Comparing Archaeological Proxies for Long-term Population Patterns: An Example from Central Italy

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Abstract
Raw counts of archaeological sites, estimates of changing settlement size and summed radiocarbon probability distributions have all become popular ways to investigate long-term regional trends in human population. Nevertheless, these three archaeological proxies have rarely been compared. This paper therefore explores the strengths and weaknesses of different kinds of archaeological evidence for population patterns, as well as how they address related issues such as taphonomic loss, chronological uncertainty and uneven sampling. Our overall substantive goal is to reconstruct demographic fluctuations in central Italy from the Late Mesolithic to the fall of the Roman Empire (7500 BC-AD 500), and with this in mind, we bring to bear an unusually detailed and extensive dataset of published central Italian archaeological surveys, consisting of some 10,971 occupation phases at 7,383 different sites. The comparative results demonstrate reassuring consistency in the suggested demographic patterns, and where such patterns diverge across different proxies (e.g. Late Bronze Age/Iron Age) they often do so in useful ways that suggest changes in population structure such as site nucleation or dispersal.

Keywords
demography, summed probability distributions, radiocarbon, aoristic methods, Mediterranean, archaeological survey, settlement patterns

1. Introduction
Over the past decade or so, there has been renewed archaeological interest in demographic reconstruction, in close step with other trends, such as the growing popularity of both cultural evolutionary and human ecological frameworks. The role of population size as a driver of cultural change was perhaps first emphasised by social anthropologists (Naroll 1956, Carneiro 1962) and then adopted by archaeologists to explain long-term variation in subsistence-settlement systems (Binford 1968; Sanders and Price 1968; Shennan 2000, 2001) or shifts in sociopolitical complexity (Feinman and Neitzel 1984; Feinman 2011). More recent studies, in Europe for example, have stressed the upward-impact of Neolithic economies on local population densities (Shennan and Edinborough 2007; Shennan 2009; Shennan et al. 2013) from the often-lower population levels present when hunter-gatherers were active in the same region. Such discussions also feed into ongoing debate about whether agricultural innovation and intensification typically develops in response to population growth or vice versa (Boserup 1965; Cohen 1977; Netting 1993; Peregrine 2004), while a range of separate research continues to emphasise how population growth in a given landscape has typically run in step with increasingly substantial cultural modifications, often in a clearly coupled human demographic-ecological system (see Butlin and Roberts 1995; Allen 2001; Mercuri et al. 2002; Fyfe et al. 2010; Walsh 2013; Langutt et al. 2016; Wigand and McCallum 2017).

With this wider background in mind, it is clear that successful characterisation of human population fluctuations over the *longue durée* (and assessment of the causes of these fluctuations) is pivotal for how we understand cultural and environmental change. While genetic (both modern and ancient) or palaeodemographic (osteological) estimates of changing population size are also important (e.g. Bocquet-Appel 2002, Cassidy et al. 2015), the most popular archaeological proxies for investigating regional demographies over the long-run have been data on counts of archaeological sites, sometimes with accompanying estimates of changing settlement size, and the summed probability distributions of radiocarbon dates (hereafter SPD). The first two have a longer archaeological pedigree in being used to estimate population across many different regional contexts (Sanders 1965; Adams 1965 and 1981; Wright and Johnson 1975; Sanders et al. 1979). More recently, over the past two decades, SPDs of archaeological (i.e. anthropogenic) radiocarbon dates have also become popular especially for inferring population in prehistoric periods (Rick 1987; Shennan and and Edinborough 2007; Bocquet-Appel et al. 2009; Shennan et al. 2013; Downey et al. 2014; Timpson et al. 2014; Balsera et al. 2015; Crema et al. 2016) and for assessing demographic responses to climate change (Weninger et al. 2009; Williams et al. 2010; Maher et al. 2011; Woodbridge et al. 2014; Flohr et al. 2016). Nevertheless, these proxies are rarely compared directly. Building on previous work (e.g. Tallavaara et al. 2010; French 2015; French and Collins 2015; Demjan and Dreslerová 2016), we advocate greater use of multiple lines of demographic evidence and here present a comparison of radiocarbon SPDs and various modelled treatments of settlement counts and sizes for central Italy from the Late Mesolithic (7500 BC) to the fall of the Roman Empire (AD 500).

Estimating past population has generally been considered a problematic goal by most archaeologists, but the past couple of decades has seen a slow resurgence of interest in reconstructing demographic variables. Population estimates build on the assumption that an observable density of archaeological evidence over time and across a study region is somehow proportional to population despite the presence of certain archaeological biases (Drennan et al. 2015, 11). Put simply, the bigger the population, the stronger the signal in the archaeological record (e.g. the higher the density of pottery sherds, stone tools, site counts, radiocarbon dates, etc.). Hence, the first step in modelling population dynamics over the long-term is to identify those archaeological materials that might provide the most reliable indirect measures of population, and exclude those more strongly affected by other factors. Furthermore, it is usually assumed that such indicators do not offer good evidence for *absolute* numbers of people in the past, but rather offer an idea of *relative* intensities of population and proportional change through time (Tallavaara et al. 2010, 252; Drennan et al. 2015, 12). In this work, we use three types of archaeological data as proxies for estimating population fluctuations over the long run: 1) Settlement data including site counts; 2) summed estimated settlement sizes, effectively a weighted version of site counts; and 3) SPDs of radiocarbon dates. Two main potential issues common to three lines of evidence relate to the presence of both research and taphonomic biases, which can negatively affect the density and visibility of the archaeological signal known in a given region. For example, all archaeological periods are not necessarily equally represented in either settlement data or radiocarbon date lists, due to a series of factors: 1) the research priorities of different archaeological excavations and surveys resulting in specific periods being better investigated than others; 2) variation in the field methods adopted; and 3) the enhanced visibility of particular diagnostic artefacts that are easier to detect and collect. In addition, the archaeological record has been shaped by a wide variety of natural and cultural taphonomic processes (e.g. agriculture, erosion, alluviation, post-depositional deposits, human and animal excavations, wind deflation, etc.; cf. Roper 1976, 372; Hirth 1978, 125; Ammerman 1985, 33; Gregg et al. 1991; Brantingham et al. 2007). Several studies have argued that a broad gradient exists in which there is increasing taphonomic loss with increasing time depth, or put another way, a higher level of destruction of earlier archaeological deposits (Surovell and Brantingham 2007; Surovell et al. 2009), leaving them underrepresented when compared with the more recent deposits.

