-pen-color green
                    set-plot-pen-mode 0
                              ; 0 for line, 1 for bar, 2 for point
                              ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
                    add-to-plot time ( count all-of-kind "females" + count all-of-kind "males" ) / ( ( mean [ my-number_of_children ] of ( all-of-kind "females" ) with
                          [ my-age >= the-minreprodage and my-age <= the-maxreprodage ] ) + 2 ) ] ]
end
```

```
to -NUMBER-OF-NUCLEAR-FAMILIES-PEN-2-5

                              ; Graph data on top of a plot with a fresh pen.

  do-every ( 1 )

         task [ if ( true ) = true

                 [ set-current-plot "Families / Households"

                   create-temporary-plot-pen "Number of mothers"

                                       ; this name will be used in the legend if enabled

                   set-plot-pen-color red

                   set-plot-pen-mode 0

                                 ; 0 for line, 1 for bar, 2 for point

                                 ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen

                   add-to-plot time count ( all-of-kind "females" ) with [ my-number_of_children > 0 ] ] ]

end


to -NUMBER-OF-HOUSEHOLDS-OF-8-PEN-18

                             ; Graph data on top of a plot with a fresh pen.

  do-every ( 1 )

         task [ if ( count all-of-kind "females" + count all-of-kind "males" > 0 )

                 [ set-current-plot "Families / Households"

                   create-temporary-plot-pen "Households of 8"

                                       ; this name will be used in the legend if enabled

                   set-plot-pen-color blue

                   set-plot-pen-mode 0

                                 ; 0 for line, 1 for bar, 2 for point

                                 ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen

                   add-to-plot time ( count all-of-kind "females" + count all-of-kind "males" ) / 8 ] ]

end


to -NUMBER-OF-HOUSEHOLDS-OF-12-PEN-25

                              ; Graph data on top of a plot with a fresh pen.

  do-every ( 1 )

         task [ if ( count all-of-kind "females" + count all-of-kind "males" > 0 )

                 [ set-current-plot "Families / Households"

                   create-temporary-plot-pen "Households of 12"

                                       ; this name will be used in the legend if enabled
```

```
          set-plot-pen-color orange
          set-plot-pen-mode 0
                 ; 0 for line, 1 for bar, 2 for point
                 ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
          add-to-plot time ( count all-of-kind "females" + count all-of-kind "males" ) / 12 ] ]
end


to -NUMBER-OF-HALF-ORPHANS-PEN-10
              ; Graph data on top of a plot with a fresh pen.
 do-every ( 1 )
     task [ if ( true ) = true
         [ set-current-plot "Number of subadults"
          create-temporary-plot-pen "Half-orphans"
                     ; this name will be used in the legend if enabled
          set-plot-pen-color black
          set-plot-pen-mode 0
                 ; 0 for line, 1 for bar, 2 for point
                 ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
          add-to-plot time count ( all-of-kind "females" ) with [ my-age <= 20 and ( count my-in-links ) = 0
] + count ( all-of-kind "males" ) with [ my-age
               <= 20 and ( count my-in-links ) = 0 ] ] ]
end


to -NUMBER-OF-NEWBORN-INDIVIDUALS-PEN-17
                 ; Graph data on top of a plot with a fresh pen.
 do-every ( 1 )
     task [ if ( true ) = true
         [ set-current-plot "Number of subadults"
          create-temporary-plot-pen "Neonates"
                     ; this name will be used in the legend if enabled
          set-plot-pen-color gray
          set-plot-pen-mode 0
                 ; 0 for line, 1 for bar, 2 for point
                 ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
          add-to-plot time count ( all-of-kind "females" ) with [ my-age <= 1 ] + count ( all-of-kind "males"
) with [ my-age <= 1 ] ] ]
```

```
end

to -NUMBER-OF-SUBADULTS-AGED-MAX-20-PEN-20
                          ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ if ( true ) = true
              [ set-current-plot "Number of subadults"
               create-temporary-plot-pen "<= 20"
                               ; this name will be used in the legend if enabled
               set-plot-pen-color red
               set-plot-pen-mode 0
                          ; 0 for line, 1 for bar, 2 for point
                          ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
               add-to-plot time count ( all-of-kind "females" ) with [ my-age <= 20 ] + count ( all-of-kind "males"
) with [ my-age <= 20 ] ] ]
end

to -NUMBER-OF-SUBADULTS-AGED-MAX-18-PEN-27
                          ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ if ( true ) = true
              [ set-current-plot "Number of subadults"
               create-temporary-plot-pen "<= 18"
                               ; this name will be used in the legend if enabled
               set-plot-pen-color orange
               set-plot-pen-mode 0
                          ; 0 for line, 1 for bar, 2 for point
                          ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
               add-to-plot time count ( all-of-kind "females" ) with [ my-age <= 18 ] + count ( all-of-kind "males"
) with [ my-age <= 18 ] ] ]
end

to -NUMBER-OF-SUBADULTS-AGED-MAX-14-PEN-14
                          ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
        task [ if ( true ) = true
```

```
            [ set-current-plot "Number of subadults"
              create-temporary-plot-pen "<= 14"
                            ; this name will be used in the legend if enabled
              set-plot-pen-color yellow
              set-plot-pen-mode 0
                        ; 0 for line, 1 for bar, 2 for point
                        ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
              add-to-plot time count ( all-of-kind "females" ) with [ my-age <= 14 ] + count ( all-of-kind "males" ) with [ my-age <= 14 ] ] ]
end


to -RATE-OF-HALF-ORPHANS-PEN-26
                 ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
       task [ if ( ( count ( all-of-kind "females" ) with [ my-age <= 20 ] + count ( all-of-kind "males" ) with [ my-age <= 20 ] ) > 0 )
            [ set-current-plot "Rate of subadults"
              create-temporary-plot-pen "Half-orphans/subadults(<21)"
                            ; this name will be used in the legend if enabled
              set-plot-pen-color black
              set-plot-pen-mode 0
                        ; 0 for line, 1 for bar, 2 for point
                        ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
              add-to-plot time 100 * ( count ( all-of-kind "females" ) with [ my-age <= 20 and ( count my-in-links ) = 0 ] + count ( all-of-kind "males" ) with
                   [ my-age <= 20 and ( count my-in-links ) = 0 ] ) / ( count ( all-of-kind "females" ) with [ my-age <= 20 ] + count ( all-of-kind "males"
                   ) with [ my-age <= 20 ] ) ] ]
end


to -RATE-OF-ORPHANS-PEN-13
               ; Graph data on top of a plot with a fresh pen.
  do-every ( 1 )
       task [ if ( ( count ( all-of-kind "females" ) with [ my-age <= 20 ] + count ( all-of-kind "males" ) with [ my-age <= 20 ] ) > 0 )
            [ set-current-plot "Rate of subadults"
              create-temporary-plot-pen "Projected orphans/subadults(<21)"
```

