Paleodemographic analysis of age at death for a population of Black Sea Scythians: An exploration by using Bayesian methods

Running title: Bayesian exploration of Scythian paleodemography

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Abstract (250 words)

Objectives

Studies of the demography of past populations involving deterministic life tables can be criticised for ignoring the errors of estimation. Bayesian methods offer an alternative, by focusing on the uncertainty of the estimates, although their results are often sensitive to the choice of prior distributions. The aim of this study is to explore a range of Bayesian methods for estimating age at death for a population of nomadic warriors – Scythians from the Black Sea region.

Materials and Methods

In total, skeletons of 312 individuals (93 children and 219 adults) from Glinoe (Moldova), dated to the 5th-2nd c. BCE, were examined. We unified the age categories corresponding to different aging methods, allowing an application of a probabilistic assessment of the age categorisation. A hierarchical Bayesian multinomial-Dirichlet-Dirichlet model was applied, with a hypothetical, subjective reference population, a real reference population, and no reference.

Results

Stationary-population life expectancy was estimated as 27.7 years (95% CI: 25.1–30.3) for a newborn (e_0), and 16.4 years (14.0–19.0) for 20-year-olds (e_{20}), although with high uncertainty, and sensitive to the model specification. Slight differences in longevity between different social strata and between the Classical and Late chronological periods were found, although with high estimation errors. A more robust finding, confirming earlier studies, was a high probability of death in young adulthood, which could depend on Scythian lifestyle (conflicts, wars).

Discussion

Our study shows a way to overcome some limitations of broad age categorisation by using the Bayesian approach with alternative model specifications, allowing to assess the impact of reference populations.

Key words

Age categorisation, Bayesian methods, Black Sea Scythians, Paleodemography, Reference populations

Research highlights (250 characters)

- Bayesian methods for age categorisation can augment skeletal data with additional knowledge
- For small samples, as for Glinoe Scythians, the estimation errors remain high
- Different prior assumptions help assess the impact of reference populations

Introduction

Existing studies of the age structures of historical populations based on the analysis of skeletal remains have been often based on standard life tables functions, as described by Acsádi and Nemeskéri (1970), coupled with a deterministic assessment of the indicators of age. These methods have important limitations, especially relevant for paleodemographic research. One of the key challenges is an imprecise estimation of age-at-death for some individuals, which can be restricted to broad age categories owing to the lack of diagnostic features in poorly preserved material. In effect, the sample sizes decrease, as only individuals with available detailed age assessment can be considered.

The results obtained for relatively small samples and low numbers of individuals in each age group diminish the reliability of conclusions, while not providing any indications as to the errors of the resulting estimates. The main point of criticism of the traditional approach more generally is that it ignores the uncertainty of the estimation and glosses over the subjective input into the process of age determination. Recently, the development of modern Bayesian statistical methods has opened up many appealing alternatives which can address some of these criticisms, not least by quantifying the estimation errors and including the subjective elements explicitly, through the prior distributions.

Bayesian methods of statistical inference offer an alternative not only to deterministic methods, but also to classical (frequentist) statistics in hypothesis testing, estimating the unknown quantities, and assessing the uncertainty of estimates (Otárola-Castillo & Torquato, 2018). The Bayesian approach relies on the explicit description of all quantities in the statistical model by probability distributions. Despite the Bayesian principles having been first formulated in the eighteenth century, the approach has been recently offering increasingly more and richer opportunities in a vast range of applications, including in paleodemography and bioarchaeology (Caussinus & Courgeau, 2010; Hoppa & Vaupel, 2002; Séguy & Buchet, 2013). The rapid uptake of Bayesian methods in practice has been largely facilitated by the development of fast computational algorithms in the last thirty years.

In the areas related to biological anthropology, Bayesian methods have been successfully applied to a number of different questions about past populations (Konigsberg & Frankenberg, 2013). Examples include an explicit treatment of uncertainty in age estimates for skeletal samples, in estimating the number of individuals from intermingled skeletal remains, or in the assessment of various features of the skeletal material, for example related to the presence of disease markers in paleopathological studies (Konigsberg & Frankenberg, 2013). These methods can be also applied to deal with broad age categories in case of poorly preserved osteological material. In this paper, their usefulness is tested on fragmented and taphonomically altered skeletal remains of ancient Scythians.

Scythians were distinct nomadic tribes and masters of mounted warfare inhabiting Eurasia in the Early Iron Age (Cunliffe, 2019). The Scythian culture, which was prevalent on Eurasian steppes between ca. 900 and 200 BCE, was not associated with any specific population, but rather was related to a wider set of characteristics. Some of the defining features of all Scythian tribes include their nomadic lifestyle, with a central position of horse riding and husbandry, tribal relations based on violence, visible presence of social stratification, as well as distinctive forms of art, involving the presence of many animal motifs

(Kubczak, 1978; Meyer, 2016). It can be assumed that Scythian specific lifestyle reflected in their biology and demographic structure.

While Scythians have been extensively studied by archaeologists for over 100 years, very little is known about their biology. The unsatisfactory state of biological research of Scythian populations is due to the fact that only limited in number osteological collections have survived to these days. Moreover, low level of preservation of human skeletal remains which are available for analyses also significantly limit research capabilities. Bioarchaeological works regarding Scythians published so far, are mainly case studies (e.g. Jordana et al., 2009; Ricaut, Keyser-Tracqui, Bourgeois, Crubézy, & Ludes, 2004; Wentz & De Grummond, 2009), or have a form of anthropological reports containing only raw data (i.e. selected measurements of skulls and long bones) for individuals excavated on the territory of former Soviet Union (see Debec, 1948; Konduktorova, 1973, 1974; Litvinova, 1999, 2004). Notable exceptions include some more recent work of Kozintsev (2007, 2008) and Movsesian and Bakholdina (2017).

The problems with Scythian skeletal remains have forced researchers to use more advanced methods (other than morphological studies), which allow to deal with poorly preserved and incomplete osteological material, including ancient DNA analysis used for study the origin of Scythians (see de Barros Damgaard et al., 2018; Järve et al., 2019; Juras et al., 2017; Krzewińska et al., 2018) or their kinship patterns (see Mary et al., 2019). Paleodemographic analysis of Scythian remains also requires other approach than the traditional one, based on deterministic life tables functions alone. Methodological improvements have been already initiated, including a simplified Bayesian approach (see Łukasik et al., 2017). However, population-level studies are still rarely conducted in case of both Siberian-Scythians from the Altai and Scythians from the Black Sea region. Those limitations apply not only to the Black Sea steppe warriors, but also to other past populations, in particular those from the earlier time periods (e.g. Neolithic Times or Bronze Age), for which the skeletal data are scarce.

In a preliminary paleodemographic study of the Black Sea Scythians (Łukasik et al. 2017), to assess the age of the individuals, a simplified, multinomial version of the model of Caussinus and Courgeau (2010) was applied. However, such attempt was fraught with important limitations. Firstly, the studied group was relatively small, with the sample size of 220 individuals, assessed by using different aging methods. Secondly, strong theoretical assumptions had to be made, including the one that the counts for broad age categories, such as adults aged 20+, were distributed in proportion to the sizes of the well-defined, five-year groups. The approach proposed in this study offers a way of overcoming those limitations, fully utilizing the potential of the Bayesian approach, while being based on a larger skeletal sample.

The aim of this study is therefore to explore the usefulness of a range of Bayesian approaches in studying the paleodemography of Scythians. To do that, we propose a Bayesian method for assessing the age distribution of ancient populations, coherently combining the information from the skeletal sample with a hypothetical and subjective, yet explicitly described reference population related to the the age-at-death assessment of the bony remains. Both types of information are used together in a full Bayesian model originally proposed by Caussinus and Courgeau (2010), providing a convenient solution where empirical reference populations are not readily available or produce biased results. The key innovation of our approach is to treat the elicited knowledge on the age-at-death distribution of the skeletal sample as yet another source of information – as well as uncertainty – which can be used to augment the skeletal data thanks to the natural features of the Bayesian approach.

We demonstrate the usefulness of such a range of Bayesian method in case of age-at-death estimations for analyzing the demographic structure of a Scythian population from the Black Sea region. We also test the sensitivity of the results to the choice of a reference population, whilst recognizing and attempting to describe the bias inherent in the age determination process through uncertainty distributions. We aim to shed light on the possible impact of the reference population on the resulting estimates, with focus on the problem of “age mimicry”, whereby the final estimates adopt the reference age structure (e.g. Bocquet-Appel & Masset 1982; Hoppa & Vaupel, 2002). To do that, we compare our subjective reference population with a real one (Lisbon reference, Séguy & Buchet, 2013: Chapter 4), and with estimates obtained by assuming no reference population, giving more weight to the sample data.

Materials: Background and fieldwork

Cemeteries

The osteological material used in this study came from three Scythian archaeological sites: Glinoe, Glinoe Sad, and Glinoe Vodovod (Figure 1). The Glinoe site (46.6684°N, 29.8001°E) is located in the Slobodzieja (Slobozia) region about 100 km South-East from Kishiniev, the capital of Moldova. The cemetery consists of 114 Scythian barrows dated from the end of the 4th century BCE to the 2nd century BCE (Sinika & Tel'nov, 2018b; Tel'nov, Chetverikov, & Sinika, 2016).

The chronological frameworks of the Glinoe sites and assessment of the cultural affiliation of the individuals buried there were determined on the basis of grave goods, among others, amphorae, epigraphic data, lamps and ceramics. Additionally, for some individuals C-14 dating was performed (see Sinika, Pospieszny, & Łukasik, 2020 and Krzewińska et al. 2018, in particular, Supporting Information Table S2 therein). The Scythian barrows predominantly contained single graves, while double and multiple graves occurred rarely. In one barrow (no. 40) human skeletal remains have not been found. In total, 226 Scythian individuals excavated from the Glinoe site were included in the analysis of the population structure (Table 1).

Glinoe Sad and Glinoe Vodovod sites are much smaller than the Glinoe one. They are located very close to each other, less than 2 km from Glinoe (Glinoe Sad: 46.6860°N, 29.8177°E; Glinoe Vodovod: 46.4107°N 29.4901°E). The Glinoe Sad cemetery consists of 14 barrows dated from Early Bronze Age to Early Iron Age, but only twelve contain burials of individuals belonging to the Scythian culture. They are dated from the second half of the 5th c. BCE to the end of 4th century BCE (Sinika, Lysenko, & Tel'nov, 2017; Sinika & Tel'nov, 2016b; Sinika, Tel'nov, & Lysenko, 2017, 2018a, 2018c). Here, multiple graves were more frequent than single ones. In the analysis of the population structure, 35 Scythian individuals recovered from this site were included (Table 1).

The Glinoe Vodovod site is located less than 200 m from Glinoe Sad. All 20 Scythian barrows excavated at this site contained human skeletal remains, representing 51 individuals (Table 1). This cemetery dates from the first half of 5th c. BCE to the first quarter of 3rd c. BCE (Sinika, Lysenko, Tel'nov, & Razumov, 2019a, 2019b, 2020; Sinika & Tel'nov, 2016a, 2018a; Sinika, Tel'nov, & Lysenko, 2018b; Sinika, Tel'nov, & Zakordonets, 2017). The majority of the barrows contained double or multiple graves. Only in two barrows single graves were found.

[Figure 1 here]

Osteological material

In total, 312 individuals belonging to the Scythian culture were included in this study, of whom 93 were classified as non-adults and 219 as adults (Table 1; see also Figure S1 in the Supporting Information). The majority of the skeletal remains recovered at Gilnoe were incomplete and poorly preserved. It is a consequence of negative impact of two main factors: 1) environmental conditions (highly acidic soil), and 2) human activity, both intentional – plundering of graves in search of Scythian gold, and accidental – ploughing of the land (Łukasik et al., 2017). All of those sites are located in agricultural areas. The use of heavy agricultural machinery in this area, together with relatively shallow grave depth, could have contributed to poor preservation of human skeletal remains.

[Table 1 here]

Aging methods

Age of subadults was assessed through tooth development and eruption (Ubelaker, 1989), measurements of long bones (Schaefer, Scheuer, & Black, 2009; Scheuer & Black, 2000, 2004) and bone fusion (Schaefer et al., 2009; Scheuer & Black, 2000, 2004). Aging of adults was based on changes of the pubic symphysis surface (Todd, 1921), cranial suture closure (different authors, after Piontek, 1999) and in some cases on tooth wear (Lovejoy, 1985). The numbers of skeletons examined by each method – or combination of methods – are shown in Figure S1 in the Supporting Information. The use of different methods of age assessment resulted from the low degree of preservation of osteological material. For both non-adults and adults, we unified the age categories corresponding to each of the methods as shown in Table 2. It allowed us to elicit a subjective prior distribution describing the age at death assessment for different skeletal stages by combining different methods used for age estimation. Such subjective assessments bear inevitable errors, both in terms of variation and possible biases, which we attempt to explicitly describe by using probability distributions.

Sex assessment

Since only in a small number of cases estimation of sex was possible based on morphological traits of skull and pelves, this variable was not included in the research. However, it should not introduce any substantial bias to our results for two main reasons. Firstly, nomadic societies were characterized by less strict labor divisions between males and females than societies leading a more sedentary lifestyle (Streatfield, 2016). Secondly, both historical sources (Mayor, 2014, p. 12; Morillo, Black, & Lococo, 2008, p. 105; Payen, 2015; Rolle, 2006, p. 175) and archaeological data (see Guliaev, 2003; Rolle, 1989, p. 88; 2006, p. 175; 2011, p. 120) confirm that young Scythian women participated in warfare alongside men, sharing similar risk of dying in combat.

Health status

For assessing the health status the following stress markers were used: linear enamel hypoplasia, cribra orbitalia and porotic hyperostosis. In the analysis of linear enamel hypoplasia only permanent teeth (incisors, canines and premolars) displaying mild-to moderate attrition were included, (see Buikstra &

Ubelaker, 1994; Goodman & Rose, 1990). Enamel defects were scored only if they were macroscopically visible and their presence were confirmed by fingernail test (Steckel, Larsen, Sciulli, & Walker, 2005).