Turning more specifically to settlement evidence, a “site count” approach to population inference is typically based on the assumption that the overall number of sites is representative of population across space and time, but such counts can of course be biased by the intensity of archaeological surveys carried out in a given region (Plog et al. 1978; Cherry 1983), by the ease with which a given site type can be observed and discovered archaeologically, etc. In addition, it is sometimes difficult to distinguish settlements from other kinds of site (e.g. cemeteries, specialized ritual sites, temporary agricultural or hunting installations), and, even if we can do so, to decide what kinds of site should be part of the counting exercise. A further issue is is that we struggle to date the creation, duration and abandonment of sites and, without the support of stratigraphic data and/or calibrated radiocarbon dates, a given site’s profile of occupational intensity through time can be only established by rough assessment of the stylistic chronologies of artefacts recovered from it. We are similarly left uncertain about the relative permanence vs seasonality of site use or about whether there is exact contemporaneity among multiple sites across a wider landscape. The spatial structure and size hierarchies of settlement sites are a further key variable that is often poorly understood. For example, a simple site count rarely does justice to changing population levels where a settlement system exhibits a move towards growing concentration of people in a few larger centres and we have to be able to observe large, contiguous spatial regions of settlement to understand how such a nucleation process plays out. Paying attention to estimates (from survey and excavation) of site size is therefore a useful addition to site counts, and typically rests on the assumption that the number of inhabitants is somehow proportional to the area of a settlement. Nonetheless, this correlation is neither likely to scale in a linear way (e.g. larger cities are often also more densely packed, albeit with less inhabited, functionally specialist zones as well) nor to be universally consistent across different regions of the world (Drennan et al. 2015, 20-25).

Turning to radiocarbon dates, large lists of archaeological radiocarbon dates can be calibrated and counted up (summed in the manner of a histogram) as a proxy for population, based on the assumption that the more people living in a given region, the more the archaeological deposits, the more organic materials, and the more radiocarbon samples collected and dated (Rick 1987). Although this approach has been widely used by archaeologists for estimating population fluctuations for the Paleolithic and the Neolithic, it faces several challenges, in addition to the general ones discussed above, which may undermine its validity (Williams 2012; Contreras and Meadows 2014; Torfing 2015). First, radiocarbon samples are often strategically collected for dating stratigraphic sequences within a site and, therefore, are not a random sample of human activity in every phase. Second, both the instrumental error associated with each date and the radiocarbon calibration curve have effects on the shape of each calibrated date’s probability distribution and hence on the SPD of all summed calibrated dates (Michczyński and Michczyński 2006, 4; Williams 2012, 581-584; Weninger et al. 2015). Third, research budgets can determine the extent to which radiocarbon samples are collected and used in an archaeological excavation, so some regions are richer in collected dates than others. Finally, certain chronological periods are more likely to be sampled than others: if datable coins, documents or fine-ware pottery exist, for instance, there is typically greater reliance on these forms of chronological evidence and less interest in paying for expensive radiocarbon dates.

Although the SPD of radiocarbon dates, site counts, and estimated settlement sizes have been widely used as proxies for population, the above limitations point to a need for cross-comparison among them where possible to strengthen our overall interpretation of demographic trends through time. The resolutions of these different kinds of evidence vary as well: an SPD of radiocarbon dates usually provides better chronological resolution, but typically less geographical coverage and control over sampling quality, when compared with site counts and estimated site sizes, but the latter are usually time-sliced to a much coarser level of resolution. For sites, there is a further imbalance between the kinds of evidence produced by extensive and methodical archaeological excavation in a given region, versus use of archaeological surface survey data. In what follows, we will therefore make use of a series of both well-established and novel statistical techniques to compare these different lines of evidence and mitigate some of their individual limitations.

2. Settlement and Population in Central Italy

Central Italy's long history of extensive archaeological excavations and systematic survey projects make this region an unusually privileged case study for assessing demographic trends and in what follows we have chosen to focus on the period from the Late Mesolithic (7500 BC) to the fall of the Roman Empire (500 AD; see Table 1 for the chronological scheme). The portion of central Italy examined here covers around 50,000 sq.km, encompassing present-day Tuscany, Lazio, and a small part of western Umbria (Fig. 1). This region can be divided into three main geographical units that, moving from west to east, include a landscape of plains and low hills, and the mountain ranges of the Anti-Appennines and Appennines (Barker and Stoddart 1994, 146-149). During the early and middle Holocene, the Middle Tyrrhenian coast was a landscape of intermittent sand dunes, lagoons, and marshy areas, which changed substantially during the Middle Bronze Age (Attema et al. 2010, 35-40). The inland area of central Italy (roughly matching with Tuscany) is dominated by a hilly landscape (e.g. Volterra, Chianti, the Sabatini and Albani hills) with a few fertile plains. The Apennines cover the eastern edge of our study area and provide upland pasture at an altitude ranging between 1000 and 2000 m. The fertile valleys and low hills of central Italy, frequently separated by a network of several rivers running in both an east-west and north-south direction, provided a suitable area for dense settlement and population, from which most of the archaeological evidence has been recovered.