```
                                    ; this name will be used in the legend if enabled

                    set-plot-pen-color gray

                    set-plot-pen-mode 0

                                ; 0 for line, 1 for bar, 2 for point

                                ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen

                    add-to-plot time 100 * ( ( count ( all-of-kind "females" ) with [ my-age <= 20 and ( count my-in-
links ) = 0 ] + count ( all-of-kind "males" ) with

                              [ my-age <= 20 and ( count my-in-links ) = 0 ] ) / ( count ( all-of-kind "females" ) with [ my-
age <= 20 ] + count ( all-of-kind "males"

                              ) with [ my-age <= 20 ] ) * ( count ( all-of-kind "females" ) with [ my-age <= 20 and ( count
my-in-links ) = 0 ] + count ( all-of-kind "males"

                              ) with [ my-age <= 20 and ( count my-in-links ) = 0 ] ) / ( count ( all-of-kind "females" ) with
[ my-age <= 20 ] + count ( all-of-kind "males"

                              ) with [ my-age <= 20 ] ) ) ] ]

end


to -RATE-OF-SUBADULTS-PEN-10

                        ; Graph data on top of a plot with a fresh pen.

  do-every ( 1 )

          task [ if ( ( count all-of-kind "females" + count all-of-kind "males" ) > 0 )

                  [ set-current-plot "Rate of subadults"

                    create-temporary-plot-pen "Subadults(<21)/total population"

                                    ; this name will be used in the legend if enabled

                    set-plot-pen-color red

                    set-plot-pen-mode 0

                                ; 0 for line, 1 for bar, 2 for point

                                ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen

                    add-to-plot time 100 * ( count ( all-of-kind "females" ) with [ my-age <= 20 ] + count ( all-of-kind
"males" ) with [ my-age <= 20 ] ) / ( count

                              all-of-kind "females" + count all-of-kind "males" ) ] ]

end


to -NUMBER-OF-GRANDMOTHERS-PEN-20

                            ; Graph data on top of a plot with a fresh pen.

  do-every ( 1 )

          task [ if ( true ) = true

                  [ set-current-plot "Three coexisting generations"
```

```
            create-temporary-plot-pen "3 generations"
                        ; this name will be used in the legend if enabled
            set-plot-pen-color black
            set-plot-pen-mode 0
                    ; 0 for line, 1 for bar, 2 for point
                    ; plot-pen-reset ; remove the ';' in the box to erase everything drawn by this pen
            add-to-plot time 2 * ( count ( all-of-kind "females" ) with [ count my-in-links > 0 and count my-out-links > 0 ] ) ] ]
end


to -PLOTS-148
        ; Add a list of behaviours
        ; (a way to package up several behaviours into a single unit).
  -PLOT-MALES-ON-GRAPH-74
  -PLOT-MALES2-ON-GRAPH-30
  -PLOT-FEMALES-ON-GRAPH-72
  -PLOT-FEMALES2-ON-GRAPH-31
  -PLOT-DEADFEMALES-ON-GRAPH-78
  -PLOT-DEADFEMALES2-ON-GRAPH-30
  -PLOT-DEADMALES-ON-GRAPH-75
  -PLOT-DEADMALES2-ON-GRAPH-34
  -LIVING-FEMALES-HISTOGRAM-73
  -AUTO-PLOT-HIST-F-33
  -LIVING-MALES-HISTOGRAM-68
  -AUTO-PLOT-HIST-M-32
  -DEADFEMALES-HISTOGRAM-69
  -AUTO-PLOT-HIST-DF-32
  -DEADMALES-HISTOGRAM-69
  -AUTO-PLOT-HIST-DM-31
  -PLOT-INPUT-MORTALITY-68
  -MALES-WITH-TRAIT-PEN-39
  -PEN-FEMALES-WITH-TRAIT-43
  -PEN-DEADMALES-WITH-TRAIT-46
  -PEN-DEADFEMALES-WITH-TRAIT-45
  -M-PLOT-TRAIT-IN-LIVING-POPULATION-68
  -F-PLOT-TRAIT-IN-LIVING-POPULATION-69
```

```
  -M-PLOT-TRAIT-IN-DEAD-POPULATION-49
  -F-PLOT-TRAIT-IN-DEAD-POPULATION-70
  -MEAN-AGE-PEN-138
  -MEAN-AGE-PEN-133
  -AVERAGE-NUMBER-OF-BIRTHS-PEN-48
  -AVERAGE-OF-LIVING-CHILDREN-PER-REPROD-FEMALE-PEN-69
  -REAL-TFR-PEN-38
  -PERCENTAGE-OF-EXOGAMOUS-WOMEN-PEN-FEMALES-67
  -PERCENTAGE-OF-EXOGAMOUS-WOMEN-PEN-DEADFEMALES-27
  -PERCENTAGE-OF-EXOGAMOUS-MEN-PEN-MALES-23
  -PERCENTAGE-OF-EXOGAMOUS-MEN-PEN-DEADMALES-34
  -NUMBER-OF-NUCLEAR-FAMILIES-PEN-5
  -NUMBER-OF-NUCLEAR-FAMILIES-PEN-2-5
  -NUMBER-OF-HOUSEHOLDS-OF-8-PEN-18
  -NUMBER-OF-HOUSEHOLDS-OF-12-PEN-25
  -NUMBER-OF-HALF-ORPHANS-PEN-10
  -NUMBER-OF-NEWBORN-INDIVIDUALS-PEN-17
  -NUMBER-OF-SUBADULTS-AGED-MAX-20-PEN-20
  -NUMBER-OF-SUBADULTS-AGED-MAX-18-PEN-27
  -NUMBER-OF-SUBADULTS-AGED-MAX-14-PEN-14
  -RATE-OF-HALF-ORPHANS-PEN-26
  -RATE-OF-ORPHANS-PEN-13
  -RATE-OF-SUBADULTS-PEN-10
  -NUMBER-OF-GRANDMOTHERS-PEN-20
end

to -REAL-NO-CHILDREN-PER-WOMAN-MONITOR-65
  if ( ( count ( all-of-kind "females" ) with [ my-age >= the-minreprodage ] ) > 0 ) [ ]
end

to -MONITORS-9
          ; Add a list of behaviours
          ; (a way to package up several behaviours into a single unit).
  -REAL-NO-CHILDREN-PER-WOMAN-MONITOR-65
end
```