The study of cribra orbitalia embraced all available skulls, for which at least one orbital roof was well preserved. If possible, the roof of both orbits were observed. The severity of cribra orbitalia was scored according to the classification system proposed by Global History of Health Project (Steckel et al., 2005). In the porotic hyperostosis research, all available skulls with at least one parietal bone present were examined. The severity of porotic hyperostosis was assessed also using the classification proposed by the Global History of Health Project (Steckel et al., 2005).

Social status

The social status of individuals deriving from past populations can be assessed on the basis of archaeological data (Ivantchik, 2011). Scythian remains from Glinoe have been categorized into one of two social classes: nobles and commoners, according to grave goods, burial construction and funerary ritual. The Scythian nobles were interred in impressive burial mounds with rich inventory (e.g. gold adornments or amphorae), whereas commoners were interred in smaller graves, with scarce grave offerings (Łukasik et al., 2017).

Methods: Bayesian age estimation

Multinomial-Dirichlet-Dirichlet model with a reference population

Estimation of age structures in ancient populations is a formidably difficult task, which is fraught with inevitably large uncertainty. In contemporary anthropology, there is a methodological consensus that this uncertainty needs to be formally quantified, ideally through probability distributions (Caussinus & Courgeau, 2010; Hoppa & Vaupel, 2002; Séguy & Buchet, 2013). The recent review in the *American Journal of Physical Anthropology* (DeWitte, 2018) and the seminal monographs dealing with this topic (Hoppa & Vaupel, 2002; Séguy & Buchet, 2013) all point towards the use of Bayesian approaches as a natural way to describe this estimation uncertainty in a formal, coherent and transparent manner.

At the same time, the use of existing reference populations is fraught with the "age mimicry" problem, the term conventionally used in the context of methods of determining the age which are based on reference tables, the age structures of which directly affect the resulting estimates (Bocquet-Appel & Masset, 1982). In other words, as Boldsen et al. (2002, 75) have put it, mimicry is the "contamination of … estimates by the age composition of the reference sample". An alternative approach, followed in this paper, is to apply Bayesian estimation methods with an informative reference prior. It has been noted that as long as such prior is *appropriate* (Boldsen et al., 2002, 78, emphasis original), the use of Bayesian methods guarantees that the final result is not influenced by mimicry.

In our case, the reference prior is subjective, and even though it makes use of traditional methods for age determination, potentially allowing some of the mimicry to reoccur through that route, it also allows for describing the associated errors in a transparent way. We do not make the claim to the optimality of such prior selection, but rather treat it as an approximation of an appropriate informative prior, while at the same time demonstrating that some other priors, especially with a lot of prior-data conflict or under small-sample situations, can make the mimicry problem reappear.

The idea behind the use of the subjective approach is based on the statistical literature on eliciting prior distributions (see O'Hagan et al., 2006, for a comprehensive treatment). Such elicitation has been used in demographic studies to deal with problematic measurements or predictions, for example of migration (e.g. Bijak & Wiśniowski, 2010; Raymer et al., 2013; Wiśniowski et al., 2013), but to our knowledge, has not yet been explored in the context of paleodemographic research.

The previous analysis of the skeletal material of Glinoe Scythians, reported in Łukasik et al. (2017), applied a simplified Bayesian approach, based exclusively on the marginal prior distribution of the age categories, and for a smaller sample of skeletons. Since then, more skeletal material became available, and a more comprehensive statistical approach could be applied, based on the full model of Caussinus and Courgeau (2010), following a hierarchical Bayesian multinomial-Dirichlet-Dirichlet specification.

Let the skeletal measurement classes (stages) be denoted by c, and five-year age groups by a. In our case, $c = 1, \dots , 31$ and $a = 1, \dots , 11$, with the last, open-ended age group ($a = 11$) of 50 years or more. The here aim is to estimate the distribution of deaths in the sample by age group, $\mathbf{p} = [p_1 \dots p_{11}]'$, where $\Sigma_a p_a = 1$. The model of Caussinus and Courgeau (2010) assumes that the empirical frequencies observed for individual classes, m_c, follow a multinomial distribution with parameters $\boldsymbol{\pi} = [\pi_1 \dots \pi_{31}]'$, such that $\Sigma_c \pi_c = 1$. The link between the two quantities, $\mathbf{p}$ and $\boldsymbol{\pi}$, is provided by conditional probabilities that a skeleton belonging to age group a is observed in class (stage) c. These probabilities are denoted by $p_{c|a}$, where $\Sigma_c p_{c|a} = 1$. Under these assumptions, the following relationship holds (idem: 120):

$$\Sigma_a p_a p_{c|a} = \pi_c. \qquad (1)$$

In the full Bayesian specification, the method requires defining two prior distributions, both for the conditional distribution $\mathbf{p}_{\cdot|\mathbf{a}}$, and for the age structure $\mathbf{p}$. Following Caussinus and Courgeau (2010), let both parameter vectors follow *a priori* Dirichlet distributions, the one for $\mathbf{p}_{\cdot|\mathbf{a}}$ with hyperparameters $\boldsymbol{\alpha}_\mathbf{a} = [\alpha_{ca}]_{1x31}$, and the one for $\mathbf{p}$, with hyperparameter $\boldsymbol{\beta} = [\beta_a]_{1x11}$. These Dirichlet distributions provide a full probabilistic expression of uncertainty about the unknown quantities of the model (1) *a priori* – independently from the data.

Following the recommendations of Caussinus and Courgeau (2010), the distribution for $\mathbf{p}_{\cdot|\mathbf{a}}$ could be derived from an existing reference population (see e.g. Séguy & Buchet, 2013), for which the mapping between the classifications of individual measurements into stages and the corresponding age groups is known. Unfortunately, for Glinoe Scythians, to assign a skeleton to a developmental stage/class, several anthropological methods and measurements had to be used at the same time. Hence, the way in which the data were collected precluded the use of a single reference population for different measurements, and multiple reference populations were not available for all measurement methods used. This did not allow us to use more advanced multi-indicator methods, such as the transition analysis of Boldsen et al. (2002) or the multivariate latent trait approach of Holman et al. (2002).

Elicitation of the hypothetical reference population

As mentioned before, for the Scythian sample, the classification of skeletons into stage classes was arrived at by independently applying three methods of measurement to the available osteological material: tooth development, bone fusion, and long bone measurement for subadults (resulting in eight initial classes of measurement, denoted by sA … sH), as well as tooth wear, pubic symphysis, and cranial suture for adults (initially seven classes, aA … aG). The classification details are listed in Table 2.

[Table 2 here]

In our case, the hypothetical reference population prior distribution for $\mathbf{p}_{\cdot|\mathbf{a}}$ was subjective and was elicited based on a range of possible age indicators. It has been constructed by assuming a hypothetical population of 312 skeletons, equal in size to the one observed for the Glinoe Scythians. This approach resembles some aspects of the so-called empirical Bayes methods (e.g. Casella, 1985) with their data-based priors, but in our case, the proposed method for the construction of the reference prior attempts to safeguard against a dual use of data in the estimation process, as explained below.

As a part of the prior construction process, for each skeleton within the sample, the anthropologists on the team assessed their subjective probabilities, with which the deceased could have belonged to one of the initial classes sA … sH and aA … aG, or one of their possible combinations, to highlight the error of age assessment. This exercise resulted in defining 31 unique measurement classes *c* for the derived combinations of the initial 15 classes, sA … sH, aA … aG. These 31 classes are equivalent to stages in the original methodology by Caussinus and Courgeau (2010). The detailed mapping between classes *c* and age groups *a* for our elicited reference population is presented in Table 3, showing 'pseudo-counts' N_{ca}, which add up to the overall number of skeletons, in order to give data and the priors similar weight (see e.g. Crooks, Green, & Brenner, 2005).

To ensure that the corresponding Dirichlet distributions describe the correct conditional probabilities ($\mathbf{p}_{\cdot|\mathbf{a}}$), and to avoid direct "age mimicry" through propagating the age structure to the estimates, which would also introduce the data twice, the pseudo-counts were rescaled so that $N'_{ca} = (312/11)\, N_{ca} / \Sigma_c N_{ca}$ for every *a*. In this way, for each of the 11 age groups, the sum of the pseudo-counts is the same and equal to 312/11 = 28.364, so that no additional information on age structures gets propagated to the estimates besides what is included in the data. The parameters of Dirichlet distributions have then been assumed as $\alpha_{ca} = N'_{ca} + 0.1$ for each combination of *c* and *a*. We have chosen to add 0.1 to the Dirichlet pseudo-counts, rather than the default 1 (Caussinus & Courgeau, 2010, p. 126) due to a high numbers of structural zeros in the table, and to make sure that the resulting distribution is not only pulled towards the categories with higher parameter values, but also actively pushed away from those below 1.

Sensitivity to the prior assumptions and model specification

In order to assess the sensitivity of the results to the prior assumptions for the age structure, the vector **p**, again following Caussinus and Courgeau (2010), has been *a priori* assumed to be in one of the two forms: (1) uniform (flat), with hyperparameters $\beta_a = 1$ for all *a*; and alternatively (2) informative, with hyperparameters β_a taken from the pre-industrial standard reported for both sexes by Séguy and Buchet

(2013, p. 147). The latter vector of β_a values has been obtained by rescaling the standard life-table deaths D_x to add up to the number of age classes, so that $\Sigma_a\beta_a = 11$ (see Table 4).

Given that the aim of the analysis is to reconstruct the life table of the Glinoe Scythians, the estimated distribution of **p** can be used to calculate life-table quantities such as deaths (d_x), survivorships (l_x), or life expectancy (e_x) for a selection of exact ages x, corresponding to the limits of the age groups a. An additional assumption has been made here for the remaining length of life at 50, which was assumed to follow a Gamma distribution $\Gamma(5,1)$ with a mean of 5 years and standard deviation of 2.2 years.

A well-known source of bias in the estimation of age structures based on archaeological data is the underestimation of the number of children in skeletal populations, either due to their worse preservation especially in acidic soil, or to burials being carried out at different locations (see e.g. Konigsberg & Frankenberg, 1994). To adjust for that, a correction has been applied following the approach proposed by Henneberg and Piontek (1975). Their method is based on estimating the potential gross reproduction rate, R_{pot}, expressing "the natality possibilities in a population with given mortality conditions" (idem: 195), defined as:

(2) $$R_{pot} = 1 - \sum_{x=15}^{w} d_x s_x,$$

with s_x being empirically-derived weights for Non-Malthusian contemporaneous populations (Hutterite, Bengal, Guinea), here assumed as follows: $s_{15–20} = 0.95$, $s_{20–25} = 0.75$, $s_{25–30} = 0.55$, $s_{30–35} = 0.35$, $s_{35–40} = 0.17$, and $s_{45–49} = 0.05$ (idem: 195; Henneberg, 1975; Strzałko, Henneberg, & Piontek, 1980).

[Table 3 here]

The correction, originally due to (Henneberg, 1977), assumes that the share of deaths of children under 15, $d_{0–15}$, can be approximated by using R_{pot} in conjunction with the average number of children U_c, as well as the net reproduction rate, R_0. The approximation is:

(3) $$d_{0–15} = 1 – (2R_0 / U_c\, R_{pot}).$$

[Table 4 here]

To complete the statistical specification of the model, we have assumed that $R_0 \sim$ Normal(1.06, 0.02), truncated at zero, and that $U_c \sim \Gamma(12,2)$ with a mean of 6 children and standard deviation of 3, thus allowing large uncertainty. Selected results are shown both with and without this correction.

In order to check yet another aspect of the robustness of the results, two types of assumptions were tested; either of a stationary population, or a stable population, with a stochastic growth rate r assumed to follow a normal distribution with the mean 0.002 and a standard deviation 0.001 per annum, in line with what might be realistically assumed for the Scythian population (see also Łukasik et al., 2017). Denoting by d_x the distribution of deaths by age in a stable population with growth rate r, and d'_x in the equivalent stationary population, the implied relationship is $d'_x = e^{rx} d_x$ (Johansson & Horowitz, 1986; Preston & Coale, 1982). For the stable population, the assumptions about r and R_0 additionally imply the mean length of a generation centred around 29 years, with some uncertainty – the mean value being the default used by Coale, Demeny, and Vaughan (1983).

In terms of data, the population studied included all 312 skeletons, of which 258 have been classified as 'commoners' and 27 as 'nobles', based on the contextual information and other findings from the graves. An additional classification has been done according to the period of the utilization of the cemetery, with 85 skeletons from the earlier, Classical Scythian period (5th–4th c. BCE) and 183 from the Late Scythian period (3rd–2nd c. BCE). For 27 skeletons, it was not possible to determine the social status, and for 44 skeletons – the historical period. Altogether, 30 models have been estimated: for each population (all, commoners, nobles, early and late periods), and under each of the two prior assumptions about the age distribution (flat and pre-industrial standard), three models were run – stationary population without correction for children, stationary population with correction, and stable population with correction.

Sensitivity to the choice of the reference population

In addition to the model estimation process discussed above, in order to assess the robustness of the proposed approach, two other sets of models were also estimated for the total skeletal population, in the baseline variant assuming stationary population and no correction for the number of children.

First, alternative reference populations, based on the literature, were employed: following Séguy and Buchet (2013), we used the tooth mineralisation coefficients for the upper right quadrant teeth (11–18) in children (*idem*: Table 4.7, p. 78) and cranial suture closure for adults (*idem*: Table 4.2, p. 66, unisex variant). To ensure that the reference population has the same weight in the estimation as our elicited one, we rescaled the reference counts to match the total number of Scythian skeletons in our sample (312). In addition, as information about teeth was only available for 80 children and information about cranial sutures only for 54 adults (see Figure S1 in the Supporting Information), we have re-weighted the resulting d_x estimates accordingly, to represent the original sample structure with 93 children and 213 adults, and to enable comparisons with our primary estimates. We have estimated the model both with and without 'flattening' the age structure of the reference population to make it uniform by age group.

Second, we have also computed a simplified variant of the model without the reference population, repeating the exercise from Łukasik et al. (2017), only on a larger and more diverse sample. The multinomial-Dirichlet model used did not involve any conditional distribution describing the reference population, as in (1), but was based on applying a Dirichlet prior on the age distribution, and estimating the posterior directly, under the multinomial assumption for the data sample.