Human settlement in central Italy during the Mesolithic is most evident in a series of caves, rock shelters and open air sites distributed from the lowlands of the Tyrrhenian coast to the mountain ranges of the Apennines. Mixed food production strategies of foraging, hunting and fishing appear likely in the Late Mesolithic, as do seasonal patterns of lowland-upland movement (Barker 1975; Martini 2001; Tozzi 2012). The first Neolithic settlements appeared in central-western Italy during the first half of the 6th millennium BC, especially in the lowlands close to rivers and lakes (Malone 2003, 257-259; Robb 2007, 25). The arrival of farming in this phase is believed to have brought a rapid and substantial increase in population, with communities permanently residing in houses and villages, supported by a mixed economy of hunting, farming and small-scale herding (Barker 1975, 144-147; Robb 2007, 26). During the Middle and Late Neolithic, farming strategies became more intensive, with greater evidence for the production and consumption of cereals and legumes, of mixed livestock (but a prevalence of cattle), and less evidence than before for hunted red deer and wild boar (Fugazzola Delpino et al. 1993; Anzidei and Zarattini 2007, 89). The central Italian Eneolithic (third millennium BC) sees a further apparent increase in site number, with some now exceeding one hectare in size (Anzidei and Carboni 2009, 94-95; Anzidei et al. 2010) and demographic growth thereafter appears to have continued during the Early (2300-1700 BC) and Middle Bronze Age (1700 – 1325/1300 BC), at least in Etruria and Latium (Peroni and di Gennaro 1986). Middle Bronze Age settlements were located across both the lowlands and highlands and continue to be sustained by a mixed economy based on intensive agriculture and animal husbandry (Peroni 1996, 202-204; Costantini and Costantini Biasini 2007). In contrast, during the Late Bronze Age (1325/1300 – 1020/950 BC) there is a marked abandonment of the lowlands, with a switch to settlements mainly on hilltops and other naturally defended locations (Barker and Stoddart 1994, 154). Further radical changes in settlement patterning then occur between the Final Bronze Age (1175/1150 – 1020/950 BC) and the Early Iron Age (1020/950 -750/725 BC) with the abandonment of many of the smaller-sized dispersed hilltop villages (those generally about 2-3 ha in size) and the concentration of population in larger nucleated and centralized urban centres (sometimes measuring over 100 ha) located in the lowlands and on plateaus (Peroni 2000; Fulminante 2014, 44-47; Alessandri 2015 and 2016;). By the later Iron Age and Archaic period, this process becomes a full-scale urbanisation episode, with the political landscape fragmented into several city-states located an average of 15-25 km apart (Cifani 2002; Vanzetti 2002; Fulminante 2014, 207-212; Redhouse and Stoddart 2011; Stoddart 2016). During the third century BC, these central Italian 'peer polities' become amalgamated into a larger, unified state under the power of Rome (Di Giuseppe 2005, 1060). By the late Republican Period (first century BC) there is further increase in the overall number of settlements peaking by the mid-second century AD (Witcher 2005 and 2008). Thereafter, archaeological data suggest a gradual decrease of the population of central Italy from the second half of the second century AD until the fall of the Roman Empire in the 5th century AD (Lewit 1991; Scheidel 2002; Turchin and Nefedov 2009, 213-216).

<table>
<tr><th>Period</th><th colspan="2">Absolute dates</th></tr>
<tr><td>Mesolithic</td><td colspan="2">10,000/9,500 – 6000/5800 BC</td></tr>
<tr><td>Early Neolithic</td><td colspan="2">6000/5800 – 4500 BC</td></tr>
<tr><td>Middle Neolithic</td><td colspan="2">4500 -3500 BC</td></tr>
<tr><td>Late Neolithic</td><td colspan="2">3500 – 3000 BC</td></tr>
<tr><td>Eneolithic</td><td colspan="2">3000 – 2300</td></tr>
<tr><td>Early Bronze Age</td><td colspan="2">2300 – 1700 BC</td></tr>
<tr><td>Middle Bronze Age</td><td colspan="2">1700 – 1325/1300 BC</td></tr>
<tr><td>Recent Bronze Age</td><td>1325/1300 – 1175/1150 BC</td><td rowspan="2">Late Bronze Age</td></tr>
<tr><td>Final Bronze Age</td><td>1175/1150 – 1020/950 BC</td></tr>
<tr><td>Early Iron Age</td><td colspan="2">1020/950 – 750/725 BC</td></tr>
<tr><td>Late Iron Age (Orientalizing Age)</td><td colspan="2">750/725 – 580 BC</td></tr>
<tr><td>Archaic Period</td><td colspan="2">580 – 480 BC</td></tr>
<tr><td>Post-Archaic Period</td><td colspan="2">480 – 350 BC</td></tr>
<tr><td>Republican Period</td><td colspan="2">350 – 30 BC</td></tr>
<tr><td>Early Imperial Period</td><td colspan="2">30 BC – 100 AD</td></tr>
<tr><td>Mid-Imperial Period</td><td colspan="2">100 – 300 AD</td></tr>
<tr><td>Late Imperial Period</td><td colspan="2">300 – 500 AD</td></tr>
</table>

Table 1. A chronological scheme for central Italy (after Guidi and Piperno 1993, Plate VI and X; Malone 2003, Table I; Attema et al. 2010, Table 2.1; Rajala 2013, Table 1; Fulminante 2014, Table 7; Alessandri 2016, Fig.2).

The above brief overview of settlement change represents a qualitative assessment of current opinion drawn from the existing literature, and the following discussion now looks to compare it with a more quantified treatment via close attention to radiocarbon dates, site counts and estimated site sizes. To produce the latter datasets, we have sought to work as exhaustively as we could through existing online databases and both electronic and print publications to create two georeferenced databases, one for sites and one for radiocarbon dates (see Fig. 1). A total of 726 uncalibrated radiocarbon dates have been identified from 171 sites and either harmonised from existing online databases in some cases (BANADORA, RADON, University of Oxford's ORAU, EUROEVOL) or, more often added from a wide range of publications (for a slightly wider chronological range to avoid edge effects, Fig.1a). This number of dates exceeds the suggested minimum threshold of 200-500 dates to produce a reliable SPD for a time interval of 10,000 years, although certain concerns about sample size will still be discussed below (Michczyńska and Pazdur 2004; Michczyńska et al. 2007; Williams 2012, 580-581). All of these radiocarbon dates are from archaeological contexts, with the majority being samples of bone, charcoal and wood. Radiocarbon dates obtained from marine samples such as shell have been removed (and are not part of the above total) to avoid the complicated issues arrising from unknown or poorly understood marine reservoir offsets.