```
to -LABELS-21
            ; Add a list of behaviours
            ; (a way to package up several behaviours into a single unit).
end

to VARIABLE-AGES-F-00001
                   ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     random-number-between the-lowerage the-upperage
end

to -RANDOM-LOCATION-20
                  ; Jump to a random unoccupied location.
  let unoccupied-location
     random-unoccupied-location ( min-pxcor ) ( 0 ) ( min-pycor ) ( max-pycor )
  set xcor
     first unoccupied-location
  set ycor
     second unoccupied-location
end

to -CREATE-FEMALES-5
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects the-femalestartergeneration [
                                        set just-created-agents
                                           ( turtle-set self just-created-agents )
                                        set kind
                                           "females" ] ]
```

```
  ask just-created-agents
     [ set xcor
          xcor
       set ycor
          ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "females" ]
  ask just-created-agents
     [ VARIABLE-AGES-F-00001
       -RANDOM-LOCATION-20 ]
end

to -RUYRFUVBQHDJOPHBNH3T6-
                      ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     random-number-between the-lowerage the-upperage
end

to -RANDOM-LOCATION-19
                   ; Jump to a random unoccupied location.
  let unoccupied-location
     random-unoccupied-location ( min-pxcor ) ( 0 ) ( min-pycor ) ( max-pycor )
  set xcor
     first unoccupied-location
  set ycor
     second unoccupied-location
end

to -GP6UWEDZIHWEEKRZYLCL6-
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
```

```
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects the-malestartergeneration [
                                         set just-created-agents
                                            ( turtle-set self just-created-agents )
                                         set kind
                                            "males" ] ]
  ask just-created-agents
     [ set xcor
          xcor
       set ycor
          ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "males" ]
  ask just-created-agents
     [ -RUYRFUVBQHDJOPHBNH3T6-
       -RANDOM-LOCATION-19 ]
end

to -LAY-OUT-LINKED-MALES-00003-1
                          ; Lay out a set of agents where the agents repel each other and the links between them act
like springs.
  do-every ( 1 ) task [
         ; place for code to set things up (if needed)
                   repeat 10
                        [ layout-spring all-of-kind "males" links .1
                                    ; a measure of the "tautness" of the spring
 8
                                    ; the "zero-force" length or the natural length of the springs
 1 ]
                                    ; a measure of repulsion between the nodes
  ]
end
```

```
to -LAY-OUT-LINKED-FEMALES-00002-1

                                ; Lay out a set of agents where the agents repel each other and the links between them
act like springs.

   do-every ( 1 ) task [

           ; place for code to set things up (if needed)

                       repeat 10

                             [ layout-spring all-of-kind "females" links .1

                                           ; a measure of the "tautness" of the spring

 8

                                           ; the "zero-force" length or the natural length of the springs

 1 ]

                                           ; a measure of repulsion between the nodes

  ]

end


to -LAY-OUT-LINKED-MALES2-1

                          ; Lay out a set of agents where the agents repel each other and the links between them act
like springs.

   do-every ( 1 ) task [

           ; place for code to set things up (if needed)

                       repeat 10

                             [ layout-spring all-of-kind "males2" links .1

                                           ; a measure of the "tautness" of the spring

 8

                                           ; the "zero-force" length or the natural length of the springs

 1 ]

                                           ; a measure of repulsion between the nodes

  ]

end


to -LAY-OUT-LINKED-FEMALES2-1

                           ; Lay out a set of agents where the agents repel each other and the links between them act
like springs.

   do-every ( 1 ) task [

           ; place for code to set things up (if needed)
```

```
                    repeat 10
                         [ layout-spring all-of-kind "females2" links .1
                                     ; a measure of the "tautness" of the spring
 8
                                     ; the "zero-force" length or the natural length of the springs
 1 ]
                                     ; a measure of repulsion between the nodes
  ]
end

to -MULTIPLY-MORTALITY-35
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ the-disaster_generator = true ]
      task [ do-after ( the-years_between_catastrophes )
                  task [ do-every ( the-years_between_catastrophes )
                              task [ set the-mortmult
                                      the-mortality_multiplier ] ] ]
end

to -MORTALITY-BACK-TO-NORMAL-2
                        ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ the-disaster_generator = true ]
      task [ do-after ( the-years_between_catastrophes + 1 )
                  task [ do-every ( the-years_between_catastrophes )
                              task [ set the-mortmult
                                      1 ] ] ]
end

to -RAISE-AND-RESET-MORTALITY-5
                         ; Add a list of behaviours
                         ; (a way to package up several behaviours into a single unit).
  -MULTIPLY-MORTALITY-35
  -MORTALITY-BACK-TO-NORMAL-2
end
```

```
to -RESET-MULTIPLY-MORTALITY-6
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  whenever task [ the-disaster_generator = false ]
        task [ set the-mortmult
               1 ]
end

to -FEMALE2-COLOR-CHILD-2
                 ; Change the color of this agent.
  set color
     brown
end

to -FEMALE2-SHAPE-CHILD-1
                 ; Change the appearance to one of the defined shapes.
  set shape
     "triangle"
end

to -F2-CH-SIZE-1
           ; Change size of this agent.
  set size
     3
end

to -F2-APPEARANCE-CHILD-2
                 ; Add a list of behaviours
                 ; (a way to package up several behaviours into a single unit).
  -FEMALE2-COLOR-CHILD-2
  -FEMALE2-SHAPE-CHILD-1
  -F2-CH-SIZE-1
end

to -FEMALE2-COLOR-2
             ; Change the color of this agent.
```

```
  set color
     brown
end

to -FEMALE2-SHAPE-1
             ; Change the appearance to one of the defined shapes.
  set shape
     "triangle"
end

to -SIZE-F2-1
         ; Change size of this agent.
  set size
     4
end

to -F2-APPEARANCE-2
             ; Add a list of behaviours
             ; (a way to package up several behaviours into a single unit).
  -FEMALE2-COLOR-2
  -FEMALE2-SHAPE-1
  -SIZE-F2-1
end

to -F2-AGE-DEPENDENT-APPEARANCE-2
                      ; Conditionally adds one of two lists of micro-behaviours.
  do-every ( 1 )
        task [ if-else ( my-age < 20 )
                  [ -F2-APPEARANCE-CHILD-2 ]
                  [ -F2-APPEARANCE-2 ] ]
end

to -STAND-UPRIGHT-2
             ; Set heading to a random angle.
  do-every ( 1 )
```