To estimate the model (1), numerical methods have been used, applying the Hamiltonian Monte Carlo algorithm implemented in the stan package for R (Stan Development Team, 2018a, 2018b). The model code is available in the Supporting Information. Each estimation run is based on 10,000 iterations for four parallel Monte Carlo chains, following 1,000 burn-in cycles, and average runtimes were in the range of 3–13 minutes per run for the hypothetical reference population, 2.5 – 4 minutes for the Lisbon one, and 5–13 seconds for no reference population. In all cases, the calculations were repeated for the non-informative and pre-industrial prior distributions assumed for the age structure of the skeletal sample. Performance of the algorithm has been assessed by inspecting the autocorrelations and trace plots, as well as built-in features of Hamiltonian Monte Carlo diagnostics in stan, all of which indicated convergence. Post-processing has been done and images generated in R (version 3.5.1).

Results: Uncertainty in demographic outcomes

The key outcomes of the substantive analysis for the whole population are reported in Figure 2 in terms of life expectancy e_x and survivorship l_x. Overall, the shape of the survivorship curve depends on the model (stationary in Figures 2a–2d, stable in Figures 2e–2f), the presence of correction for the number of children, which lowers the e_0 (no correction in Figures 2a–2b, correction in Figures 2c–2f). To some extent, the results also depend on the choice of the prior for the age distribution **p**, although with largely overlapping 95-per cent intervals for the estimates under alternative prior assumptions.

Assuming a stationary population and a pre-industrial prior, life expectancy at birth (e_0) was estimated as 27.7 years (95% credible intervals from 25.1 to 30.3), and at age 20 (e_{20}) as 16.4 years (14.0 to 19.0). In line with the expectations, slightly higher values of e_x for all age groups were obtained under the stable population assumption, whilst correcting the number of underrepresented infants reduced the e_0 considerably. A visible drop in the number of survivors, l_x, especially around the age of 20–30 years, confirms earlier results reported in Łukasik et al. (2017), additionally supporting the hypothesis about Scythian warriors possibly "dying young" in combat.

The width of the estimated uncertainty bands predominantly reflects a relatively small skeletal sample. The results highlight an important role of the applied correction for the number of children and of the stable population assumption. The former is shifting e_x and l_x downwards for early ages, but with wide uncertainty intervals (Figures 2c, 2d), while the latter is moving e_x and l_x slightly upwards throughout the life course, but also including additional uncertainty propagating from the stochastic assumptions about the intrinsic population growth rate, r, and the net reproduction rate, R_0 (Figures 2e, 2f). The results for the whole skeletal sample are also reported in Table 5 terms of the life table deaths, d_x.

[Figure 2 here]

[Table 5 here]

Figures 3 and 4 present comparisons of e_x estimates between different subgroups of the Glinoe Scythian population, stratified either by social status (Figures 3a–3f), or historical period (Figures 4a–4f). No clear differences in e_x among individuals differing in social status were observed: even though under the pre-industrial prior slightly higher values of life expectancy were found for nobles than for commoners, under the flat prior the pattern was reverse. In all cases the differences were dwarfed by high errors of estimation, with overlapping 95-per cent credible intervals (Figure 3). The intervals were especially wide for the nobles – a result of a small number of skeletons. Similarly, under the same prior, slightly higher values of e_x were obtained for the Classical Scythian period than for the Late Scythian period, except for the youngest ages (Figure 4), although again most of the differences were not sufficiently distinct. More detailed results for various subsamples are also included in Tables S1–S4 in the Supporting Information.

[Figure 3 here]

[Figure 4 here]

Sensitivity of the results

The outcomes of the sensitivity analysis revealed high impact of the reference population assumptions on the results of the estimation, in line with what would be expected according to the "age mimicry" argument. The comparisons in terms of d_x for our hypothetical reference population, the Lisbon one (provided for reference in Table S5 in the Supporting Information), and estimation using no reference population, are shown in Figure 5, with the underlying figures reported in Tables S6 and S7. A clear peak of mortality in the 30s in the posterior estimates for the Lisbon reference population is a case in point: such elevated mortality results from the conflict between the reference population prior and our skeletal sample, indicated by vastly different structures *by stage* for adults (Table S5). At the same time, similar structures by stage for children lead to the results being less sensitive to the specification of the model, prior and reference populations, also according to expectations (see e.g. Boldsen et al. 2002). These conclusions are valid for the reference populations both without and with 'flattened' structure by age, the latter with even more extreme departures from the sample information for adults, especially under the informative, post-industrial prior (detailed results are reported in Table S6).

[Figure 5 here]

One key lesson from comparing the results is that alternative models and reference populations also include strong assumptions, especially for adults. In this example, the Lisbon reference population also proved susceptible to another type of mimicry, as can be seen by comparing the two approaches with the one using no reference population. This suggests a conflict between the data and the Lisbon prior and/or insufficient data sample size, but also raises a more general point: if an informative reference prior is not appropriate for the data at hand, the problem of mimicry in some form may return even in the Bayesian approach. This discussion goes beyond the scope of the current paper but reinforces the importance of a careful choice of the reference prior.

At the same time, the median results obtained with the subjective reference prior align with those for no reference, which suggests that the prior did not introduce additional information about the age structures from the reference population, but at the same time relied on the initial age assessment, which could be biased. Here, when compared with the no-reference approach, the method based on subjective reference priors adds more uncertainty related to age determination especially where it is expected: much more for adults, where the limitations of current methods much are more pronounced, rather than juveniles (see the discussion in Boldsen et al. 2002). In this way, we explicitly acknowledge the imperfection of the age determination process through wide uncertainty bounds. The no-reference approach, in turn, proved to be too optimistic in terms of producing uncertainty bounds which are visibly too narrow for such an uncertain endeavour as reconstructing the age structure in the presence of such high uncertainty of measurement and classification.

The skeletal remains of the populations inhabiting the Black Sea region in the early Iron Age are for the most part poorly preserved. This is mainly due to the widespread occurrence of highly acidic soil in the Black Sea region (see Ursu, Overenco, Marcov, & Curcubăț, 2014; Watson, 1967), and human activity connected with, among others, the transformation of these areas into farmlands and destruction of relatively shallow graves by deep plowing. In addition, secondary burials of Late Nomads, dated to the Middle Ages, have been found dug into Scythian burial mounds, causing violation or even damage of the original Scythian graves (Sinika, Razumov, Lysenko, & Tel'nov, 2015). Plundering of the graves of Scythian elites in search of objects made of gold also contributed to fragmentation and destruction of the human remains (see Gerling, 2015). Moreover, the vast majority of the Scythian skeletons available for research come from the excavations conducted between the 1960s and 1990s, and their long-term storage also had an impact on the condition of the osteological material.

The poor level of preservation of human skeletal remains not only determines the choice of research methods that can be used, but also somewhat forces the need of searching for new ways and solutions to deal with such material. In the case of paleodemographic analysis of the Glinoe Scythians, the use of one uniform method of age-at-death assessment for the whole examined group reduced the sample size (in the example above, to 54 adults and 80 subadults). Small sample size in turn leads to the need to adopt further arbitrary assumptions, which lower the reliability of the results and their interpretations.

Results: Health status of Scythian warriors

In terms of contextual information corroborating the obtained age-at-death estimates, the analysis of health status of Scythians revealed that the examined population was characterized by relatively low prevalence of stress indicators (Table 6). Linear enamel hypoplasia on permanent teeth occurred in around one third of the sample. Cribra orbitalia was noticed in less than 30% of all individuals, while porotic hyperostis was found only in one case (less than 2%). Similar results were obtained for all analysed sites. There were no marked differences in prevalence of linear enamel hypoplasia between the Scythian elite members and the commoners. The frequency of linear enamel hypoplasia also did not differ much between individuals from the Classical Scythian phase and the Late Scythian phase. However, this may be a consequence of relatively small number of individuals belonging to the Scythian elite or those coming from the Classical Scythian period. In the case of porotic changes, the differences between those groups were not analysed due to insufficient sample sizes.

[Table 6 here]

Discussion: Uncertain demography of Scythian warriors

The results, with overlapping uncertainty bands, indicate that the skeletal sample is either still too small to allow definite conclusions – or that the differences between the subgroups are not overly important. There seem to be some difference between the early period (slightly higher e_x, except for the youngest ages) and the late one (slightly lower e_x), which may indicate better childhood survival, counterbalanced by later-life disadvantages. Again, the error bounds surrounding the estimates are very wide. The results of the sensitivity analysis highlight the importance of informative priors, and the additional assumptions, especially on the correction of missing children in the sample. The reference population assumptions and the background mortality prior play a key role in the estimation, especially with respect to the assessment of the uncertainty of the l_x and e_x estimates. On the other hand, differences between the stationary and stable population assumptions, with realistic parameters, are relatively minor.

Overall, the wide uncertainty intervals are not surprising, given the small sample and the number of assumptions that needed to be made in the estimation process. The key limitations of the analysis include therefore the inevitable high levels of sensitivity of the posterior distributions of the age profiles to the underlying assumptions, and their heavy reliance on informative priors. Still, the use of elicited subjective priors for reference populations allows for combining judgement on measurement error with data from skeletal samples to get as accurate estimates as possible in the absence of detailed reference population datasets. At the same time, comparing the results with those obtained for an actual reference population and for no reference population, confirms once again the strong sensitivity of the results on the choice of the prior information.

Possible extensions of this analysis could include enhancing the database on Glinoe Scythians through further excavations to increase the samples, and fine-tuning the prior assumptions. The latter could for example take into account additional contextual information on skeletons, such as on the state of health, an initial assessment of which is discussed above, or cause of death. From the methodological point of view, the construction of the priors could be further modified. Whilst still remaining in the realm of the Caussinus and Courgeau (2010) method, the prior distribution for $\mathbf{p}_{.|\mathbf{a}}$ could be based on a Dirichlet mixture model, with several independent reference populations, one for each method of assessing age, mapped onto the measurement classes. This approach could require larger samples for each method, but in principle should be feasible in the future, once more information on measurements and reference populations becomes available.

Discussion: Anthropological and historical interpretations

Survivorship of Scythians from Glinoe sites

Our research revealed that the Scythian population from Glinoe is characterized by a relatively high, even if uncertain, values of stationary-population life expectancy at birth (median of 27.7 years, 95% credible intervals from 25.1 to 30.3) and relatively low value at age 20 (median of 16.4 years, 14.0 to 19.0) in comparison to other Iron Age European populations (see Supporting Information, Table S8). Note relatively low values of life expectancy of adults (e_{20}) also reported for another Scythian sample (Ukraine). Previous research, carried out on a smaller Scythian sample (data only for one Glinoe site), suggested the lower values of e_{20} could have been attributed to the participation of younger adults in combat activities (Łukasik et al., 2017).

Scythians appeared in the history as nomadic tribes and masters of mounted warfare who conquered large areas of the Eurasian continent (Cunliffe, 2019; Kubczak, 1978; Petrenko, 1995; Phillips, 1972; Piotrowicz, 1939, p. 18; Wendelken, 2000). For this reason, the relatively low value of e_{20} could have to some extent resulted from the excess deaths among adults because of their participation in military actions. This hypothesis is additionally supported by an elevated probability of death and sharply decreasing probability of survival in the twenties under any set of assumptions a priori (Figure 2b, d, f). Table 7 presents two sets of posterior probabilities of such "accident hump" in the Scythian population, defined as $P({}_5d_{25} > {}_5d_{30})$ and $P({}_{10}d_{20} > {}_{10}d_{30})$, for different model specifications and under different prior assumptions. It can be seen that in most cases, these probabilities are high, in the range of 0.61–0.62 for the former and to 0.79–0.81 for the latter, except for the Lisbon reference population, where the lack of an accident hump can be explained by the nature of the reference collection and the effect of "age mimicry" (see Figure 5).

[Table 7 here]

Besides warfare, another possibility of the relative excess of young adults in the cemetery sample is underrepresentation of old adults. Some bioarchaeological studies have shown, that bones are more fragile and less strong at the end of life cycle due to early life experiences, including diet and nutrition, activity patterns, and reproduction. However, in the examined sample dense bone tissue and strong bones were observed also in senile individuals, likely due to high mechanical loading during lifetime, supporting the notion of context-specific patterns of bone status (see Agarwal 2008, 2016).

Survivorship and life expectancy in human populations depend not only on their involvement in violence, but also an interplay of biological and environmental factors, including living conditions, health status, and diet (see Pinhasi, 2008). In our sample, the prevalence of the examined stress markers prevalence was relatively low in comparison with other contemporaneous human populations, which can be indicative of relatively good health (Supporting Information Tables S9-S11). This conclusion is similar to the ones reported in previous studies (Łukasik, 2015). It should be underlined, however, that those indicators belong to nonspecific stress markers, and are only general measures of health in past populations (Lewis & Roberts, 1997; Ortner & Buikstra, 2019; Steckel & Rose, 2003).

On the other hand, any frequent stress episodes would have affected the whole population in an age-indiscriminate way, rather than being concentrated amongst young adults, who normally exhibit the highest levels of immunological resistance and are typically the strongest in the population (see Elgert, 2009, p. 65). Additionally, the relatively high value of life expectancy at birth (e_0) suggests that the Scythian population under study was rather well-adapted to environmental constraints. This additionally supports the hypothesis that the decrease of survivorship of young Scythian adults could be attributed to lifestyle factors, such as wars and conflict – not very dissimilar to the 'accident hump' of mortality among contemporary populations, especially young men.

For past human populations engaged in warfare a high prevalence of skeletal traces of violence can be expected (see Martin & Harrod, 2015; Mayor, 2014; Owens, 2007; Walker, 1989). With ongoing excavations at Glinoe sites, which provide relatively well-preserved skeletal remains of Scythians as compared with previous samples, a new perspective of trauma analysis has arisen. The paleopathology of trauma in Scythians is planned for future research.

Comparison of life expectancy between Scythian nobles and commoners

Slight differences in the values of e_0 and e_{20} between nobles and commoners were noticed, but the size of these effects proved to be well within the error bounds. According to historical sources, individuals from both social strata were involved in military actions, but their battle positions were different (Herodotus, IV, 65). Most probably, the Scythian commoners fought mainly in the front line, in the closest range from the enemy, while the nobles stayed in the back line. The latter played a similar role to an army commander in the modern warfare. Taking into account the positions of Scythian warriors during military actions, it can be supposed that the probability of death among the nobles was relatively lower than of the commoners, with a higher value of e_{20} for the former group. Another factor, which might affect the values of e_0 and e_{20}, were the biological features of Scythians. The analysis of linear enamel hypoplasia shows that the Scythian nobles were characterized by somewhat better health than the commoners (Łukasik, 2015).