To create the database of archaeological sites in central Italy, the lead author conducted a comprehensive review, standardisation, and synthesis of settlement data from reports and gazetteers relating to 59 different archaeological surveys of varying intensity across ca.10,000 sq.km (Fig. 1b). Settlement data have been recorded, where possible, as georeferenced polygons per time-slice (unprojected WGS84, with each slice having a 200-year resolution where possible) and when the former was impossible, as circular buffers based on published estimates of site size per time-slice (dataset available online, Palmisano et al 2017). This allows us to assess changes in site location and extent, wider spatial configurations of sites in the landscape and regional site size hierarchies. One major caveat is that it was only possible to estimate site sizes per phase for those larger multi-period sites that had also been extensively excavated and/or surveyed methodically. A total of 7,383 sites and 10,971 occupation phases have been collected using the above approach (many sites were occupied in multiple periods). In addition, the very uncertain or fuzzy definitions of site function provided by many publications (e.g. the ambiguity of the assumption that every site is a settlement) urges further interpretative caution (cf. Gallant 1986; Wandsnider 1998). As noted above, sites not only refer to dwelling places, but can refer to temporary activity areas (e.g. campsites), industrial zones (mines), and cemeteries. For the purposes of this paper, however, we have chosen to deal exclusively with those places identified as human habitation sites or possible habitations, and hereafter then use the terms site and settlement interchangeably to refer to this subset.

3. Methods

3.1 Radiocarbon summed probability distributions

The method used in this paper to aggregate radiocarbon dates builds largely on previous work that seeks to test observed SPDs of radiocarbon dates against theoretical null models and/or under permutation (Shennan et al. 2013, Timpson et al. 2014; Crema et al. 2016), and to address issues such as "wealth-bias" of particular site phases (Timpson et al. 2014), the effect of taphonomic site-loss through time (Shennan et al. 2013), and the artefacts in SPD plots due to radiocarbon calibration curves (Williams 2012; Weninger et al. 2015). First, we reduce the potential bias of oversampling specific site-phases by aggregating uncalibrated radiocarbon dates from the same site that are within 100 years of each other and dividing by the number of dates that fall in this bin. Once this is done for all sites, the probabilities from each bin are summed: in our case, 726 radiocarbon dates have been grouped into 375 bins. This procedure ensures that each site-phase is equally weighted. Nevertheless, it is important to bear in mind that this approach could underestimate real population because it does not take account of the size of the site (dates from the same site and phase are lumped, whether the site is Rome or a small farmstead). In other words this approach adopts the pessimistic, or at least conservative, view that the intensity of radiocarbon dates for certain site phases comes from biases in the intensity of investigation rather than the larger size of the site in that phase. Following previous work (Williams 2012; Weninger et al. 2015) demonstrating that normalised calibrated dates produce abrupt, artificial peaks in SPDs at steep portions of the radiocarbon calibration curve (throughout we have used IntCal13, Reimer et al. 2013), we have opted to work in what follows with unnormalised dates.

Finally, an exponential null model representing taphonomic site loss through time and expected population increase going forward has been fitted to the observed SPD in order to produce a 95% critical envelope (composed of 1,000 random SPDs) and statistically test if the observed pattern significantly departs from this model (for a detailed explanation of the method see Timpson et al. 2014, 555-556). Deviations above and below the 95% limits of the envelope respectively indicate periods of population growth and decline greater than expected. Because 5% of the observed SPD could fall outside the confidence interval by pure chance, a global p-value has also been calculated in order to assess the area of the observed SPD outside the confidence envelope. It is worth pointing out that this value takes into account the overall shape of the SPD and, therefore, it is not unusual to have global p-values that are not statistically significant even when positive or negative local deviations are detected.

3.2 Archeological settlement data and probabilistic approaches

In our analysis, we used a resolution of 56 time steps each lasting 200 years, over a slight broader chronological range starting with period t_1 (10,000-9,800 BC) and ending with period t_{56} (800-1000 AD) to avoid edge effects. Then, we calculated the site count and summed the estimated site sizes for each time step in order to assess how the population changes across time every 200 years. This approach has been broadly used by archaeologists but can be problematic given the temporal uncertainty of archaeological data and the varying accuracy of different types of artefacts (e.g. pottery) in dating site-phases and periods. In fact, typo-chronological schemes defined by archaeological cultures can produce site-phases sometimes spanning several thousand years if dated by long-lived pottery types or surface material alone. Fig. 2 shows the frequency per 200-year time-step of 10,971 site occupation phases. The site-phases have different time spans according to their respective dating precision: longer time spans and higher uncertainty occur when the dating is based on artefacts with little diagnostic value and in contrast shorter time spans when uncertainty is lower – these time spans, it should be emphasised, are not the same as the actual longevity of the site in the past. Figure 2 makes it clear that most site-phases (around 5,000 of them) have a time span equal to or lower than 200 years. Nevertheless, other site-phases have a much longer time spans (up to 2,000 or 3,000 years) due to the low precision dating of some artefacts. The ones showing a time span of three thousand years are typically those recorded as Neolithic (Table 1) in the gazetteer of site and excavation reports.

In order to address this issue of temporal uncertainty while at the same time making use of all the chronological information in the archaeological data, we have adopted a probabilistic, 'aoristic' approach (see previous applications in Ratcliffe 2000; Johnson 2004; Crema et al. 2010, 1118-1121; Crema 2012, 446-448; Kolář et al. 2016; Orton at al. 2017). The method builds on the assumption that the total probability of an archaeological event (site occupation phase in our case) within a given time span is 1, which indicates an absolute certainty that the site was in use in that time span. If we then divide by the length of the site's chronological range we can represent the probability of existence for each temporal block (implicitly therefore adopting a default uniform assumption). Put simply, using time-steps of 200 years, a site-phase ranging from 2200 to 1400 BC has an aoristic weight of 0.25 for each time-step (2200-2000, 2000-1800, 1800-1600, 1600-1400; see Fig. 3a). Instead, a site-phase with a shorter time-span ranging from 2000 to 1600 BC has an aoristic weight of 0.5 for each time-step and so on (2000-1800, 1800-1600; Fig. 3b). Having assigned such weights to each site, we can then sum them all in order to obtain the aoristic sum for each temporal block (Fig. 3).