```
        task [ set heading
               0 ]
end

to -AGEING-145
          ; Increase the age attribute on every tick.
  do-every ( 1 )
        task [ set my-age
               my-age + 1 ]
end

to -DIE-F-11
  set dead
     true
end

to -AGETRANSFER-6
            ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
end

to -F2-TRAITTRANSFER-1
               ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-f2trait
     [ my-f2trait ] of myself
end

to -LINE-NUMBER-TRANSFER-F2-1
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-f2line
     [ my-f2line ] of myself
end

to -CREATE-DEADFEMALES2-8
```

```
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                    set just-created-agents
                       ( turtle-set self just-created-agents )
                    set kind
                       "deadfemales2" ] ]
  ask just-created-agents
     [ set xcor
          xcor
       set ycor
          ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "deadfemales2" ]
  ask just-created-agents
     [ -AGETRANSFER-6
       -F2-TRAITTRANSFER-1
       -LINE-NUMBER-TRANSFER-F2-1 ]
end

to -PROB-DEATH-F2-4
               ; Notes<br>; <br>; <br>; <br>;
  if random-float 1.0 <= probability-death my-age
    [ -DIE-F-11
      -CREATE-DEADFEMALES2-8 ]
end

to -FEMALE2-DEATH-CYCLE-3
```

```
  do-every 1
          task [ -PROB-DEATH-F2-4 ]
                              ; Notes <br>; <br>; <br>; <br>;
end

to -FEMALE2-TRAIT0-3
                 ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-f2trait
               0 ]
end

to -FEMALE2-TRAITGIVER-1
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age >= the-f2trait_age ]
      task [ if random-float 1.0 <= ( the-f2trait_probability )
              [ set my-f2trait
                   1 ] ]
end

to -FEMALE2-ARTEFACTS-DISEASES-2
                           ; Add a list of behaviours
                           ; (a way to package up several behaviours into a single unit).
  -FEMALE2-TRAIT0-3
  -FEMALE2-TRAITGIVER-1
end

to -SETUP-FEMALE2-LINE-1
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  do-at-time ( 0 )
           task [ set my-f2line
                    list who 0 ]
end

to -CHANGE-NUMBER-OF-CHILDREN-F2-2
```

```
                                ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-number_of_children
      my-number_of_children + 1
end

to -BIRTHAGE-18
              ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
      0
end

to -ADD-LINK-FROM-MOTHER-F2-3
                           ; Add a directed link from another.
  create-link-from myself
end

to -FEMALE2-LINE-3
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-next-f2line-set
      true
  set my-next-f2line
      [ lput my-number_of_children my-f2line ] of myself
end

to -CREATE-FEMALE2-OFFSPRING-4
  let just-created-agents
      nobody
      ; Create additional agents initialising them as if at set up time.
      ; The following code was generated by a call to create-agent.
  set just-created-agents
      nobody
  ask patch pxcor pycor
      [ sprout-objects 1 [
                     set just-created-agents
                       ( turtle-set self just-created-agents )
```

```
                    set kind
                      "females2" ] ]
  ask just-created-agents
     [ set xcor
         xcor
       set ycor
         ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "females2" ]
  ask just-created-agents
     [ -BIRTHAGE-18
       -ADD-LINK-FROM-MOTHER-F2-3
       -FEMALE2-LINE-3 ]
end

to -CHANGE-NUMBER-OF-CHILDREN-M2-2
                        ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-number_of_children
     my-number_of_children + 1
end

to -BIRTHAGE-M-12
             ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     0
end

to -ADD-LINK-FROM-MOTHER-M2-2
                     ; Add a directed link from another.
  create-link-from myself
end

to -FEMALE2-LINE-M2-2
```

```
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-next-f2line-set
     true
  set my-next-f2line
     [ lput my-number_of_children my-f2line ] of myself
end

to -CREATE-MALE2-OFFSPRING-5
  let just-created-agents
     nobody
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                   set just-created-agents
                      ( turtle-set self just-created-agents )
                   set kind
                      "males2" ] ]
  ask just-created-agents
     [ set xcor
         xcor
       set ycor
         ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "males2" ]
  ask just-created-agents
     [ -BIRTHAGE-M-12
       -ADD-LINK-FROM-MOTHER-M2-2
       -FEMALE2-LINE-M2-2 ]
end

to -MENOPAUSE-79
```

```
              ; Remove behaviours from a specified agent or set of agents.
  when task [ my-age >= the-maxreprodage ]
      task [ remove-behaviours-from self [ "-FEMALE2-REPRODUCTION-5" ] ]
end

to -CHILDREN-COUNTER-59
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-number_of_children
               0 ]
end

to -CHANGE-NUMBER-OF-CHILDREN-F2-1
                             ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-number_of_children
     my-number_of_children + 1
end

to -BIRTHAGE-8
             ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     0
end

to -ADD-LINK-FROM-MOTHER-F2-1
                         ; Add a directed link from another.
  create-link-from myself
end

to -FEMALE2-LINE-1
               ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-next-f2line-set
     true
  set my-next-f2line
     [ lput my-number_of_children my-f2line ] of myself
```

```
end

to -CREATE-FEMALE2-OFFSPRING-3
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                     set just-created-agents
                        ( turtle-set self just-created-agents )
                     set kind
                        "females2" ] ]
  ask just-created-agents
     [ set xcor
         xcor
       set ycor
         ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
     [ kind-initialisation "females2" ]
  ask just-created-agents
     [ -BIRTHAGE-8
       -ADD-LINK-FROM-MOTHER-F2-1
       -FEMALE2-LINE-1 ]
end

to -CHANGE-NUMBER-OF-CHILDREN-M2-1
                         ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-number_of_children
     my-number_of_children + 1
end
```

```
to -BIRTHAGE-M-5
           ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     0
end

to -ADD-LINK-FROM-MOTHER-M2-1
                   ; Add a directed link from another.
  create-link-from myself
end

to -FEMALE2-LINE-M2-1
              ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-next-f2line-set
     true
  set my-next-f2line
     [ lput my-number_of_children my-f2line ] of myself
end

to -CREATE-MALE2-OFFSPRING-4
  let just-created-agents
     nobody
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                 set just-created-agents
                    ( turtle-set self just-created-agents )
                 set kind
                    "males2" ] ]
  ask just-created-agents
     [ set xcor
          xcor
```