Comparison of life expectancy between the Classical Scythian phase and Late Scythian phase

Some differences in the value of life expectancy between individuals from the Classical Scythian and Late Scythian period were noticed. As expected, slightly higher value of e_x was found in individuals coming from the Classical Scythian phase, than the Late Scythian phase. According to historical sources, the Classical phase (the 5th and the 4th c. BCE) was a period of Scythian dominance in Eurasia, when their economic, political and cultural development reached its peak (Melyoukova, 1995). At that time, the Scythians overcame other populations and occupied a large territory of the Eurasian continent. So, it is not surprising that the values of e_x were higher at that time than in the Late Scythian phase. Also of note is a higher number of child skeletons in the sample from the Classical Period, which may reflect changes in burial practices.

In Scythian history, the 3rd c. BCE is considered as the beginning of decline in their dominance (Melyoukova, 1995). However, it remains unknown, why this group disappeared from the pages of history. Nevertheless, several factors might have been involved in this phenomenon. Firstly, the lost war against the army of Philip II of Macedon partially weakened the Scythian position (Wendelken, 2000). Additionally, constant Sarmatian attacks also might have contributed to the decline of their power and strength (Marčenko & Vinogradov, 1989; Melyoukova, 1995). Moreover, climate changes in the Black Sea region (steppe formation) during the Late Scythian period might have affected the economic stability of Scythian populations (Melyoukova, 1995). All those factors are presumably reflected in the values of paleodemographic parameters of Scythians from the Late phase (the low value of e_x and the high value of q_x). Interestingly, the impact of climate change on the group's demographics has been also suggested for the Scythians from Central Asia (Panyushkina, 2012).

Conclusions

Confirming earlier findings (Łukasik et al., 2017), the current skeletal material indicates that Glinoe Scythians were characterized by a relatively high probability of death in early adulthood. The results suggest that the demographic structure could depend on their lifestyle (conflicts, wars), which contributed to the elevated mortality of young adults, despite their relatively good health, as confirmed by a detailed analysis of the skeletal material. In purely descriptive terms, some slight differences between subgroups under study, such as nobles and commoners, or the early and late period, have been identified. Still, the probabilistic estimates confirm that the samples are not large enough to allow for definite conclusions, as all these differences fall within the wide error bounds and are sensitive to model specification and the selection of prior assumptions.

The size of the sample, large estimation errors, and high sensitivity to the choice of prior assumptions and reference populations about the age structure pose natural limits on the interpretation of the presented results. These limitations notwithstanding, this study hopes to make a methodological contribution by providing suggestions and considerations for using subjective prior distributions in situations when reference populations are not available or not appropriate, and which at the same time enable formally assessing the uncertainty of estimation of age structures.

Even though the original method we followed (Caussinus & Courgeau 2010) assumes proper (i.e. existing) reference populations, the matrix Dirichlet prior, which we elicited instead, can be reconceptualised as a link structure in model (1), connecting observed skeletal stages with age groups. At the same time, it is worth noting that even the empirical (observed) reference priors may not be appropriate for a given population, which can also give grounds to some form of mimicry, given that ultimately the information on age-stage structures needs to come from somewhere.

We argue that such elicited link structures, explicitly acknowledging the uncertainty of age classification, can form a useful addition to the existing paleodemographic toolkit. The method we propose is but an approximation of a fully informative reference prior and our subjective reference population is still a placeholder, which would require further refinement. Recognising that the experts undertaking classification are also biased, and subjective hypothetical priors can be thus also subject to the mimicry effect, more work is clearly needed on the elicitation process itself, possibly also to establish standards for creating hypothetical reference populations, as was done in other disciplines (see O'Hagan et al. 2006). Such approaches could use different ageing methods for the same indicator or involving many experts, so including yet another source of cross-expert and cross-method uncertainty.

The potential prize for pursuing this path is worth reaching out for: a comprehensive description of uncertainty coming from the observed variability in the data sample as well as the errors of measurement (age assessment), acknowledging its imperfections, formally combined together through the means of Bayesian statistics. In the case of Glinoe Scythians, the high levels of this uncertainty are but an inherent feature of currently available skeletal information about this fascinating, if not very well known, historical population.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request. The R code and the corresponding stan code for estimating the age structures and life table parameters are enclosed in the Supporting Information.

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Tables

Table 1. Examined samples by the number and percentage of the deceased in age categories

Age category	Glinoe		Glinoe SAD		Glinoe Vodovod		Total	
	N	%	N	%	N	%	N	%
Subadults	**51**	**54.8**	**19**	**20.4**	**23**	**24.7**	**93**	**29.8**
Infants I (0–7 years)	26	47.3	15	27.3	14	25.5	55	17.6
Infants II (7–15 years)	15	65.2	2	8.7	6	26.1	23	7.4
Juveniles (15–20 years)	8	61.5	2	15.4	3	23.1	13	4.2
Unknown (< 20 years)	2	100.0	0	0.0	0	0.0	2	0.6
Adults	**175**	**79.9**	**16**	**7.3**	**28**	**12.8**	**219**	**70.2**
Young (20–35 years)	85	85.0	8	8.0	7	7.0	100	32.1
Middle (35–50 years)	54	81.8	3	4.5	9	13.6	66	21.2
Old (> 50 years)	12	80.0	1	6.7	2	13.3	15	4.8
Unknown (>20 years)	24	63.2	4	10.5	10	26.3	38	12.2
Total	**226**	**72.4**	**35**	**11.2**	**51**	**16.3**	**312**	**100.0**

Source: Own elaboration based on the skeletal material

Table 2. Classification chart for skeletons in the Glinoe sample

Measurement class: Subadults	**Tooth development and eruption: stages numbered consecutively (after Ubelaker, 1989)**	**Bone fusion (Schaefer et al., 2009; Scheuer & Black, 2000, 2004)**	**Measurements of long bones (Schaefer et al., 2009; Scheuer & Black, 2000, 2004)**
sA (perinatal)	1–5	Depends on the bones: individual assignment to specific classes	Depends on the bones: individual assignment to specific classes
sB (1–3 years)	6–9		
sC (4–6 years)	10–12		
sD (7–9 years)	13–15		
sE (10–12 years)	16–18		
sF (13–15 years)	18–19		
sG (16–18 years)	19–20		
sH (18–20 years)	19–20		
Measurement class: Adults	**Tooth crown wear (Lovejoy, 1985): Categories**	**Morphology of the pubic symphysis (Todd, 1921): Categories**	**Cranial suture closure (different authors, after Piontek, 1999): Categories**
aA (20–25 years)	C-D	II-III	S3
aB (25–30 years)	E	IV-V	S3
aC (30–35 years)	F	VI	S3
aD (35–40 years)	G	VII	S2
aE (40–45 years)	H	VIII	S2
aF (45–50 years)	H	IX	S2
aG (50+ years)	I	X	S1, C1, L1–3

Source: Own elaboration

Table 3. Input matrix $\mathbf{N} = [n_{ca}]_{31x11}$ for constructing Dirichlet priors for the conditional distributions of $\mathbf{p}_{\cdot|\mathbf{a}}$

Classes *c*		***a***	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
(see Table 2)	**Skeletons**	***x***	**0–5**	**5–10**	**10–15**	**15–20**	**20–25**	**25–30**	**30–35**	**35–40**	**40–45**	**45–50**	**50+**
sA ***or*** sA, sB ***or*** sB	24		24.00	0	0	0	0	0	0	0	0	0	0
sA, sB, sC	2		1.00	1.00	0	0	0	0	0	0	0	0	0
sA, sB, sC, sD, sE, sF, sG, sH	1		0.25	0.25	0.25	0.25	0	0	0	0	0	0	0
sB, sC	10		6.33	3.67	0	0	0	0	0	0	0	0	0
sC	14		5.36	8.64	0	0	0	0	0	0	0	0	0
sC, sD	6		1.40	4.00	0.60	0	0	0	0	0	0	0	0
sC, sD, sE, sF, sG, sH, aA	1		0	0.25	0.25	0.25	0.25	0	0	0	0	0	0
sD	8		0	8.00	0	0	0	0	0	0	0	0	0
sD, sE	1		0	0.50	0.50	0	0	0	0	0	0	0	0
sD, sE, sF	1		0	0.35	0.60	0.05	0	0	0	0	0	0	0
sE	5		0	0.75	4.00	0.25	0	0	0	0	0	0	0
sE, sF	5		0	0.50	3.34	1.17	0	0	0	0	0	0	0
sF	2		0	0	1.23	0.77	0	0	0	0	0	0	0
sF, sG	4		0	0	1.47	2.53	0	0	0	0	0	0	0
sF, sG, sH	7		0	0	1.83	5.17	0	0	0	0	0	0	0

sG, SH ***or*** sH	2	0	0	0	2.00	0	0	0	0	0	0	0
aA	19	0	0	0	0	16.15	2.85	0	0	0	0	0
aA, aB	34	0	0	0	0	15.30	15.30	3.40	0	0	0	0
aA, aB, aC	18	0	0	0	0	5.71	5.71	5.69	0.90	0	0	0
aA, aB, aC, aD, aE, aF, aG	34	0	0	0	0	4.83	4.86	4.86	4.86	4.86	4.86	4.86
aB	2	0	0	0	0	0.30	1.40	0.30	0	0	0	0
aB, aC	26	0	0	0	0	2.60	10.40	10.40	2.60	0	0	0
aC	1	0	0	0	0	0	0.15	0.70	0.15	0	0	0
aC, aD, aE	1	0	0	0	0	0	0.05	0.30	0.30	0.30	0.05	0
aD	3	0	0	0	0	0	0	0.45	2.10	0.45	0	0
aD, aE	16	0	0	0	0	0	0	1.60	6.40	6.40	1.60	0
aD, aE, aF	21	0	0	0	0	0	0	1.05	6.30	6.30	6.30	1.05
aD, aE, aF, aG	1	0	0	0	0	0	0	0.05	0.24	0.24	0.24	0.24
aE, aF	26	0	0	0	0	0	0	0	2.60	10.40	10.40	2.60
aE, aF, aG	2	0	0	0	0	0	0	0	0.10	0.63	0.63	0.63
aG	15	0	0	0	0	0	0	0	0	0	2.25	12.75

Source: Own elaboration based on the sample material

Table 4. Pre-industrial prior distribution for **p**, corresponding to life expectancy at birth of 34 years

Group *a*	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Age *x*	**0–5**	**5–10**	**10–15**	**15–20**	**20–25**	**25–30**	**30–35**	**35–40**	**40–45**	**45–50**	**50+**
D_x	319	35	19	24	29	31	32	35	37	41	398
β_a	3.509	0.385	0.209	0.264	0.319	0.341	0.352	0.385	0.407	0.451	4.378

Source: Adapted from Séguy and Buchet (2013, p. 147)

Table 5. Estimates of ${}_5d_x$ under different specifications of the model for the whole skeletal sample (N=312)

Model	Stationary population			Stationary with correction			Stable with correction		
Quantiles	2.5%	Median	95%	2.5%	Median	95%	2.5%	Median	95%
Non-informative prior									
${}_5d_0$ (x 1,000)	77.2	122.8	179.6	73.0	259.1	426.3	59.6	237.6	407.3
${}_5d_5$	34.6	81.6	135.4	40.1	167.0	317.5	32.9	153.4	299.5
${}_5d_{10}$	5.8	38.3	82.7	7.8	77.0	181.3	7.3	71.3	171.7
${}_5d_{15}$	6.5	36.3	75.0	3.3	21.9	57.6	4.0	23.0	59.6
${}_5d_{20}$	38.3	145.6	254.6	22.4	89.4	210.1	24.2	94.3	214.5
${}_5d_{25}$	12.7	127.9	278.5	7.7	76.6	216.1	8.4	82.8	225.7
${}_5d_{30}$	7.2	89.8	213.9	4.7	55.5	165.1	4.9	60.3	173.5
${}_5d_{35}$	7.0	79.7	197.7	4.0	48.8	151.5	4.6	53.4	160.1
${}_5d_{40}$	6.7	86.3	204.0	3.7	52.7	156.0	4.2	58.3	170.0
${}_5d_{45}$	6.9	89.2	210.6	3.8	54.5	160.0	4.1	60.3	172.5
${}_\omega d_{50}$	18.2	71.5	135.7	10.7	43.7	104.3	12.1	49.5	116.1
Pre-industrial prior (see Table 4)									
${}_5d_0$ (x 1,000)	92.3	140.6	200.6	92.7	297.2	483.8	68.0	272.6	458.5
${}_5d_5$	20.9	72.9	128.4	27.3	147.6	299.3	20.5	135.9	283.8
${}_5d_{10}$	0.0	31.7	83.8	0.0	62.0	179.1	0.0	56.9	169.4
${}_5d_{15}$	0.0	33.2	76.8	0.0	19.5	58.6	0.0	20.9	60.0
${}_5d_{20}$	2.2	144.4	270.9	2.6	86.7	218.4	1.8	91.9	226.2
${}_5d_{25}$	0.2	130.5	322.5	0.1	77.5	245.2	0.1	84.4	260.7
${}_5d_{30}$	0.0	74.3	230.9	0.0	45.1	168.8	0.0	46.9	181.0
${}_5d_{35}$	0.1	75.4	225.7	0.1	45.3	166.5	0.1	49.7	183.5
${}_5d_{40}$	0.2	93.9	226.6	0.2	55.7	170.9	0.2	61.4	188.0
${}_5d_{45}$	0.1	48.1	186.9	0.1	29.2	133.5	0.1	31.7	146.9
${}_\omega d_{50}$	59.3	113.8	193.5	30.7	69.8	151.6	35.3	78.6	166.6

Source: Own elaboration based on the skeletal material

Table 6. Skeletal health indicators in the examined population

Site	**Linear enamel hypoplasia**			**Cribra orbitalia**			**Porotic hyperostosis**		
	n	N	%	n	N	%	n	N	%
Glinoe	38	122	31.2	11	39	28.2	1	36	2.7
Glinoe SAD	4	11	36.4	3	13	23.1	0	10	0.0
Glinoe Vodovod	9	24	37.5	6	23	26.1	0	22	0.0
Total	51	157	32.5	20	75	26.7	1	68	1.5