Aoristic weights change when you modify the temporal resolution of the analysis (aoristic weights would be lower with time-steps of 100 years). Such aoristic analysis typically also assumes a uniform probability distribution (as noted above), which means that each year has the same probability of being the one in which the archaeological event occurred. Thus, an issue arises when a large sample of archaeological events with the same time-span occurs within the same temporal block. This results in homogeneous patterns, where large numbers of sites begin and end at the same time, because of the temporal structure of the data. While it is often difficult to judge the likely longevity of an individual site without considerable amounts of absolute dating, it is often evident that site durations are shorter than their assign chronological ranges. To mitigate this tension between wide chronological uncertainties and narrower likely site durations, we can use Monte Carlo methods to generate randomised start dates for sites with low-resolution information (see Crema 2012, 450-451; Kolář et al. 2016, 518-519; Orton et al. 2017, 5-6), using two slightly different methods: (1) a date is randomly drawn from a uniform distribution corresponding to the relevant chronological range of the site-phases concerned (Fig. 4a); (2) we adopt the same approach but draw the start date conditional on the shape of the relevant portion of the radiocarbon SPD (see below) so that sites are more likely to be chosen from periods of high radiocarbon probability density (Fig. 4c). This latter method has the advantage of using more information and indicating how closely the settlement data can agree in principle with the radiocarbon data, but it also builds in an element of circularity if comparisons are being made with the radiocarbon SPD results. Then, to the start date drawn by one of the methods above, we also add a site duration randomly generated from a normal distribution with a mean of 200 years and standard deviation of 50 years. This typical duration was chosen to correspond to the modal site phase lengths exihibited in fig 2 and offer clear contrast for those periods where uncertainties are much larger (e.g. 1000 years), but clearly the choice of mean expected site duration is slightly arbitrary and would best be informed by a wider range of evidence. In any case, this approach (Fig. 4b and 4d) allows us to deal with those site-phases having a coarser resolution and time spans ranging over thousands of years. We can then simulate multiple time series and generated a 95% critical envelope for all randomised start dates and durations of site occupation phases. The width of the envelope is indicative of the degree of temporal uncertainty in site occupation through time. The resulting probabilistic distributions of site frequencies through time, based on the aoristic sums and Monte Carlo simulations, provide useful comparisons with the raw site frequency data and the summed settlement sizes.

4. Results

4.1 Summed Probability Distribution of Radiocarbon Dates

Figure 5 shows the SPD of 726 radiocarbon dates from 7500 BC to 500 AD, for both normalised and unnormalised dates with the former producing more artificially spiky probability distributions at steeper portions of the radiocarbon calibration curve as noted above. Despite our stated preference for the summing of unnormalised dates, it should be apparent that the overall pattern of SPDs does not differ substantially in either case in this instance. Figure 5c shows the (unnormalised) SPD of the data compared with a 95% envelope for an exponential null model. Deviations above and below the null model respectively represent population growth or decline beyond that expected under a long-term exponential trend (and/or greater or lesser long-term taphonomic effects). The results show a significant overall departure of the observed SPD (black solid line) from the theoretical envelope of the exponential model ($p=0.001$). Significant population growth occurs during the Late Neolithic/Eneolithic (~3.2-2.8 ka BC; 2.6-2.4 ka BC) and population decreases, although not significantly, between 2.2-1.7 ka BC. A further dramatic increase of population is indicated during the Final Bronze Age and Early Iron Age (1.1-0.8 ka BC). After this period, the radiocarbon population proxy gradually decreases until the fall of the Roman Empire.

4.2 Archaeological site counts and sizes

Figure 6 shows the frequency per 200-year time-block of 10,971 site occupation phases. In this analysis, five different versions of a proxy derived from archaeological settlement data have been used to model population dynamics over the long run: raw site counts, summed settlement area, aoristic sum, randomised site start date and duration (uniform assumption) and randomised site start date and duration (SPD-weighted assumption). The results for all five approaches show an increase in population at the beginning of the Neolithic (~6 ka BC) and peaks during the Late Neolithic (~3.5 ka BC), the Eneolithic (~ 2.3-2.1 ka BC), the Middle Bronze Age (1.7-1.5 ka BC), the Recent Bronze Age/Early Iron Age (1.1-0.7 ka BC), and the Late Republican/Early Imperial Roman period (100 BC-AD 100). These peaks are punctuated by population stagnation between 3.0-2.4 ka BC and

2.1-1.8 ka BC, and population declines between 4.8-4.4 ka BC and 2.4-2.1 ka BC. Overall, all proxies show similar trends in terms of relative change of population through time between 7.5 ka BC and 500 AD (see below for a quantitative comparison). However, a striking difference among these five versions occurs between 1200 and 1000 BC where the site count, the aoristic weight and the randomised site start date values all show a slight decrease but the summed estimated size of settlements increases strongly (Fig. 6b). This reflects a pattern of settlement nucleation during the Early Iron Age (1020/950 – 750/725 BC), which resulted in the concentration of population in a smaller number of larger sites. Finally, from a long-term perspective, it seems that the population of central Italy started increasing dramatically in the Final Bronze Age and further peaked during the Roman Period between 300 BC and AD 200 (Fig. 6a).

4.3 Comparing all population proxies

Despite the different chronological resolution of the radiocarbon dates and the site occupation periods, the overall demographic trends appear roughly similar, and several points of convergence can be detected. In particular, all proxies suggest a first increase of population at the beginning of the Neolithic (~6000 BC) and a further growth during the Late Neolithic and Eneolithic (see Fig. 7). A noticeable difference occurs at 2.3 ka BC when the raw site count and the summed site sizes both peak, while the radiocarbon SPD looks flat and both the aoristic weight and the randomised duration drop (Fig. 7). However, any perceived peak here is in fact an artefact of the temporal uncertainty in the occupation period of a number of sites broadly dated as Bronze Age (2.3-1.0 ka BC) in the archaeological survey and excavation reports. More generally, this is because under conditions of considerable temporal uncertainty, the site raw count will tend to overestimate the population in a given time-span. All proxies comfortably converge in depicting a dramatic increase of population between 1.1 ka and 0.8 ka BC. A noticeable difference in the demographic trends appears during the Roman Period (500 BC-AD 500), where the SPD of radiocarbon dates declines (Fig. 5) and massively underestimates a widely-agreed and widely-evidenced boom in population at this time (Fig. 6a). This is due to reliance by most Roman archaeologists on traditional typo-chronological schemes defined by coins and fine ware pottery for dating as opposed to the use of radiocarbon dating.