```
     set ycor
       ycor
     initialise-object
     initialise-previous-state ]
  ask just-created-agents
    [ kind-initialisation "males2" ]
  ask just-created-agents
    [ -BIRTHAGE-M-5
     -ADD-LINK-FROM-MOTHER-M2-1
     -FEMALE2-LINE-M2-1 ]
end

to -FEMALE2-REPRODUCTION-6
  when task [ time > 0 ]
      task [ when task [ my-age >= the-minreprodage ]
             task [ if ( ( count ( all-of-kind "males2" ) with [ my-age >= 16 and my-age <= 50 ] ) > 0 )
                   [ do-after ( random-integer-between 0 the-childspacing )
                         task [ do-every ( the-childspacing )
                                  task [ if random-float 1.0 <= ( the-reprodprobability )
                                        [ if-else ( random-number-between 0 1 <= the-fbirthratio )
                                              [ -CHANGE-NUMBER-OF-CHILDREN-F2-1
                                               -CREATE-FEMALE2-OFFSPRING-3 ]
                                              [ -CHANGE-NUMBER-OF-CHILDREN-M2-1
                                               -CREATE-MALE2-OFFSPRING-4 ]
                                                              ; Notes <br>; <br>; <br>; <br>;
 ] ] ] ] ] ]
end

to -AGETRANSFER-17
            ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
    [ my-age ] of myself
end

to -F2-TRAITTRANSFER-5
```

```
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-f2trait
     [ my-f2trait ] of myself
end

to -LINE-NUMBER-TRANSFER-F2-2
                         ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-f2line
     [ my-f2line ] of myself
end

to -EXOTRAITF2-1
               ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitf2
     1
end

to -CREATE-FEMALE-8
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                    set just-created-agents
                       ( turtle-set self just-created-agents )
                    set kind
                       "females" ] ]
  ask just-created-agents
     [ set xcor
          xcor
       set ycor
          ycor
```

```
        initialise-object
        initialise-previous-state ]
  ask just-created-agents
      [ kind-initialisation "females" ]
  ask just-created-agents
      [ -AGETRANSFER-17
        -F2-TRAITTRANSFER-5
        -LINE-NUMBER-TRANSFER-F2-2
        -EXOTRAITF2-1 ]
end

to -DIE-F2-1
  set dead
      true
end

to -PROB-REMOVE-F2-AND-CREATE-F-10
  if ( my-age >= the-fexoage and my-age <= the-fexoagemax )
     [
     ; conditionally removes a female from the females2 group depending on her age;
 if random-float 1.0 <= the-fexoprob2to1
          [ -CREATE-FEMALE-8
            -DIE-F2-1 ] ]
end

to -FEMALE2-EXOGAMY-6
  do-every 1
          task [ -PROB-REMOVE-F2-AND-CREATE-F-10 ]
                                   ; Notes <br>; <br>; <br>; <br>;
end

to -EXOTRAITF2TO0-2
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
       task [ set my-exotraitf2
```

```
            0 ]
end

to -EXOTRAITF0TO2-5
             ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-exotraitf
            0 ]
end

to -MALE2-COLOR-CHILD-2
               ; Change the color of this agent.
  set color
     gray
end

to -MALE2-SHAPE-CH-1
             ; Change the appearance to one of the defined shapes.
  set shape
     "triangle"
end

to -SIZE-M2-CHILD-1
             ; Change size of this agent.
  set size
     3
end

to -M2-APPEARANCE-CHILD-2
                ; Add a list of behaviours
                ; (a way to package up several behaviours into a single unit).
  -MALE2-COLOR-CHILD-2
  -MALE2-SHAPE-CH-1
  -SIZE-M2-CHILD-1
end
```

```
to -MALE2-COLOR-3
            ; Change the color of this agent.
  set color
     gray
end

to -MALE2-SHAPE-1
            ; Change the appearance to one of the defined shapes.
  set shape
     "triangle"
end

to -SIZE-M2-1
          ; Change size of this agent.
  set size
     4
end

to -M2-APPEARANCE-3
             ; Add a list of behaviours
             ; (a way to package up several behaviours into a single unit).
  -MALE2-COLOR-3
  -MALE2-SHAPE-1
  -SIZE-M2-1
end

to -M2-AGE-DEPENDENT-APPEARANCE-2
                    ; Conditionally adds one of two lists of micro-behaviours.
  do-every ( 1 )
       task [ if-else ( my-age < 20 )
              [ -M2-APPEARANCE-CHILD-2 ]
              [ -M2-APPEARANCE-3 ] ]
end
```

```
to -STAND-UPRIGHT-3
             ; Set heading to a random angle.
  do-every ( 1 )
        task [ set heading
               0 ]
end

to -AGEING-146
          ; Increase the age attribute on every tick.
  do-every ( 1 )
        task [ set my-age
               my-age + 1 ]
end

to -DIE-M2-1
         ; Remove this agent from the model.
  set dead
     true
end

to -AGETRANSFER-9
            ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
end

to -M2-TRAITTRANSFER-1
               ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-m2trait
     [ my-m2trait ] of myself
end

to -LINE-NUMBER-TRANSFER-M2-1
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-f2line
```

```
      [ my-f2line ] of myself
end

to -CREATE-DEADMALES2-2
  let just-created-agents
      nobody
      ; Create additional agents initialising them as if at set up time.
      ; The following code was generated by a call to create-agent.
  set just-created-agents
      nobody
  ask patch pxcor pycor
      [ sprout-objects 1 [
                      set just-created-agents
                         ( turtle-set self just-created-agents )
                      set kind
                         "deadmales2" ] ]
  ask just-created-agents
      [ set xcor
           xcor
        set ycor
           ycor
        initialise-object
        initialise-previous-state ]
  ask just-created-agents
      [ kind-initialisation "deadmales2" ]
  ask just-created-agents
      [ -AGETRANSFER-9
        -M2-TRAITTRANSFER-1
        -LINE-NUMBER-TRANSFER-M2-1 ]
end

to -PROB-DEATH-M2-3
               ; Notes<br>; <br>; <br>; <br>;
  if random-float 1.0 <= probability-death my-age
     [ -DIE-M2-1
```

```
      -CREATE-DEADMALES2-2 ]
end

to -MALE2-DEATH-CYCLE-1
  do-every 1
         task [ -PROB-DEATH-M2-3 ]
                        ; Notes <br>; <br>; <br>; <br>;
end

to -MALE2-TRAIT0-1
            ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-m2trait
            0 ]
end

to -MALE2-TRAITGIVER-1
              ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age >= the-m2trait_age ]
      task [ if random-float 1.0 <= ( the-m2trait_probability )
            [ set my-m2trait
                1 ] ]
end

to -MALE2-ARTEFACTS-DISEASES-1
                   ; Add a list of behaviours
                   ; (a way to package up several behaviours into a single unit).
  -MALE2-TRAIT0-1
  -MALE2-TRAITGIVER-1
end

to -AGETRANSFER-32
            ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     [ my-age ] of myself
```

```
end

to -M2-TRAITTRANSFER-4
                 ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-m2trait
     [ my-m2trait ] of myself
end

to -LINE-NUMBER-TRANSFER-M2-2
                      ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-m2line
     [ my-m2line ] of myself
end

to -EXOTRAITM2-1
             ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-exotraitm2
     1
end

to -CREATE-MALE-1
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
     ; The following code was generated by a call to create-agent.
  set just-created-agents
     nobody
  ask patch pxcor pycor
     [ sprout-objects 1 [
                    set just-created-agents
                       ( turtle-set self just-created-agents )
                    set kind
                       "males" ] ]
  ask just-created-agents
     [ set xcor
```