Source: Own elaboration based on the skeletal material

Table 7. Posterior probabilities related to the presence of an 'accident hump' in different models

Model	**Non-informative prior**		**Pre-industrial prior (see Table 4)**	
Probabilities	$P({}_5d_{25} > {}_5d_{30})$	$P({}_{10}d_{20} > {}_{10}d_{30})$	$P({}_5d_{25} > {}_5d_{30})$	$P({}_{10}d_{20} > {}_{10}d_{30})$
Stationary	0.6225	0.8164	0.6215	0.8018
Stationary with correction	0.6131	0.8135	0.6187	0.7976
Stable with correction	0.6127	0.8015	0.6241	0.7914
Lisbon reference population	0.4167	0.2541	0.4469	0.2440
No reference population	0.9234	0.9944	0.9235	0.9940

Source: Own elaboration based on the skeletal material

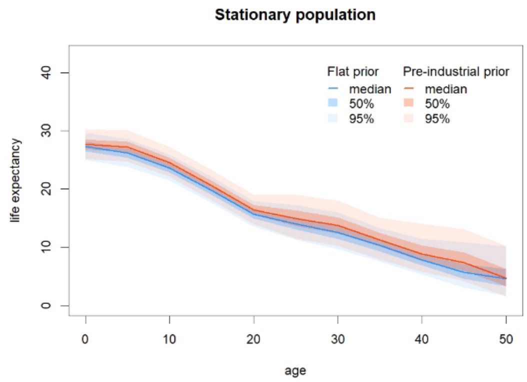
Figures

Figure 1. Location of three Scythian archaeological sites around Glinoe

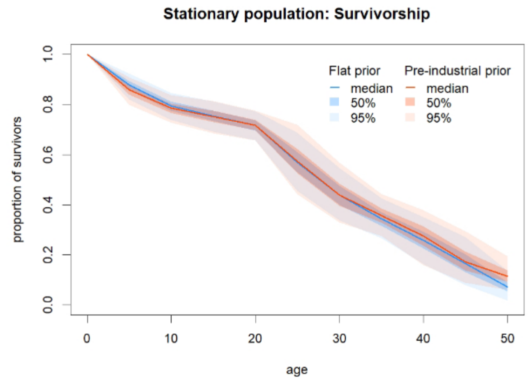
Source: Google Maps

Figure 2. Life expectancy and survivorship estimates based on the full skeletal sample (*N*=312)

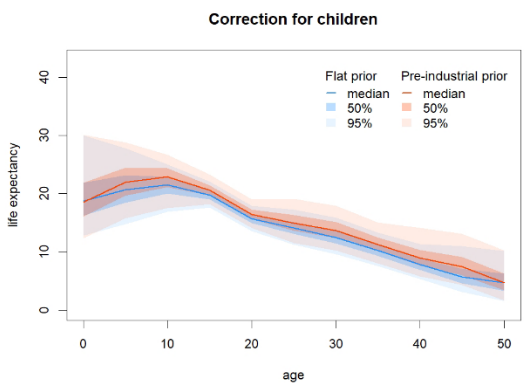
a) Life expectancy (e_x), stationary model



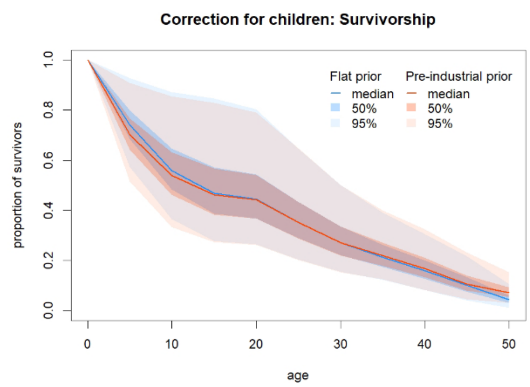
b) Life table survivorship (l_x), stationary model



c) Stationary e_x, with correction for children



d) Stationary l_x, with correction for children



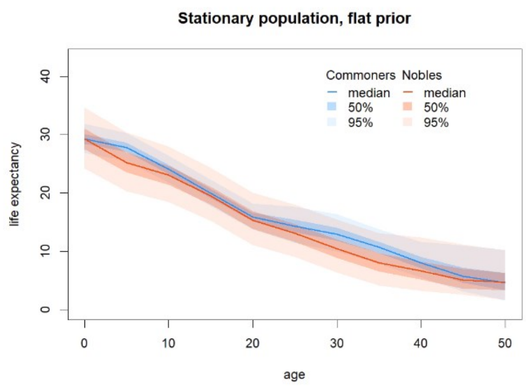
e) Stable population e_x, with correction

f) Stable population l_x, with correction

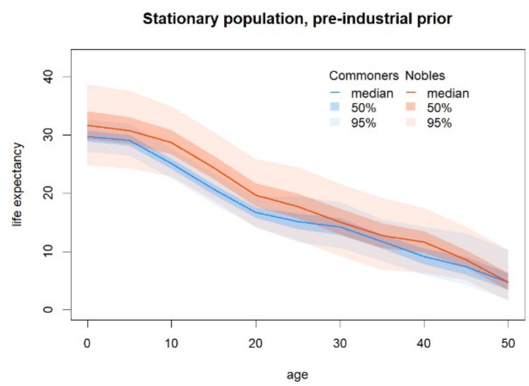
Source: Own elaboration based on the sample material

Figure 3. Life expectancy estimates for the 'commoners' (*N*=258) and 'nobles' (*N*=27) under different prior assumptions for the age distribution: flat and pre-industrial (Séguy & Buchet, 2013, p. 147)

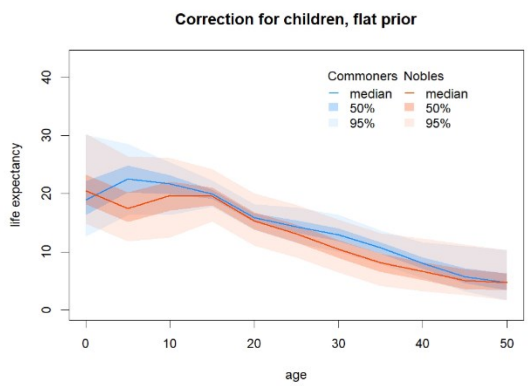
a) Stationary population e_x, flat prior



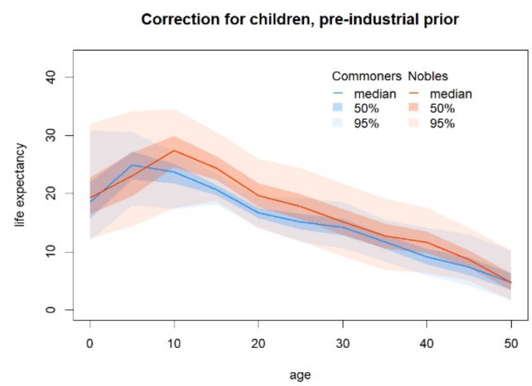
b) Stationary population e_x, pre-industrial prior



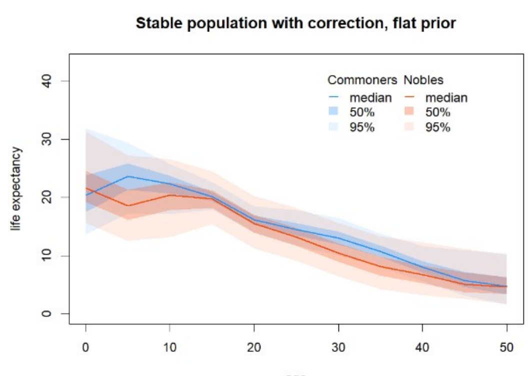
c) Stationary e_x with correction, flat prior



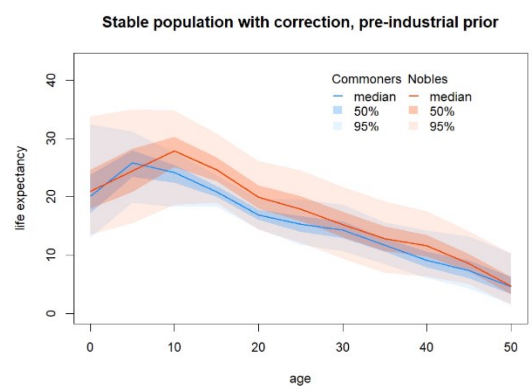
d) Stationary e_x with correction, pre-industrial prior



e) Stable e_x with correction, flat prior



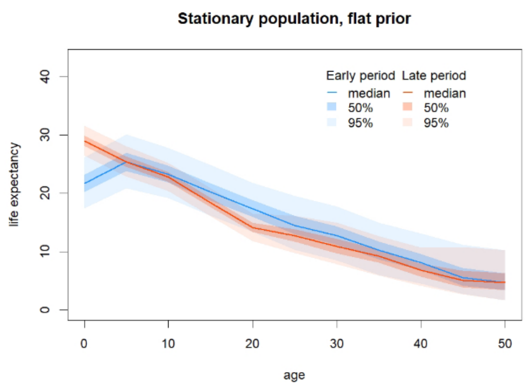
f) Stable e_x with correction, pre-industrial prior



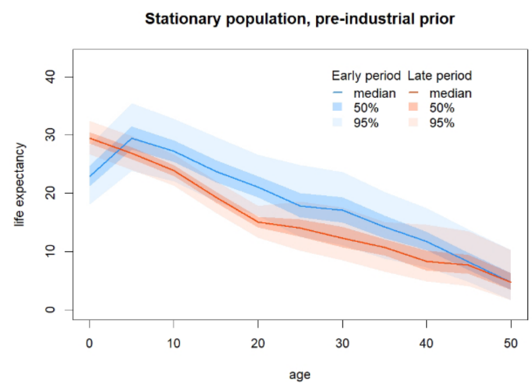
Source: Own elaboration based on the sample material

Figure 4. Life expectancy estimates for the early (*N*=85) and late periods (*N*=183) under different prior assumptions for the age distribution: flat and pre-industrial (Séguy & Buchet, 2013, p. 147)

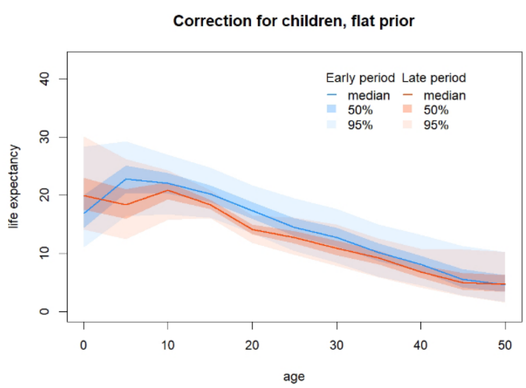
a) Stationary population e_x, flat prior



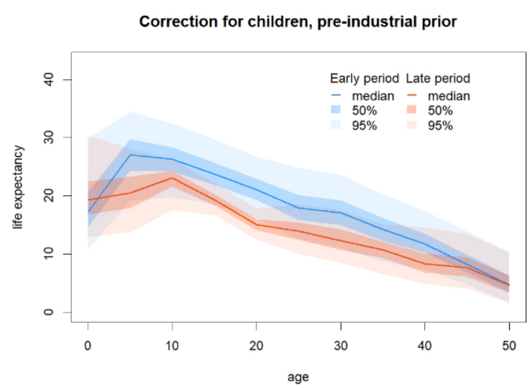
b) Stationary population e_x, pre-industrial prior



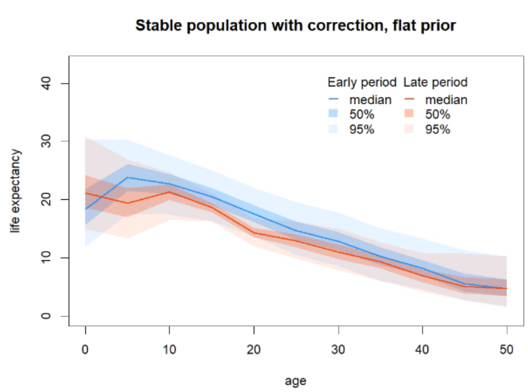
c) Stationary e_x with correction, flat prior



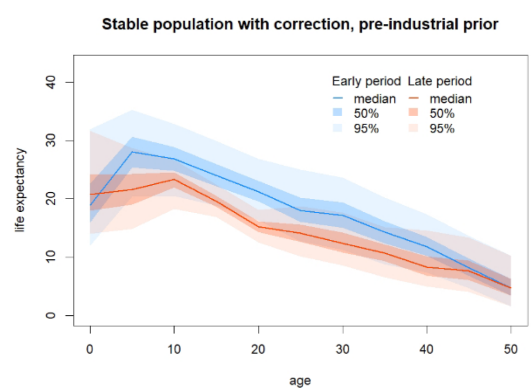
d) Stationary e_x with correction, pre-industrial prior



e) Stable e_x with correction, flat prior

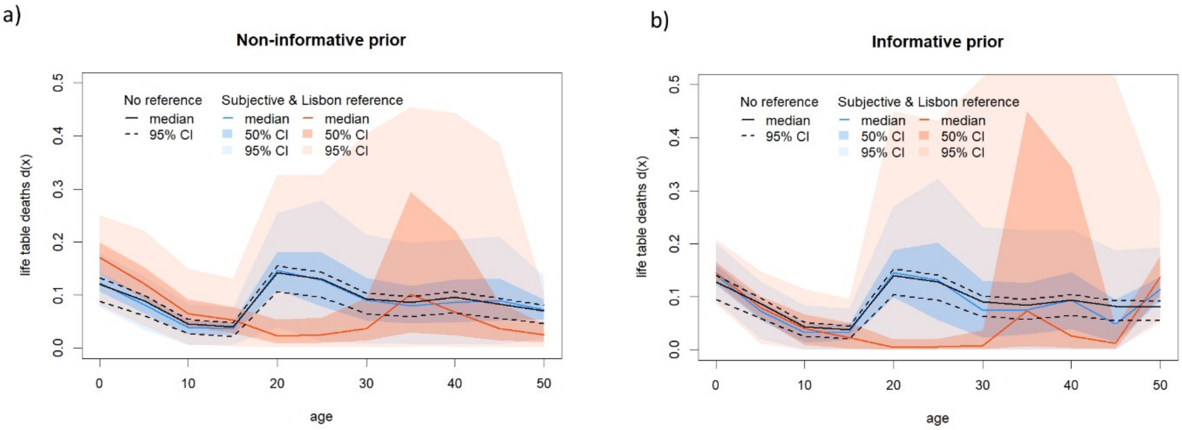


f) Stable e_x with correction, pre-industrial prior



Source: Own elaboration based on the sample material

Figure 5. Sensitivity analysis of the estimates of d_x for the full skeletal sample of Glinoe Scythians: Comparison of the hypothetical and Lisbon (Séguy & Buchet, 2013) reference populations, and none