5. Discussion

Our study provides what is, to our knowledge, a first application of a multi-proxy approach for assessing population dynamics in central Italy on a long-term perspective from the Mesolithic to the fall of the Roman Empire. We have built a large archaeological dataset consisting of 726 radiocarbon dates and 10,971 occupation phases from 7,383 sites in order to contribute to the current debate about the validity of different methods for reconstructing demographic trends, with further attention to methodological management of radiocarbon calibration effects, investigativebiases and temporal uncertainty in archaeological settlement data. Overall, the archaeological radiocarbon SPD and the various versions of the settlement proxy produced broadly similar demographic trends (Fig. 7). Pairwise Pearson’s correlations among all proxies is statistically significant for the period from 7.5 to 0.8 ka BC, ranging in magnitude between 0.53 and 0.98 (Fig. 8). Unsurprisingly given the evidence for settlement nucleation as population increases in the later periods, there is not a significant linear correlation between site counts and summed settlements size (r=0.23): an increase or decrease in site numbers can correspond to an increase or decrease in estimated summed settlement size. In particular, the results show a broad agreement in the demographic trends produced by the SPD of radiocarbon dates and the other five related settlement indices, confirming that the former one can be regarded as a robust proxy for modelling population fluctuations through time, at least up to 800 BC (see Fig. 7). In effect, a non-systematic sample of radiocarbon dates collected from a few hundred sites can mimic a quasi-random sample of occupation phases. However, as we have seen, the picture becomes misleading from 800 BC onwards because archaeologists working in these periods usually rely on traditional pottery-based relative chronologies.

Unlike the radiocarbon dates, the other five proxies derived from archaeological settlement data provide a better coverage both chronologically and spatially in the area under investigation, as they are the results of intensive and extensive archaeological surveys carried out in Latium and Tuscany. Their cross-comparison is not only useful for defining population fluctuations through the full time-range of the study but also for detecting change in spatial settlement patterns when nucleation occurred in the form of an extreme concentration of population in a few large centres during the Early Iron Age (1020/950-725 BC). Thus, during the Final Bronze Age, we have 287 sites measuring a total size of 300 hectares (Fig. 9), while in the Early Iron Age there 212 sites measuring a total size of 1,200 hectares (Fig. 9). There is therefore a weak correlation between site counts and summed settlement sizes (r=0.23, Fig. 8), contrasting with a higher value (r=0 .59) between those two proxies up to the Final Bronze Age (1175/1150-1020/950 BC). In other words, we need the summed site area information, as well as the various measures based on site counts if we are to arrive at a valid picture. The main drawbacks of the archaeological settlements, as data, are their coarse chronological resolution in comparison with the radiocarbon dates.

All proxies show an increase of population in the early Neolithic (~6.0-5.5 ka BC) when compared with the population level in the earlier Late Mesolithic (Fig. 7). This increase seems, therefore, to be associated with the earliest adoption of farming economies and a much more stationary population settled in permanent houses and villages (Barker 1975, 144-147; Malone 2003, 267-269; Robb 2007, 26). A further substantial increase of population observable in all proxies occurs in the second half of the fourth millennium BC and results in two peaks during the Eneolithic (3.2-2.8 ka and 2.6-2.4 ka BC) punctuated by a population decline between 2.8-2.6 ka BC (Fig. 5c and Fig.7). In this period, communities started living in settlements greater than one hectare in size and based on more intensive mixed economies (agriculture, hunting, herding) comprising specialized techniques in the cultivation of different kinds of cereals and pulses (see Celant 2000; Anzidei and Carboni 2009; Anzidei et al. 2010, 342). At first glance, the second population peak occurring during the Eneolithic at 2.5 ka BC in the radiocarbon SPD seems to be shifted by 200 years from the one observed in the site count and the summed settlement size data (2.3 ka BC; see Fig. 7). This could be a result of the difference in temporal resolution between the SPD of radiocarbon dates and the archaeological settlement data, but regardless, it is likely that the peak at 2.3 ka BC in the site count and summed estimated settlement size data is an artefact of temporal uncertainty in archaeological site-phases broadly dated to the Bronze Age and assigned to a long time span (2300-1000 BC). This is likely to overestimate the number of sites that effectively were occupied at the beginning of the Early Bronze Age. In fact, the aoristic weight data and the randomised site start dates do not report any such peak (see Fig. 5b and 7). In contrast, the two peaks observable in the SPD of radiocarbon dates between 3.2-2.8 ka BC and 2.6-2.5 ka BC show a reasonable match with ones in the time-series of the aoristic sum (cf. Fig. 5b and 7). All six lines of evidence show a decrease of population between 2.2-1.7 ka BC that could be related to less favourable climatic conditions although further work would be needed to explore this possibility thoroughly for the Italian case (Weninger et al. 2009; Wiener 2014; Jung and Weninger 2015).

After 1.7 ka BC, all measures show gradual population growth, which peaked dramatically during the Final Bronze Age and the Early Iron Age (1.2-0.9 ka BC). The divergence between the summed settlement size and the other settlement measures in this latter period is explained by the radical changes occurring in settlement patterns between the Final Bronze Age (ca. 1175-1020/950 BC) and the beginning of the Early Iron Age (ca. 1020/950-750/25 BC). This period sees the abandonment of small-sized dispersed villages (generally 2-3ha) located in open positions or on small hilltops and the occupation of a smaller number of sites of larger sizes (50-100 ha) distributed over the lowlands and plateaus (Peroni 2000; Fulminante 2014, 44-47; Alessandri 2015 and 2016; Redhouse and Stoddart 2011; Stoddart 2016; Fig. 9). This process culminated in full-scale urbanisation and early-state societies during the Late Iron Age (750/725-580 BC) and Archaic period (580-480 BC), when the political landscape was fragmented into several city-states located at an average distance of 15-25 km. The dramatic growth of population occurring in the Final Bronze Age (1175-1020/950 BC) and Early Iron Age (1020/950-750 BC) also had a significant impact on the landscape cover with an abrupt increase in cultivated trees (e.g. olive, walnut, chestnut) rather than a simple increase in landscape openness/forest loss (Alessio et al. 1986; Magri and Sadori 1999; Mercuri et al. 2002). During the Roman period (500 BC-AD 500), the population boomed massively (Fig. 6b) and reached a peak in the Early and Middle Imperial Period (30 BC-AD 150; see also Witcher 2008 and 2009). Then, from the middle second century AD onwards the population gradually decreased, concomitantly with a wave of epidemics (e.g. the Antonine plague) and endemic civil warfare, and reached pre-Roman period levels at the fall of the Roman Empire (see Scheidel 2002; Turchin and Nefedov 2009, 233-239; Witcher 2009).