```
         xcor
       set ycor
         ycor
       initialise-object
       initialise-previous-state ]
  ask just-created-agents
      [ kind-initialisation "males" ]
  ask just-created-agents
      [ -AGETRANSFER-32
       -M2-TRAITTRANSFER-4
       -LINE-NUMBER-TRANSFER-M2-2
       -EXOTRAITM2-1 ]
end

to -DIE-M2-3
  set dead
      true
end

to -PROB-REMOVE-M2-AND-CREATE-M-4
  if ( my-age >= the-mexoage and my-age <= the-mexoagemax )
     [
     ; conditionally removes a male from the males2 group depending on her age;
 if random-float 1.0 <= the-mexoprob2to1
         [ -CREATE-MALE-1
          -DIE-M2-3 ] ]
end

to -MALE2-EXOGAMY-2
  do-every 1
         task [ -PROB-REMOVE-M2-AND-CREATE-M-4 ]
                                        ; Notes <br>; <br>; <br>; <br>;
end

to -EXOTRAITM2TO0-3
```

```
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-exotraitm2
               0 ]
end

to -EXOTRAITM0TO2-2
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  when task [ my-age = 0 ]
      task [ set my-exotraitm
               0 ]
end

to -FEMALE2-COLOR-DEAD-4
                    ; Change the color of this agent.
  set color
     31
end

to -DEADFEMALES2-SHAPE-2
                    ; Change the appearance to one of the defined shapes.
  set shape
     "triangle"
end

to -SIZE-F2-D-1
             ; Change size of this agent.
  set size
     3
end

to -APPEARANCE-DEAD-FEMALES2-4
                         ; Add a list of behaviours
                         ; (a way to package up several behaviours into a single unit).
  -FEMALE2-COLOR-DEAD-4
```

```
  -DEADFEMALES2-SHAPE-2
  -SIZE-F2-D-1
end

to -MALE2-COLOR-D-4
              ; Change the color of this agent.
  set color
     1
end

to -DEADMALES2-SHAPE-2
                ; Change the appearance to one of the defined shapes.
  set shape
     "triangle"
end

to -SIZE-D-M2-1
           ; Change size of this agent.
  set size
     3
end

to -APPEARANCE-DEAD-MALES2-4
                    ; Add a list of behaviours
                    ; (a way to package up several behaviours into a single unit).
  -MALE2-COLOR-D-4
  -DEADMALES2-SHAPE-2
  -SIZE-D-M2-1
end

to -VARIABLE-AGES-F2-1
                ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     random-number-between the-lowerage2 the-upperage2
end
```

```
to -RANDOM-LOCATION2-6
                    ; Jump to a random unoccupied location.
  let unoccupied-location
     random-unoccupied-location ( 0 ) ( max-pxcor ) ( min-pycor ) ( max-pycor )
  set xcor
     first unoccupied-location
  set ycor
     second unoccupied-location
end

to -CREATE-FEMALES2-5
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
  if ( the-femalestartergeneration2 > 0 )
    [
    ; The following code was generated by a call to create-agent.
 set just-created-agents
         nobody
      ask patch pxcor pycor
         [ sprout-objects the-femalestartergeneration2 [
                                        set just-created-agents
                                           ( turtle-set self just-created-agents )
                                        set kind
                                           "females2" ] ]
      ask just-created-agents
         [ set xcor
              xcor
           set ycor
              ycor
           initialise-object
           initialise-previous-state ]
      ask just-created-agents
         [ kind-initialisation "females2" ]
```

```
       ask just-created-agents
          [ -VARIABLE-AGES-F2-1
            -RANDOM-LOCATION2-6 ] ]
end

to -VARIABLE-AGES-M2-1
                    ; Set an attribute, parameter, or Netlogo variable to a new value.
  set my-age
     random-number-between the-lowerage2 the-upperage2
end

to -RANDOM-LOCATION2-4
                    ; Jump to a random unoccupied location.
  let unoccupied-location
     random-unoccupied-location ( 0 ) ( max-pxcor ) ( min-pycor ) ( max-pycor )
  set xcor
     first unoccupied-location
  set ycor
     second unoccupied-location
end

to -CREATE-MALES2-5
  let just-created-agents
     nobody
     ; Create additional agents initialising them as if at set up time.
  if ( the-malestartergeneration2 > 0 )
    [
    ; The following code was generated by a call to create-agent.
 set just-created-agents
         nobody
       ask patch pxcor pycor
          [ sprout-objects the-malestartergeneration2 [
                                            set just-created-agents
                                               ( turtle-set self just-created-agents )
                                            set kind
```

```
                                                    "males2" ] ]
        ask just-created-agents
           [ set xcor
               xcor
             set ycor
               ycor
             initialise-object
             initialise-previous-state ]
        ask just-created-agents
           [ kind-initialisation "males2" ]
        ask just-created-agents
           [ -VARIABLE-AGES-M2-1
             -RANDOM-LOCATION2-4 ] ]
end

to -STARTER-GENERATION-2-SLIDERS-3
                          ; Add a list of behaviours
                          ; (a way to package up several behaviours into a single unit).
end

to-report random-integer-between [n1 n2]
 report n1 + random (1 + n2 - n1)
end

to-report random-number-between [n1 n2]
 report n1 + random-float (n2 - n1)
end

; following based on http://www.nr.com/forum/showthread.php?t=1396

to-report random-unoccupied-location [min-xcor max-xcor min-ycor max-ycor]
  let unoccupied-patch one-of patches with
                           [min-xcor <= pxcor and
                            max-xcor >= pxcor and
                            min-ycor <= pycor and
```

```
                                  max-ycor >= pycor and
                                  not any? objects-here with [not hidden?]]
 if-else is-patch? unoccupied-patch
   [report [(list pxcor pycor)] of unoccupied-patch]
   [report (list xcor ycor)]
end

to-report update-attributes
  ifElse my-next-fline-set
    [set my-fline my-next-fline
     set my-next-fline-set false]
    [set my-next-fline my-fline]
  ifElse my-next-f2line-set
    [set my-f2line my-next-f2line
     set my-next-f2line-set false]
    [set my-next-f2line my-f2line]
  report false
end

to initialise-patch-attributes
end

to initialise-globals [globals-not-to-be-initialised]
 set update-patch-attributes-needed false
end

to update-patch-attributes
end

to-report update-turtle-state
 report false
end

to initialise-previous-state
end
```

```
to update-all-turtle-states
end

to initialise-attributes
 set my-next-fline-set false
 set my-next-f2line-set false
end