Source: Own elaboration based on the sample material

■

“Paleodemographic analysis of age at death for a population of Black Sea Scythians: An exploration by using Bayesian methods”

Sylwia Łukasik, Jakub Bijak, Marta Krenz-Niedbała, Vitaly Sinika

Supporting Information

This document contains the following supporting information, supplementing the discussion and results presented in the article “Paleodemographic analysis of age at death for a population of Black Sea Scythians: An exploration by using Bayesian methods”:

- Figure S1: Detailed description of the features of the Glinoe Scythian sample
- Tables S1 – S4: Estimated values of ${}_5d_x$ for various subpopulations of Glinoe Scythians
- Tables S5 – S7: Sensitivity analysis of selected results for the Lisbon and no reference priors
- Tables S8 – S11: Additional Contextual information from comparative studies
- Boxes S1 – S2: R and stan code used in the estimation for the hypothetical reference population

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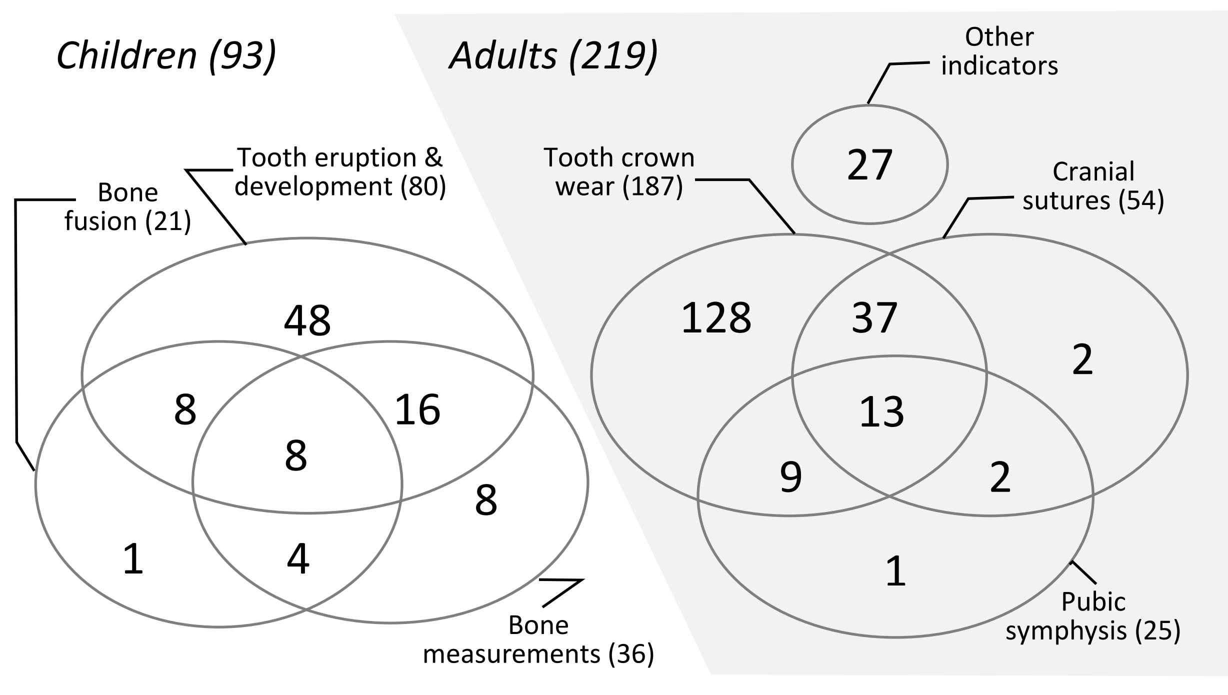

Figure S1. Methods of age assessment for the sample of 312 Glinoe Scythian skeletons
Source: Own elaboration

Table S1. Estimates of ${}_5d_x$ under different model specifications for Glinoe Scythian 'commoners' (*N*=258)

Model	Stationary population			Stationary with correction			Stable with correction		
Quantiles	2.5%	Median	95%	2.5%	Median	95%	2.5%	Median	95%
Non-informative prior									
${}_5d_0$ (x 1,000)	63.5	106.8	157.9	86.8	297.6	495.4	57.6	271.3	468.9
${}_5d_5$	7.3	39.4	83.7	13.1	106.2	253.1	9.3	96.1	237.8
${}_5d_{10}$	2.4	29.9	78.3	5.7	79.1	215.4	4.6	71.4	206.2
${}_5d_{15}$	7.7	42.9	87.3	4.4	24.7	63.9	4.4	26.3	66.8
${}_5d_{20}$	39.7	156.5	275.6	21.0	89.8	209.1	22.7	95.2	222.3
${}_5d_{25}$	13.0	139.7	303.4	7.8	81.2	221.9	8.6	85.9	229.7
${}_5d_{30}$	7.8	95.1	231.5	4.1	54.7	161.9	4.8	59.7	176.5
${}_5d_{35}$	5.9	78.3	203.3	3.5	44.9	142.6	4.0	49.5	155.7
${}_5d_{40}$	6.3	90.7	217.6	3.4	52.5	156.0	3.6	57.6	168.8
${}_5d_{45}$	7.8	103.8	238.0	4.2	59.2	166.8	5.0	66.9	186.7
${}_\omega d_{50}$	22.0	83.6	158.2	12.4	48.5	114.8	13.6	55.3	127.7
Pre-industrial prior (see Table 4)									
${}_5d_0$ (x 1,000)	80.3	125.6	181.6	100.3	358.9	586.4	69.5	327.0	555.4
${}_5d_5$	0.1	29.2	75.5	0.3	76.3	229.3	0.3	68.9	216.2
${}_5d_{10}$	0.0	15.0	76.0	0.0	39.5	202.4	0.0	36.1	192.2
${}_5d_{15}$	0.2	43.8	91.0	0.0	24.6	66.6	0.2	26.1	69.0
${}_5d_{20}$	1.2	151.6	292.8	1.5	85.6	220.3	1.1	91.5	232.9
${}_5d_{25}$	0.3	151.6	356.9	0.2	86.5	252.1	0.1	91.0	270.9
${}_5d_{30}$	0.0	72.7	244.3	0.0	41.6	168.0	0.0	45.5	179.7
${}_5d_{35}$	0.1	71.9	234.2	0.1	41.3	161.2	0.1	45.4	174.4
${}_5d_{40}$	0.2	97.1	242.4	0.1	54.5	170.8	0.2	61.0	187.5
${}_5d_{45}$	0.1	58.1	210.2	0.1	33.3	144.9	0.1	36.5	159.2
${}_\omega d_{50}$	69.4	131.9	221.3	34.0	76.6	163.6	39.0	86.5	182.5

Source: Own elaboration based on the skeletal material

Table S2. Estimates of ${}_5d_x$ under different model specifications for Glinoe Scythian 'nobles' (*N*=27)

Model	**Stationary population**			**Stationary with correction**			**Stable with correction**		
Quantiles	2.5%	Median	95%	2.5%	Median	95%	2.5%	Median	95%
Non-informative prior									
${}_5d_0$ (x 1,000)	0.7	21.9	111.9	2.0	58.5	286.5	1.5	50.6	270.0
${}_5d_5$	16.0	98.6	240.7	37.5	265.5	549.2	31.1	243.1	529.3
${}_5d_{10}$	2.6	47.8	173.0	6.4	126.2	413.0	4.8	114.7	400.8
${}_5d_{15}$	1.0	26.0	127.0	0.6	15.0	89.6	0.5	15.6	90.5
${}_5d_{20}$	12.8	125.3	332.8	7.4	73.2	248.1	7.0	75.9	259.5
${}_5d_{25}$	3.9	91.3	323.4	2.3	53.9	226.5	2.4	57.5	240.9
${}_5d_{30}$	4.7	112.4	359.8	3.2	65.0	246.4	3.6	70.1	260.5
${}_5d_{35}$	7.3	134.2	393.1	4.1	78.0	264.8	4.5	86.2	287.7
${}_5d_{40}$	3.6	89.7	320.3	2.6	53.4	205.5	2.7	58.3	225.5
${}_5d_{45}$	2.5	60.9	258.4	1.4	35.6	165.1	1.6	39.5	180.5
${}_\omega d_{50}$	1.3	34.5	171.9	0.8	20.4	108.0	0.9	22.9	121.7
Pre-industrial prior (see Table 4)									
${}_5d_0$ (x 1,000)	29.6	106.2	246.9	61.4	278.0	587.7	52.9	252.7	553.9
${}_5d_5$	0.4	74.8	221.1	2.1	194.0	484.8	2.1	179.7	461.1
${}_5d_{10}$	0.0	5.8	111.6	0.0	13.0	266.0	0.0	11.7	250.9
${}_5d_{15}$	0.0	2.2	69.7	0.0	1.2	43.2	0.0	1.3	43.9
${}_5d_{20}$	0.1	99.2	317.2	0.1	53.8	225.7	0.0	56.2	238.6
${}_5d_{25}$	0.0	52.6	329.0	0.0	28.2	214.1	0.0	30.4	223.9
${}_5d_{30}$	0.0	65.8	351.8	0.0	35.8	225.8	0.0	39.0	244.1
${}_5d_{35}$	0.1	106.3	392.6	0.1	58.6	248.9	0.1	63.0	269.7
${}_5d_{40}$	0.0	41.6	282.8	0.0	23.0	171.5	0.0	25.4	186.4
${}_5d_{45}$	0.0	20.2	204.6	0.0	11.0	120.7	0.0	12.7	133.6
${}_\omega d_{50}$	76.0	220.0	429.5	39.4	120.5	284.5	45.4	136.5	315.1

Source: Own elaboration based on the skeletal material

Table S3. Estimates of ${}_5d_x$ under different model specifications; Classical Scythian period (*N*=85)

Model	**Stationary population**			**Stationary with correction**			**Stable with correction**		
Quantiles	2.5%	Median	95%	2.5%	Median	95%	2.5%	Median	95%
Non-informative prior									
${}_5d_0$ (x 1,000)	183.2	284.2	401.4	138.2	376.6	569.6	101.7	347.0	547.4
${}_5d_5$	13.9	76.4	176.0	14.3	98.1	242.0	11.0	89.5	229.1
${}_5d_{10}$	4.1	48.6	136.1	4.5	61.7	183.2	3.8	56.8	173.5
${}_5d_{15}$	8.2	58.5	141.1	6.4	43.3	127.0	6.4	46.0	134.9
${}_5d_{20}$	2.9	54.6	177.9	2.0	39.7	158.2	2.2	42.0	168.7
${}_5d_{25}$	5.2	87.2	224.3	4.5	64.4	204.2	4.7	69.0	218.8
${}_5d_{30}$	2.6	58.3	206.4	1.9	42.9	175.7	2.1	47.4	192.7
${}_5d_{35}$	3.8	71.5	215.4	3.0	53.7	186.4	3.1	59.2	205.0
${}_5d_{40}$	2.1	49.5	186.0	1.4	36.4	158.1	1.7	40.6	172.0
${}_5d_{45}$	4.3	73.6	217.3	2.9	54.0	184.7	3.3	60.7	208.0
${}_\omega d_{50}$	4.4	53.2	162.7	3.5	39.7	136.4	3.7	45.7	156.3
Pre-industrial prior (see Table 4)									
${}_5d_0$ (x 1,000)	223.7	332.9	456.1	180.3	446.1	649.4	142.7	413.6	620.2
${}_5d_5$	0.6	57.1	158.4	0.7	71.4	216.9	0.4	66.0	204.1
${}_5d_{10}$	0.0	23.4	128.9	0.0	29.3	164.7	0.0	27.2	158.2
${}_5d_{15}$	0.0	52.8	139.6	0.1	37.8	125.2	0.0	39.5	130.6
${}_5d_{20}$	0.0	26.4	175.5	0.0	18.9	150.9	0.0	20.3	158.3
${}_5d_{25}$	0.1	93.9	238.3	0.1	65.8	216.4	0.1	71.4	230.6
${}_5d_{30}$	0.0	26.3	206.6	0.0	19.2	167.5	0.0	20.2	181.1
${}_5d_{35}$	0.0	42.5	201.7	0.0	31.6	171.1	0.0	34.0	186.7
${}_5d_{40}$	0.0	18.6	162.5	0.0	13.5	128.6	0.0	14.6	143.5
${}_5d_{45}$	0.1	32.9	174.6	0.0	23.5	142.9	0.0	26.6	162.0
${}_\omega d_{50}$	68.7	169.6	312.7	46.1	123.5	279.1	51.5	139.2	309.1

Source: Own elaboration based on the skeletal material

Table S4. Estimates of ${}_5d_x$ under different model specifications; Late Scythian period (N=*183*)