6. Conclusions

Time series of summed radiocarbon dates and of settlement data (e.g. counts and/or estimated settlement size) have been the most popular proxies in archaeology for modelling population dynamics through time. Nevertheless, with a few exceptions these proxies have rarely been assessed comparatively. In this paper, we therefore adopted a multi-proxy approach, comparing several different archaeological indices to assess the extent to which they corroborate or diverge from one another. The resulting six time series and their cross-comparison allow us to explore the strengths and weaknesses of different lines of evidence and develop a better understanding of demographic trends in central Italy between the Mesolithic and the fall of the Roman Empire. The overall agreement between the radiocarbon SPD dates and the settlement-based proxies corroborates the use of the former as a good indicator of changes in prehistoric population density in archaeological research, despite the limitations pointed out in this paper and also emphasised by other authors. Overall, there is general agreement among all proxies in identifying an increase of population in the Early Neolithic, in the Eneolithic, in the Final Bronze Age/Iron Age and a last demographic boom during the Roman Period. Although not the focus of this paper, the further advantage of these different kinds of demographic proxy is that that can be juxtaposed with palaeoclimate data, pollen records of land cover and/or similar data from neighbouring Italian regions to compare and contrast patterns of coupled human-environmental dynamics at both local and supra-regional scales.

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Appendix A. Supplementary data and code

Data, source codes and scripts used in this work can be found in the journal data paper by Palmisano et al. (in press) and UCL Discovery online repository: 10.14324/000.ds.1575442

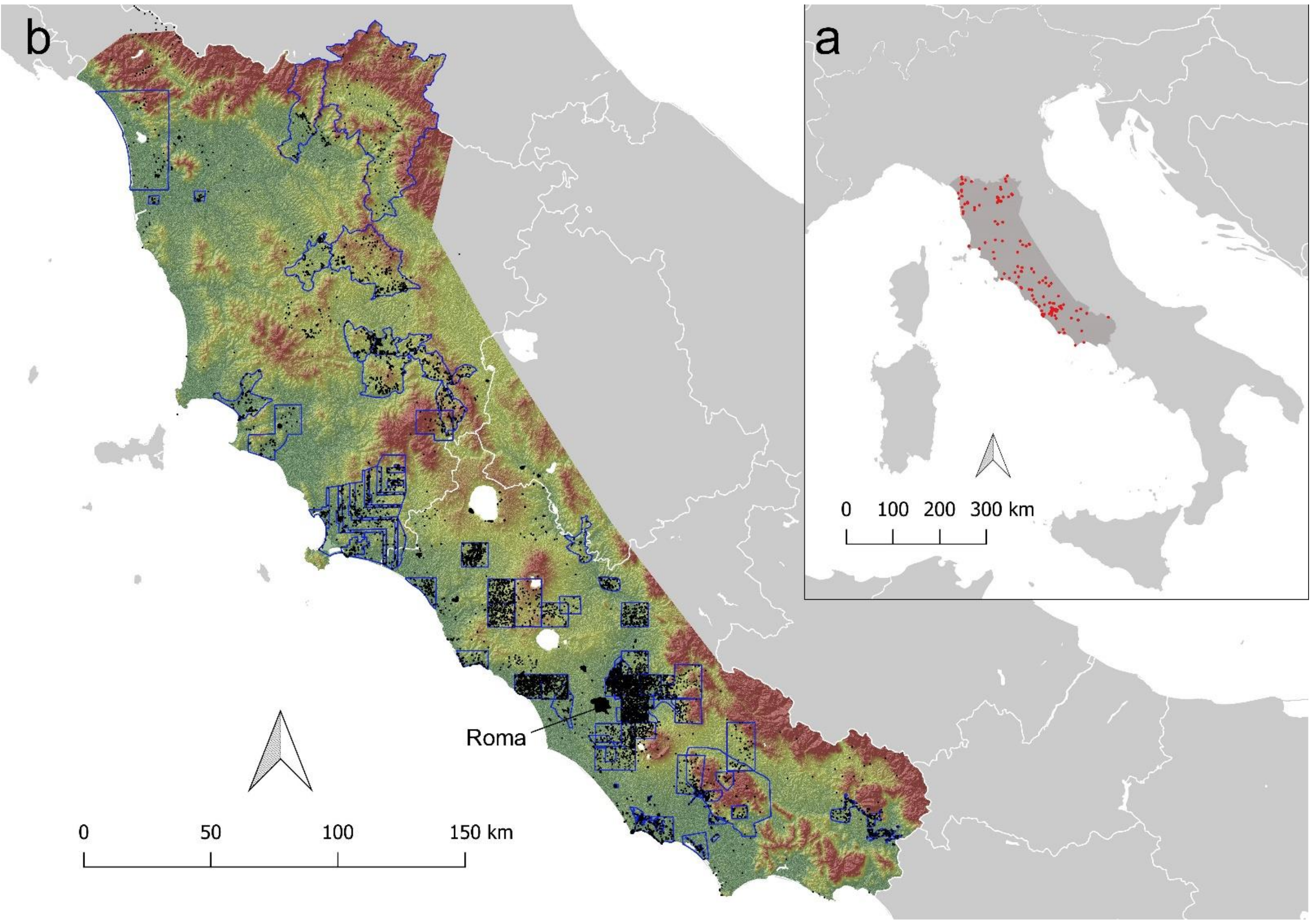

Figure 1. Map showing the a) distribution of radiocarbon samples and b) sites (the blue polygons indicate the bundary of the archaeological surveys).