; The following are NetLogo library procedures and reporters used by the BehaviourComposer
; New BSD license
; See http://modelling4all.org
; Authored by Ken Kahn; Last updated 13 Feb 2015

to start [globals-not-to-be-initialised]
 initialise
 the-model globals-not-to-be-initialised
 finish-setup
 create-pens 1 ; for drawing lines
 ask pens [hide-turtle]
end

to setup
  setup-except []
end

to setup-except [globals-not-to-be-initialised]
 start globals-not-to-be-initialised
 set total-time 0
 if go-until (delta-t - .000001) []  ; ignore result
 ask objects [initialise-previous-state]
end

to initialise
 let saved-state-restored-after-setup state-restored-after-setup
```

```
 if-else maximum-plot-generations > 0
    [if-else plot-generation <= maximum-plot-generations
        [set plot-generation plot-generation + 1
          ; clear all but plots and output
         clear-patches
         clear-drawing
         clear-turtles]
        [clear-all
         set plot-generation 0]]
    [clear-all]
 reset-ticks
 reset-timer
 set time -1
 set times-scheduled []
 set behind-schedule 0
 set plotting-commands []
 set histogram-plotting-commands []
 set button-command ""
 set radian 57.29577951308232
 set need-to-clear-drawing false
 set observer-commands []
 set stop-running false
 if delta-t = 0 [set delta-t 1] ; give default value if none given
 if frame-duration = 0 [set frame-duration delta-t]
 if world-geometry = 0 [set world-geometry 1]
 ask-every-patch task [initialise-patch-attributes]
 set state-restored-after-setup saved-state-restored-after-setup
end

to initialise-object
 set scheduled-behaviours []
 set current-behaviours []
 set behaviour-removals []
 set rules []
 set dead false
```

```
 initialise-attributes
end

to finish-setup
 ; faster than ask objects since doesn't shuffle
 set objects-with-something-to-do objects
 let ignore1 objects with [update-attributes]
 ask objects with [rules != []] [run-rules]
 update-all-turtle-states
 set time 0
end

to go
 reset-timer ; reset timer so pause and resume don't have leftover time
 if go-until -1
    [set stop-running false ; so it can be started up again
     stop]
    set total-time total-time + timer
end

to setup-only-if-needed
  if times-scheduled = 0 [setup]
end

to-report go-until [stop-time]
 ; this is run by the 'go' button and runs the scheduled events and updates the turtle states and plots
 setup-only-if-needed
 if observer-commands != []
    [run-observer-commands]
 if-else times-scheduled = []
   ; following uses a hack to avoid the overhead of ask shuffling the agent set
   [set objects-with-something-to-do objects with [rules != []]
    ask objects-with-something-to-do [run-rules] ; nothing scheduled but rules may be triggered by time
    ; rules may have added behaviours or set 'dead' so can't re-use objects-with-something-to-do
    ask objects [finish-tick]
```

```
    if observer-commands != []
       [run-observer-commands]
    set time time + frame-duration]
   [if-else time <= 0
      [set cycle-finish-time first times-scheduled]
      [set cycle-finish-time cycle-finish-time + frame-duration]
     if stop-time > 0 [set cycle-finish-time stop-time]
     while [times-scheduled != [] and first times-scheduled <= cycle-finish-time]
       [; nothing happening so skip ahead to next event
        set time first times-scheduled
        set times-scheduled but-first times-scheduled
        set objects-with-something-to-do objects with [scheduled-behaviours != [] or rules != []]
        ask objects-with-something-to-do [start-tick]
        ; above may have added behaviours or set 'dead' so can't re-use objects-with-something-to-do
        ask objects [finish-tick]
        if observer-commands != []
           [run-observer-commands]
        if need-to-clear-drawing
           [clear-drawing
            set need-to-clear-drawing false]]]
 if observer-commands != []
    [run-observer-commands]
 update-all-turtle-states
 if update-patch-attributes-needed [ask-every-patch task [update-patch-attributes]]
 tick-advance time - ticks
 run-plotting-commands
 report not any? objects = 0 or stop-running or (stop-time > 0 and time >= stop-time)
end

to run-observer-commands
  let commands observer-commands
  set observer-commands []
  ; run each command without ANY commands pending
  forEach commands [run ?]
end
```

```
to run-plotting-commands

 forEach plotting-commands [if is-agent? first ? [ask first ? [update-plot item 1 ? runresult item 2 ? runresult item 3 ?]]]

 forEach histogram-plotting-commands [if is-agent? first ? [ask first ? [update-histogram item 1 ? item 2 ? item 3 ?]]]

end


to add-to-plot [x y]

  ; if using multiple plot generations need to get the pen back to the beginning without drawing a line

  ; assumes the plot starts at zero (or very close to it -- after setup)

  if-else x <= .000001

     [plot-pen-up plotXY x y plot-pen-down]

     [plotXY x y]

end


to create-plot [name-of-plot x-label y-label x-code y-code]

 ; working around a limitation of NetLogo that only via the Controller can new plots be created

 ; some of the arguments are only of use to the BehaviourComposer

  set plotting-commands fput (list self name-of-plot x-code y-code) plotting-commands

end


to create-histogram [name-of-plot x-label y-label x-code y-code]

  set histogram-plotting-commands fput (list self name-of-plot x-code y-code) histogram-plotting-commands

  set-current-plot name-of-plot

  set-plot-pen-mode 1 ; bars

end


to update-plot [name-of-plot x y]

 if time >= 0

  [set-current-plot name-of-plot

   plotxy x y]

end


to update-histogram [name-of-plot population-reporter value-reporter]

 if time >= 0
```

```
  [set-current-plot name-of-plot
   histogram [runresult value-reporter] of runresult population-reporter]
end

;; behaviours are represented by a list:
;; scheduled-time behaviour-name
;; behaviours are kept in ascending order of the scheduled-time

to remove-behaviour-now [name]
 set scheduled-behaviours remove-behaviour-from-list name scheduled-behaviours
end

to do-every [interval actions]
 ; does it now and schedules the next occurrence interval ticks in the future
 ; schedules first in case action updates the current-behaviour variable
 if-else not is-number? interval or interval <= 0
   [user-message (word "Can only repeat something a positive number of times. Not " interval " " actions)]
   [if-else time < 0
      [insert-behaviour 0 (list (list actions interval))]
      [do-every-internal interval actions]]
end

to do-every-internal [interval actions]
 insert-behaviour time + interval (list (list actions interval))
 run-procedure actions
end

to do-every-dynamic [interval-reporter actions]
 insert-behaviour time + run-result interval-reporter (list (list actions interval-reporter))
 run-procedure actions
end

to do-after [duration actions]
 ; schedules this duration ticks in the future
 if-else is-list? current-behaviour
```