Model	Stationary population			Stationary with correction			Stable with correction		
Quantiles	2.5%	Median	95%	2.5%	Median	95%	2.5%	Median	95%
Non-informative prior									
${}_5d_0$ (x 1,000)	9.6	42.9	96.6	17.6	125.2	312.4	14.5	111.1	296.7
${}_5d_5$	36.4	87.7	148.9	52.4	258.9	482.4	46.5	238.6	461.1
${}_5d_{10}$	1.2	22.9	68.9	3.1	64.0	209.2	2.9	59.0	198.7
${}_5d_{15}$	5.2	35.8	81.0	2.7	21.1	59.3	3.2	22.0	61.3
${}_5d_{20}$	47.8	186.1	331.1	25.8	110.3	262.2	27.8	115.7	265.4
${}_5d_{25}$	6.5	133.2	351.9	4.0	78.4	250.1	3.9	83.2	264.9
${}_5d_{30}$	7.1	128.6	303.6	4.3	75.1	220.6	4.3	81.2	231.6
${}_5d_{35}$	3.5	82.4	258.2	2.1	49.0	182.4	2.0	52.5	194.8
${}_5d_{40}$	5.3	97.3	246.5	2.8	55.9	176.1	3.2	62.1	186.7
${}_5d_{45}$	4.0	80.8	230.7	2.6	48.8	164.2	2.7	53.5	176.9
${}_\omega d_{50}$	4.2	43.5	109.2	2.3	25.5	75.9	2.9	28.8	82.9
Pre-industrial prior (see Table 4)									
${}_5d_0$ (x 1,000)	31.1	72.5	133.2	47.5	214.8	451.6	35.6	193.4	418.5
${}_5d_5$	16.1	72.5	134.4	20.3	211.9	434.7	19.2	193.9	408.9
${}_5d_{10}$	0.0	6.3	61.1	0.0	17.8	173.4	0.0	15.9	164.8
${}_5d_{15}$	0.1	33.8	79.9	0.1	19.5	59.0	0.1	20.5	60.3
${}_5d_{20}$	4.0	190.9	364.0	0.9	107.7	276.3	0.4	115.7	288.0
${}_5d_{25}$	0.0	115.5	410.7	0.0	69.4	299.6	0.0	70.5	310.8
${}_5d_{30}$	0.0	107.2	332.6	0.0	61.0	237.5	0.0	68.0	251.6
${}_5d_{35}$	0.0	58.9	298.8	0.0	34.4	207.0	0.0	37.5	223.9
${}_5d_{40}$	0.1	110.1	271.6	0.1	62.8	195.6	0.1	69.2	212.1
${}_5d_{45}$	0.1	29.7	202.4	0.0	17.8	132.3	0.0	19.6	145.0
${}_\omega d_{50}$	42.7	97.1	182.2	22.2	57.7	133.2	25.1	64.7	148.9

Source: Own elaboration based on the skeletal material

Table S5. Original Lisbon reference populations from Séguy and Buchet (2013), unscaled

	Children: tooth mineralisation stages (contingency table for teeth 11-18)								Adults: Suture closure coefficient (x10) stages		
Age \ stage	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**0 – 04**	**5 – 13**	**14 – 40**
0-5	180	170	0	0	0	0	0	0	0	0	0
5-10	0	33	29	62	20	0	0	0	0	0	0
10-15	0	0	0	2	35	39	15	0	0	0	0
15-20	0	0	0	0	0	13	54	8	11.2	1.7	1.7
20-25	0	0	0	0	0	0	0	0	34.1	10.0	4.2
25-30	0	0	0	0	0	0	0	0	28.5	10.2	12.8
30-35	0	0	0	0	0	0	0	0	22.1	13.6	17.0
35-40	0	0	0	0	0	0	0	0	17.2	21.2	17.6
40-45	0	0	0	0	0	0	0	0	17.0	21.3	22.0
45-50	0	0	0	0	0	0	0	0	18.1	17.5	30.0
50+	0	0	0	0	0	0	0	0	62.9	126.5	503.7
% structure	***27%***	***31%***	***4%***	***10%***	***8%***	***8%***	***10%***	***1%***	***20%***	***21%***	***58%***
Glinoe sample	13	25	7	8	5	8	10	0	3	43	8
% structure	***17%***	***33%***	***9%***	***11%***	***7%***	***11%***	***13%***	***0%***	***6%***	***80%***	***15%***

Source: Séguy and Buchet (2013): Table 4.2, p66 (adults) and Table 4.7, p78 (children)

Table S6. Sensitivity analysis: Stationary population estimates of ${}_5d_x$ for the Glinoe population; Lisbon reference population (Séguy & Buchet, 2013: Chapter 4)

Reference	**Rescaled with original age distribution**						**Rescaled with uniform age distribution**					
Model	Non-informative prior			Pre-industrial prior			Non-informative prior			Pre-industrial prior		
Quantiles	2.5%	Median	95%	2.5%	Median	95%	2.5%	Median	95%	2.5%	Median	95%
${}_5d_0$ (x 1,000)	80.2	170.6	250.4	86.5	145.2	207.3	75.5	154.8	230.7	115.3	188.3	270.4
${}_5d_5$	42.2	120.9	220.9	11.4	79.4	148.1	40.2	101.5	193.7	10.0	89.2	172.1
${}_5d_{10}$	6.4	64.4	149.2	0.0	39.5	114.2	7.3	56.0	124.6	0.0	49.6	129.5
${}_5d_{15}$	2.9	52.1	131.0	0.0	22.9	95.6	3.0	42.9	104.9	0.0	25.1	103.2
${}_5d_{20}$	0.7	23.0	327.7	0.0	4.1	449.9	0.7	17.8	113.2	0.0	3.1	62.7
${}_5d_{25}$	0.9	25.0	326.6	0.0	4.8	433.0	0.7	19.8	138.5	0.0	3.6	67.7
${}_5d_{30}$	1.2	36.4	404.3	0.0	7.5	513.6	0.9	26.5	319.7	0.0	4.3	82.7
${}_5d_{35}$	2.3	101.4	454.0	0.0	72.9	570.1	2.5	166.0	531.0	0.0	7.3	157.9
${}_5d_{40}$	1.9	67.6	442.8	0.0	26.0	557.8	2.1	87.2	524.2	0.0	7.4	141.4
${}_5d_{45}$	1.2	36.7	386.9	0.0	11.7	513.3	1.1	34.3	451.0	0.0	7.4	104.3
${}_\omega d_{50}$	1.0	24.3	103.4	51.8	137.6	280.8	1.0	29.0	212.4	282.2	552.4	620.7

Note: For the estimation, the Lisbon reference population from Table S5 was rescaled to match the sample size (in this case *N*=130), including the broad age classification (54 adults and 76 subadults). In the latter two models, the age distribution of the reference sample was additionally made uniform.
Source: Own elaboration based on the skeletal material

Table S7. Sensitivity analysis: Stationary population estimates of ${}_5d_x$ for the Glinoe population; no reference population (see Łukasik et al. 2017)

Model	Non-informative prior			Pre-industrial prior		
Quantiles	2.5%	Median	95%	2.5%	Median	95%
${}_5d_0$ (x 1,000)	87.9	119.9	158.2	94.5	127.7	167.1
${}_5d_5$	61.2	89.0	123.3	59.3	87.0	121.4
${}_5d_{10}$	26.3	45.5	71.7	24.2	43.1	69.2
${}_5d_{15}$	21.7	39.3	64.2	19.9	37.1	61.4
${}_5d_{20}$	106.6	141.5	182.0	104.6	139.6	180.0
${}_5d_{25}$	95.8	129.4	168.8	93.8	127.2	166.3
${}_5d_{30}$	63.9	91.9	126.6	61.9	89.9	124.7
${}_5d_{35}$	58.6	85.9	119.5	56.9	83.9	117.4
${}_5d_{40}$	66.4	95.1	130.7	64.8	93.3	128.6
${}_5d_{45}$	56.0	82.7	116.3	54.5	81.3	114.6
${}_\omega d_{50}$	45.9	70.3	101.9	54.4	80.7	113.8

Source: Own elaboration based on the skeletal material

Table S8. Life expectancies (in years) at birth (e_0), and in early adulthood, (e_{20}) from Early Iron Age populations (stationary population model, without correction of the number of children)

Site and dating	e_0	e_{20}	Data source
Glinoe sites, Moldova (5th-2nd c. BCE)	27.7	16.4	Authors' calculations
Pontecagnano, Compania, Italy (7th-6th c. BCE)	15.3	n.a.	Lombardi Pardini, Polosa, and Pardini (1984)
Classic period (Athens & Corinth), Italy (6th-3rd c. BCE)	24.7	n.a.	Angel (1969)
Pantanello, Greek colony (7th-2nd c. BCE)	21.2	20.6	Henneberg and Henneberg (2000)
Mamai-gora, Ukraine (3rd-2nd c. BCE)	26.9	15.8	Litvinova (2004)
Osteria dell'osa, Italy (9th-7th c. BCE)	32.5	23.2	Macchiarelli and Salvadei (1994)
Marvele, Lithuania (2nd-3rd c. CE)	27.2	16.8	Jankauskas and Urbanavičius (1997)
S'Illot des Porros, Spain (4th c. BCE-2nd c. CE)	28.5	17.5	Alesan, Malgosa, and Simo (1999)

Note: n.a. – not available from the particular source

Table S9. Comparative data for linear enamel hypoplasia (only adult individuals).

Site and dating	N	%	Reference
Smörkullen, Sweden (1st-3rd c. CE)	85	16.5	Liebe-Harkort (2012)
Apollonia, Bulgaria (5th-2nd c. BCE)	122	25.4	Keenleyside (2008)
Szirakwan, Armenia (9th-6th c. BCE)	n.a.	23.6	Khudaverdyan, Yengibaryan, Vardanyan, Karalyan, and Matevosyan (2014)
Glinoe sites, Moldova (5th-2nd c. BCE)	120	30.8	This study
Sipina, Italy (6th-3rd c. BCE)	80	31.2	Masotti, Onisto, Marzi, and Gualdi-Russo (2013)
Casalecchio di Reno, Italy (4th-3rd c. BCE)	94	31.3	after Masotti et al. (2013)
Rogowo, Poland (2nd c CE)	52	38.5	Krenz-Niedbała and Kozlowski (2013)
Rimini, Italy (1st-4th c. CE)	28	57.1	Facchini, Rastelli, and Brasili (2004)
Lori Berd I, Armenia (6th-5th c. BCE)	n.a.	57.2	Khudaverdyan et al. (2014)
Different site, Croatia (3rd-4th c. CE)	161	65.8	Šlaus (2008)
Balone, Italy (5th c. BCE)	124	83.3	after Masotti et al. (2013)
Lucus Feroniae, Italy (1st-3rd c. CE)	50	82.0	Manzi, Salvadei, Vienna, and Passarello (1999)
Isola Sacra, Italy (1st-3rd c. CE)	58	81.0	Manzi et al. (1999)
Ravenna area, Italy (1st-4rd c. CE)	25	84.0	Facchini et al. (2004)
Vallerano, Italy (2nd-3rd c. CE)	77	92.9	Cucina et al. (2006)
Urbino, Italy (1st-3rd c. CE)	35	100.0	Paine, Vargiu, Signoretti, and Coppa (2009)
Ferrone, Italy (7th-6th c. BCE)	64	100.0	after Masotti et al. (2013)

Note: n.a. – not available from the particular source

Table S10. Comparative data for cribra orbitalia

Site and dating	Adults			All individuals			Reference
	N	n	%	N	n	%	
Glinoe sites, Moldova (5th-2nd c. BCE)	50	7	14.0	75	20	26.7	This study
Zadar, Croatia (1st c. BCE)	97	10	10.2	129	26	20.1	Novak and Šlaus (2010)
Appolonia, Bługaria (5th-3rd c. BCE)	114	13	22.1	n.a.	n.a.	28.0	Keenleyside and Panayotova (2006)
Sipina, Italy (7th-3rd c. BCE)	13	15	23.2	56	59	25.4	Manzon and Gualdi-Russo (2016)
Smörkullen, Sweden (1st-3rd c. CE)	82	30	36.6	n.a.	n.a.	n.a.	Liebe-Harkort (2012)
Szirakwan, Armenia (9th-6th c. BCE)	n.a.	n.a.	42.9	n.a.	n.a.	n.a.	Khudaverdyan et al. (2014)
Lori Berd I, Armenia (6th-5th c. BCE)	n.a.	n.a.	42.5	n.a.	n.a.	n.a.	Khudaverdyan et al. (2014)
Ravenna area, Italy (1st-4th c. CE)	27	16	59.3	35	21	60.0	Facchini et al. (2004)

Note: n.a. – not available from the particular source

Table S11. Comparative data for porotic hyperostosis

Site and dating	Adults			All individuals			Reference
	N	n	%	N	n	%	
Glinoe sites, Moldova (5th-2nd c. BCE)	37	0	0.0	68	1	1.5	This study
Lori Berd I, Armenia (6th-5th c. BCE)	n.a.	n.a.	12.5	n.a.	n.a.	n.a.	Khudaverdyan, Devedzhyan, and Yeganyan (2013)
Spina, Italy (6th-3rd c. BCE)	28	145	19.3	28	185	15.1	Manzon and Gualdi-Russo (2016)
Szirakwan, Armenia (9th-8th c. BCE)	n.a.	n.a.	23.9	n.a.	n.a.	n.a.	Khudaverdyan et al. (2013)
Rimini, Italy (1st-4th c. CE)	22	6	31.0	29	9	13.3	Facchini et al. (2004)
Ravenna area, Italy (1st-4th c. CE)	18	10	47.8	23	11	55.6	Facchini et al. (2004)

Note: n.a. – not available from the particular source

Box 1. R code for executing the Bayesian models with elicited

```
#########################################################################
# Model for estimating age for the Glinoe Scythian skeletons in Stan  #
#     Notation follows Caussinus and Courgeau (2010), pp. 124-127     #
#           Version with informative (pre-industrial) prior           #
#########################################################################

library(rstan)

### Inits and data ###

ages <- 11
stages <- 31
pah <- matrix(rep(0,30),nrow=15,ncol=2)

counts <- matrix(rep(0, 15*stages), nrow=15, ncol=stages)
filenames <-
c("basic_all","basic_commoners","basic_nobles","basic_stage1","basic_stage2","child
ren_all","children_commoners","children_nobles","children_stage1","children_stage2"
,"stable_all","stable_commoners","stable_nobles","stable_stage1","stable_stage2")

### Informative pre-industrial prior, from Seguy and Buchet (2013, p. 147) ###

infoprior <- c(3.509, 0.385, 0.209, 0.264, 0.319, 0.341, 0.352, 0.385, 0.407, 0.451,
4.378)

# Whole sample
counts[1,] = counts[6,] = counts[11,] = c(24, 2, 1, 10, 14, 6, 1, 8, 1, 1, 5, 5, 2,
4, 7, 2, 19, 34, 18, 34, 2, 26, 1, 1, 3, 16, 21, 1, 26, 2, 15)

# Commoners
counts[2,] = counts[7,] = counts[12,] = c(19, 1, 0, 5, 7, 3, 0, 4, 1, 0, 2, 5, 2, 4,
7, 1, 17, 31, 17, 27, 2, 23, 1, 1, 3, 13, 19, 1, 25, 2, 15)

# Nobles
counts[3,] = counts[8,] = counts[13,] = c(0, 0, 1, 0, 0, 1, 1, 2, 0, 0, 1, 0, 0, 0,
0, 0, 2, 2, 1, 7, 0, 3, 0, 0, 0, 3, 2, 0, 1, 0, 0)

# Cemetery stage 1
counts[4,] = counts[9,] = counts[14,] = c(18, 1, 0, 3, 4, 3, 0, 2, 1, 0, 1, 2, 1, 1,
3, 1, 1, 6, 4, 10, 2, 1, 1, 1, 3, 0, 5, 1, 4, 2, 2)

# Cemetery stage 2
counts[5,] = counts[10,] = counts[15,] = c(4, 1, 1, 6, 7, 2, 1, 5, 0, 0, 2, 2, 1, 2,
4, 1, 15, 23, 13, 23, 0, 22, 0, 0, 0, 13, 15, 0, 14, 0, 6)

Ref <- as.matrix(read.table("Reference.txt"), nrow=ages, ncol=stages, byrow=TRUE)
alpha <- matrix(rep(0, ages*stages), nrow=ages, ncol=stages)
alpha[,] <- Ref[,] + 0.1

for (iter in 1:15) {

# Non-informative Dirichlet prior
#  Scythian_data  <-  list(I  =  stages,  J  =  ages,  N  =  sum(counts[iter,]),  m  =
counts[iter,], pa = c(rep(1, ages)), pcsa=alpha)

# Informative Dirichlet prior
Scythian_data <- list(I = stages, J = ages, N = sum(counts[iter,]), m = counts[iter,],
pa = infoprior, pcsa=alpha)

# Initial values to aid convergence for the stable population model
myinits <- function() {
```

```
  list(Uc = 6, R = 0.002, R0 = 1.06, a50 = 5) }
### Model runs ###

if (iter <= 5) {
  fit <- stan(file = 'Scythians_basic.stan', data = Scythian_data, iter = 11000,
warmup = 1000, chains = 4)}

if ((iter > 5) & (iter<=10)) {
  fit <- stan(file = 'Scythians_children.stan', data = Scythian_data, iter = 11000,
warmup = 1000, chains = 4)}

if (iter > 10) {
  fit <- stan(file = 'Scythians_stable_corr.stan', data = Scythian_data, init =
myinits, iter = 11000, warmup = 1000, chains = 4)}

print(get_elapsed_time(fit))

posterior <- extract(fit)

# Probabilities of the accident hump: [1] P(5d25 > 5d30) and [2] P(10d20 > 10d30)

pah[iter,1] <- length(which(posterior$ah[,1]>0))/length(posterior$ah[,1])
pah[iter,2] <- length(which(posterior$ah[,2]>0))/length(posterior$ah[,2])

### Outputs - Life expectancy by age group ###

fname <- paste("Scythians_",filenames[iter],"_inf.csv", sep="")

if (iter <= 5) {
  output <- summary(fit, pars= c("page","lx","dx","ex","ah"), digits = 3) }

if ((iter > 5) & (iter<=10)) {
  output <- summary(fit, pars= c("page","lx","dx","ex","Rpot","Im", "Ibs","ah"),
digits = 3) }

if (iter > 10) {
  output <- summary(fit, pars= c("page","lx","dx","ex","Rpot","Im", "Ibs", "R","ah"),
digits = 3) }

write.csv(output$summary, file=fname)

### Some diagnostic checks: probabilities by age ###

stan_trace(fit, pars= "page") # Trace plots
stan_ac(fit, pars= "page") # Autocorrelations
stan_diag(fit) # Hamiltonian MC diagnostics

}

write.csv(pah, file="Scythians_inf_accident_hump.csv")
```

Notes: The routine requires Rstan – please refer to https://mc-stan.org/ for details on installation and execution. The current application was run in R version 3.6.2, with RStudio 1.2.5033 and RStan 2.19.2. The reference population needs to be saved in the same folder, as a tab-delimited file 'Reference.txt', with rows corresponding to age groups and columns to stages; so, in our case, 11 rows and 31 columns (the main version). The three files with the stan code (see Box 2) also need to be stored in the same folder. The code for sensitivity analysis is a simplified version of the one listed here, and can be obtained from the authors upon request: please email Jakub Bijak on J.Bijak@soton.ac.uk.

Box 2. Stan code for the Bayesian calculations, to be called from within R (see Box 1)

a) Basic version, stationary population (Scythians_basic.stan)

```
data {
  int<lower=0> I; // number of stages
  int<lower=0> J; // number of age groups
  int<lower=0> N; // number of observations
  vector<lower=0>[J] pa; // prior Dirichlet pseudocounts for age groups
  vector<lower=0>[I] pcsa[J]; // prior Dirichlet pseudocounts for stage given age
  int<lower=0> m[I]; // data by stage
}

parameters {
  simplex[J] page; // probabilities for age groups
  simplex[I] pcstage[J]; // conditional probabilities for stages given age
  real<lower=0> a50; // Average number of years lived 50+
}

transformed parameters {
  vector<lower=0>[I] pstage; // probabilities by stage
  matrix<lower=0>[I, J] temp;

// Life table quantities
  vector<lower=0>[J] lx; // l(x)
  vector<lower=0>[J] dx; // d(x)
  vector<lower=0>[J] llx; // L(x)
  vector<lower=0>[J] ttx; // T(x)
  vector<lower=0>[J] ex; // e(x)
  vector[2] ah; // accident hump effects

  for (i in 1:I)
    for (j in 1:J)
     temp[i,j] = page[j]*pcstage[j,i];

  for (i in 1:I)
     pstage[i] = sum(temp[i]);

// Life table calculations
  for (j in 1:J)
     dx[j] = page[j];

  lx[1] = sum(dx);

  for (j in 2:J)
    lx[j] = lx[j-1] - dx[j-1];

// Life tables, alpha[1] = 0.1
  llx[1] = 5 * lx[2] + 0.1 * dx[1];

  for (j in 2:J-1)
     llx[j] = (lx[j] + lx[j+1]) * 2.5;

  llx[J] = lx[J] * a50;

  ttx[1] = sum(llx);

  for (j in 2:J)
     ttx[j] = ttx[j-1] - llx[j-1];

  for (j in 1:J)
     ex[j] = ttx[j]/lx[j];
```

```
  ah[1] = dx[6] - dx[7];
  ah[2] = dx[5] + dx[6] - dx[7] - dx[8];
}

model {

// Model estimation phase
for (j in 1:J)
   pcstage[j] ~ dirichlet(pcsa[j]);

page ~ dirichlet(pa);
m ~ multinomial(pstage);

// Auxiliary sampling for life tables
a50 ~ gamma(5,1);
}
```

b) Stationary population with correction for the number of children (Scythians_children.stan)

```
data {
  int<lower=0> I; // number of stages
  int<lower=0> J; // number of age groups
  int<lower=0> N; // number of observations
  vector<lower=0>[J] pa; // prior Dirichlet pseudocounts for age groups
  vector<lower=0>[I] pcsa[J]; // prior Dirichlet pseudocounts for stage given age
  int<lower=0> m[I]; // data by stage
}

parameters {
  simplex[J] page; // probabilities for age groups
  simplex[I] pcstage[J]; // conditional probabilities for stages given age
  real<lower=0> a50; // Average number of years lived 50+, assumed
  real<lower=0> Uc; // The average lifetime number of children, ditto
}

transformed parameters {
  vector<lower=0>[I] pstage; // probabilities by stage
  matrix<lower=0>[I, J] temp; // auxiliary variable
  real<lower=0> mult; // multipier for the children
  real Rpot; // Rpot from Henneberg and Piontek (1975)
  real Ibs; // Ibs from Henneberg and Piontek (1975)
  real Im; // Crow's (1958) index, on corrected data
  vector[2] ah; // accident hump effects

// Life table quantities
  vector<lower=0>[J] lx; // l(x)
  vector<lower=0>[J] dx; // d(x)
  vector<lower=0>[J] llx; // L(x)
  vector<lower=0>[J] ttx; // T(x)
  vector<lower=0>[J] ex; // e(x)

  for (i in 1:I)
    for (j in 1:J)
      temp[i,j] = page[j]*pcstage[j,i];

  for (i in 1:I)
      pstage[i] = sum(temp[i]);

// Henneberg and Piontek's (1975: 194-6) Ibs and Rpot, computed on raw data
Rpot = 1 - (0.95 * page[4] + 0.75 * page[5] + 0.55 * page[6] + 0.35 * page[7] + 0.17
* page[8] + 0.05 * page[9]);
Ibs = Rpot - sum(page[1:3]);
```

```
// Multiplier for the number of 0-15 year olds
mult = 1 - 2/(Rpot * Uc);

// Life table calculations, with correction, rescaled to a radix of l[1]=1
  for (j in 1:3)
     dx[j] = page[j] * mult / sum(page[1:3]);

  for (j in 4:J)
     dx[j] = page[j] * (1 - mult) / sum(page[4:J]);

  lx[1] = sum(dx);

  for (j in 2:J)
    lx[j] = lx[j-1] - dx[j-1];

// Life tables, alpha[1] = 0.1
  llx[1] = 5 * lx[2] + 0.1 * dx[1];

  for (j in 2:J-1)
     llx[j] = (lx[j] + lx[j+1]) * 2.5;

  llx[J] = lx[J] * a50;

  ttx[1] = sum(llx);

  for (j in 2:J)
     ttx[j] = ttx[j-1] - llx[j-1];

  for (j in 1:J)
     ex[j] = ttx[j]/lx[j];

// Crow's (1958) index, computed on corrected data
  Im = sum(dx[1:3])/lx[4];

  ah[1] = dx[6] - dx[7];
  ah[2] = dx[5] + dx[6] - dx[7] - dx[8];
}

model {

// Model estimation phase
for (j in 1:J)
   pcstage[j] ~ dirichlet(pcsa[j]);

page ~ dirichlet(pa);
m ~ multinomial(pstage);

// Sampling for the auxiliary parameters
a50 ~ gamma(5,1);
Uc ~ gamma(12,2);
}
```

c) Stable population with correction for the number of children (Scythians_stable_corr.stan)

```
data {
  int<lower=0> I; // number of stages
  int<lower=0> J; // number of age groups
  int<lower=0> N; // number of observations
  vector<lower=0>[J] pa; // prior Dirichlet pseudocounts for age groups
  vector<lower=0>[I] pcsa[J]; // prior Dirichlet pseudocounts for stage given age
  int<lower=0> m[I]; // data by stage
}
```

```
parameters {
  simplex[J] page; // probabilities for age groups
  simplex[I] pcstage[J]; // conditional probabilities for stages given age
  real<lower=0> a50; // Average number of years lived 50+, assumed
  real<lower=0> Uc; // The average lifetime number of children, ditto
  real R; // The growth rate of the population, ditto
  real<lower=0> R0; // Net reproduction rate
}

transformed parameters {
  vector<lower=0>[I] pstage; // probabilities by stage
  matrix<lower=0>[I, J] temp; // auxiliary variable
  real<lower=0> mult; // multipier for the children
  real Rpot; // Rpot from Henneberg and Piontek (1975)
  real Ibs; // Ibs from Henneberg and Piontek (1975)
  real Im; // Crow's (1958) index, on corrected data
  vector[2] ah; // accident hump effects

// Life table quantities
  vector<lower=0>[J] lx; // l(x)
  vector<lower=0>[J] stdx; // stable d(x), as observed from page
  vector<lower=0>[J] audx; // auxiliary d(x), stationary equivalent
  vector<lower=0>[J] dx; // life table d(x), assuming radix l[1]=1
  vector<lower=0>[J] llx; // L(x)
  vector<lower=0>[J] ttx; // T(x)
  vector<lower=0>[J] ex; // e(x)

  for (i in 1:I)
    for (j in 1:J)
      temp[i,j] = page[j]*pcstage[j,i];

  for (i in 1:I)
      pstage[i] = sum(temp[i]);

// Henneberg and Piontek's (1975: 194-6) Ibs and Rpot, computed on raw data
Rpot = 1 - (0.95 * page[4] + 0.75 * page[5] + 0.55 * page[6] + 0.35 * page[7] + 0.17
* page[8] + 0.05 * page[9]);
Ibs = Rpot - sum(page[1:3]);

// Multiplier for the number of 0-15 year olds
mult = 1 - 2*R0/(Rpot * Uc);

// Correction of dx for the undercount of children
  for (j in 1:3)
      stdx[j] = page[j] * mult / sum(page[1:3]);

  for (j in 4:J)
      stdx[j] = page[j] * (1 - mult) / sum(page[4:J]);

// Stationary equivalent dx for different growth rates R (Chamberlain 2009:31)
  for (j in 1:J)
    audx[j] = stdx[j] * (1 + R)^((j-1)*5);

  for (j in 1:J)
    dx[j] = audx[j]/sum(audx);

// Life table calculations, with radix of l[1]=1
  lx[1] = sum(dx);

  for (j in 2:J)
    lx[j] = lx[j-1] - dx[j-1];
```

```
// Life tables, alpha[1] = 0.1

  llx[1] = 5 * lx[2] + 0.1 * dx[1];

  for (j in 2:J-1)
     llx[j] = (lx[j] + lx[j+1]) * 2.5;

  llx[J] = lx[J] * a50;

  ttx[1] = sum(llx);

  for (j in 2:J)
     ttx[j] = ttx[j-1] - llx[j-1];

  for (j in 1:J)
     ex[j] = ttx[j]/lx[j];

// Crow's (1958) index, computed on corrected data
  Im = sum(dx[1:3])/lx[4];

  ah[1] = dx[6] - dx[7];
  ah[2] = dx[5] + dx[6] - dx[7] - dx[8];
}

model {

// Model estimation phase
for (j in 1:J)
   pcstage[j] ~ dirichlet(pcsa[j]);

page ~ dirichlet(pa);
m ~ multinomial(pstage);

// Sampling for the auxiliary parameters
a50 ~ gamma(5,1);
Uc ~ gamma(12,2);
R ~ normal(0.002,0.001);
R0 ~ normal(1.06,0.02);
}
```

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