```
    ; from the time this event was scheduled to run; not necessarily the current time
    [do-at-time first current-behaviour + duration actions]
    [if-else time > 0
      [do-at-time time + duration actions]
      [do-at-time duration actions]]
end

to do-at-time [scheduled-time actions]
 if-else scheduled-time <= time
   [run actions]
   [insert-behaviour scheduled-time (list actions)]
end

to start-tick
 set behaviours-at-tick-start scheduled-behaviours
 set current-behaviours scheduled-behaviours
 set scheduled-behaviours []
 while [current-behaviours != []]
      [let simulation-time first first current-behaviours
       if-else simulation-time > time
         [set scheduled-behaviours merge-behaviours scheduled-behaviours current-behaviours
          set current-behaviours []] ; stop this round
         [set current-behaviour first current-behaviours
          forEach but-first current-behaviour run-procedure
          set current-behaviour 0
          ; procedure may have reset current-behaviours to []
          if current-behaviours != []
             [set current-behaviours but-first current-behaviours]]]
 if rules != [] [run-rules]
 if behaviour-removals != []
    [forEach behaviour-removals
       [ask first ? [remove-behaviour-now item 1 ?]]
     set behaviour-removals []]
end
```

```
to finish-tick

 ; this should happen after all objects have run start-tick

 let ignore update-attributes

 if dead [die]

end


to-report all-of-kind [kind-name]

 report objects with [kind = kind-name]

end


to when [condition action]

 set rules fput (list condition action false) rules

end


to whenever [condition action]

 set rules fput (list condition action true) rules

end


to run-rules

 let current-rules rules

 set rules []

 ; so can remove a rule below while still going down the list

 ;; could add error handling below

 forEach current-rules

    [if-else runresult first ?

       [run first but-first ?

        if item 2 ?

           ; is a 'whenever' rule so put it back on the list of rules

           [set rules fput ? rules]]

       [set rules fput ? rules]]

end


to insert-behaviour [scheduled-time rest-of-behaviour]

 ; inserts in schedule keeping it sorted by scheduled time

 set times-scheduled insert-ordered scheduled-time times-scheduled
```

```
 set scheduled-behaviours insert-behaviour-in-list scheduled-time rest-of-behaviour scheduled-behaviours
end

to-report insert-ordered [new-time times]
  if-else member? new-time times
    [report times]
    [report sort fput new-time times]
end

to-report insert-behaviour-in-list [scheduled-time rest-of-behaviour behaviours]
 ; recursive version took 10% longer
 let earlier-behaviours []
 while [behaviours != []]
    [let current-time first first behaviours
      if current-time = scheduled-time
        [let new-behaviour lput first rest-of-behaviour first behaviours
          report sentence earlier-behaviours fput new-behaviour but-first behaviours]
      if current-time > scheduled-time
        [report sentence earlier-behaviours fput fput scheduled-time rest-of-behaviour behaviours]
     set earlier-behaviours lput first behaviours earlier-behaviours
     set behaviours but-first behaviours]
 report sentence earlier-behaviours (list fput scheduled-time rest-of-behaviour)
end

to-report remove-behaviour-from-list [procedure-name behaviours]
 report map [remove-behaviour-from-behaviours-at-time-t procedure-name ?] behaviours
end

to-report remove-behaviour-from-behaviours-at-time-t [procedure-name behaviours-at-time-t]
 forEach but-first behaviours-at-time-t ; first is the time -- skip that
   [if equivalent-micro-behaviour? (ifelse-value is-list? ? [first ?] [?]) procedure-name
      [report remove ? behaviours-at-time-t]]
 report behaviours-at-time-t
end
```

```
to-report equivalent-micro-behaviour? [task-1 task-2]
 if (task-1 = task-2) [report true]
 ; different copies of the same micro-behaviour are equivalent for removals
 let serial-number-length 6
 let task-description-1 (word task-1)
 ; need to obtain the procedure name of the task by extracting it from print format
 ; ignore first 30 characters, serial number, and final parenthesis
 if (length task-description-1 - (serial-number-length + 1) <= 30) [report false]
 let name-1 substring task-description-1 30 (length task-description-1 - (serial-number-length + 1))
 let name-2 0
 if-else (is-string? task-2)
   ; older way was to use strings rather than tasks
   [set name-2 substring task-2 0 (length task-2 - serial-number-length)]
   [let task-description-2 (word task-2)
    if (length task-description-2 - (serial-number-length + 1) <= 30) [report false]
    set name-2 substring task-description-2 30 (length task-description-2 - (serial-number-length + 1))]
 report name-1 = name-2
end

to remove-behaviours [behaviours]
 forEach behaviours [remove-behaviour ?]
end

to remove-behaviours-from [obj behaviours]
  if-else is-agent? obj or is-agentset? obj
    [ask obj [remove-behaviours behaviours]]
    [if obj != 0.0  ; no need to warn if variable is not initialised
       [user-message (word "Attempted to remove the behaviours " behaviours " from NOBODY.")]]
end

to remove-behaviour [name]
  set behaviour-removals fput (list self name) behaviour-removals
end

to-report merge-behaviours [behaviours1 behaviours2]
```

```
 ; both lists are already sorted
 if behaviours1 = [] [report behaviours2]
 if behaviours2 = [] [report behaviours1]
 if-else first first behaviours1 < first first behaviours2
   [report fput first behaviours1 merge-behaviours but-first behaviours1 behaviours2]
   [report fput first behaviours2 merge-behaviours behaviours1 but-first behaviours2]
end

to-report second [l]
 report first but-first l
end

to ask-every-patch [procedure-name]
 ; a hack but faster since doesn't randomise the patches as ask does
 let ignore patches with [run-false procedure-name]
end

to-report run-false [procedure-name]
 run procedure-name
 report false
end

to-report list-to-agentset [agent-list]
 ; deprecated but kept for backwards compatibility
 report turtle-set agent-list
end

to run-procedure [name]
 if-else is-list? name
    [let target-or-frequency item 1 name
     if-else is-number? target-or-frequency
        [do-every-internal target-or-frequency first name]
        [if-else is-agent? target-or-frequency
            [ask target-or-frequency [run first name]]
            [do-every-dynamic target-or-frequency first name] ]]
```

```
    [run name]
end
```

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Thesis title: From Individuals to Settlement Patterns. Bridging the Gap Between the Living and the Dead in Early Medieval Populations Using an Agent-Based Demographic Model

I hereby certify that this thesis has been composed by me and is based on my own work, unless stated otherwise. No other person's work has been used without due acknowledgement in this thesis. All references and verbatim extracts have been quoted, and all sources of information, including graphs and data sets, have been specifically acknowledged.

Place/Date: Oxford, 1st January 2017 **Signature:**