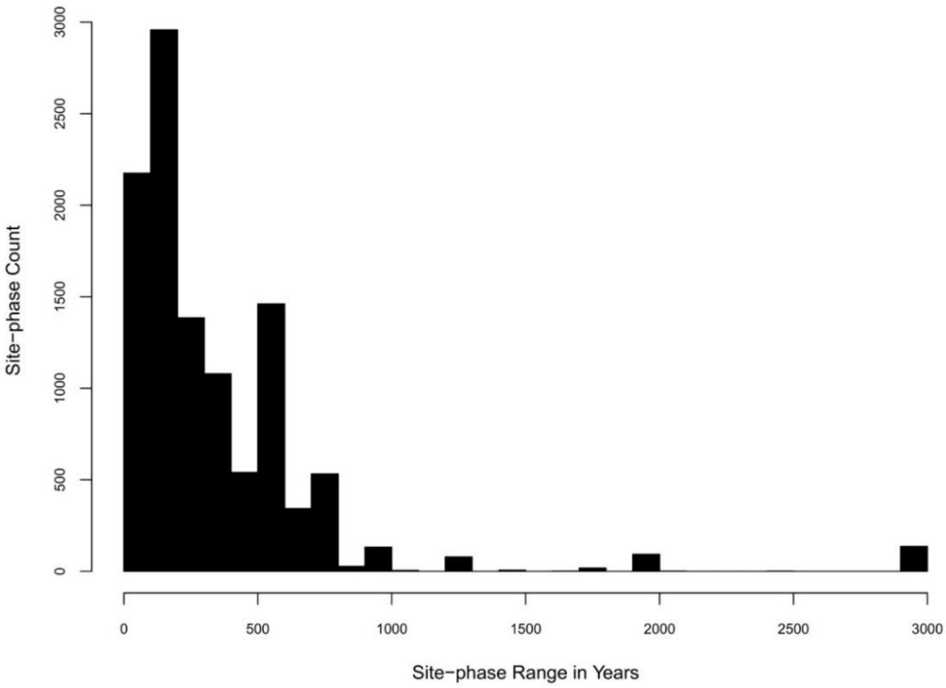

Figure 2. Histogram showing the frequency of site-phases per time-span.

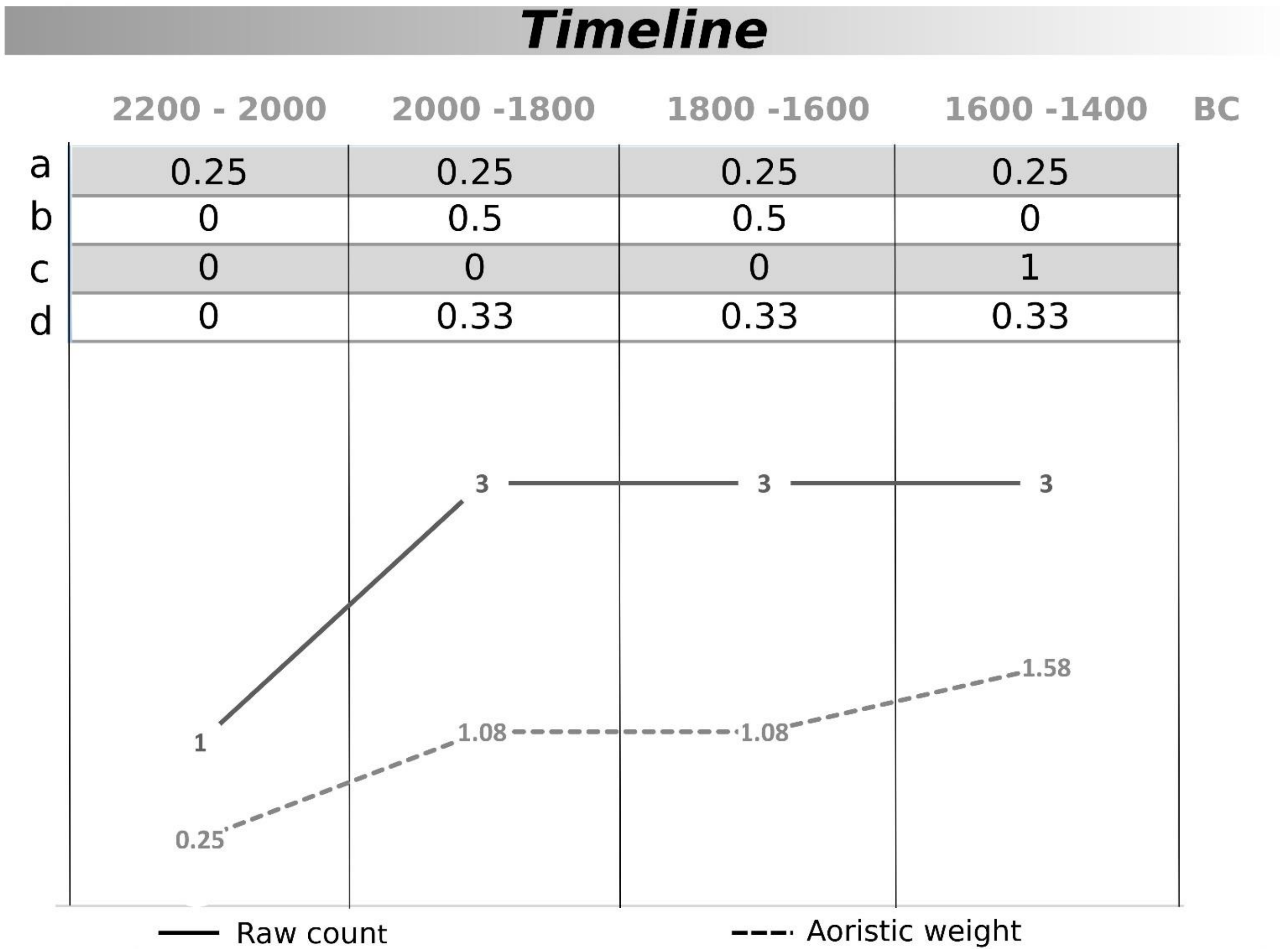

Figure 3. Four different site-phases (a-d) with varying chronological ranges indicated horizontally by the length of their temporal blocks. Each 200 years time-step reports an aoristic weight, which represents the probability of existence of a site within each temporal block. The aoristic sum (dashed line) is plotted vs. the raw count of sites (solid line).

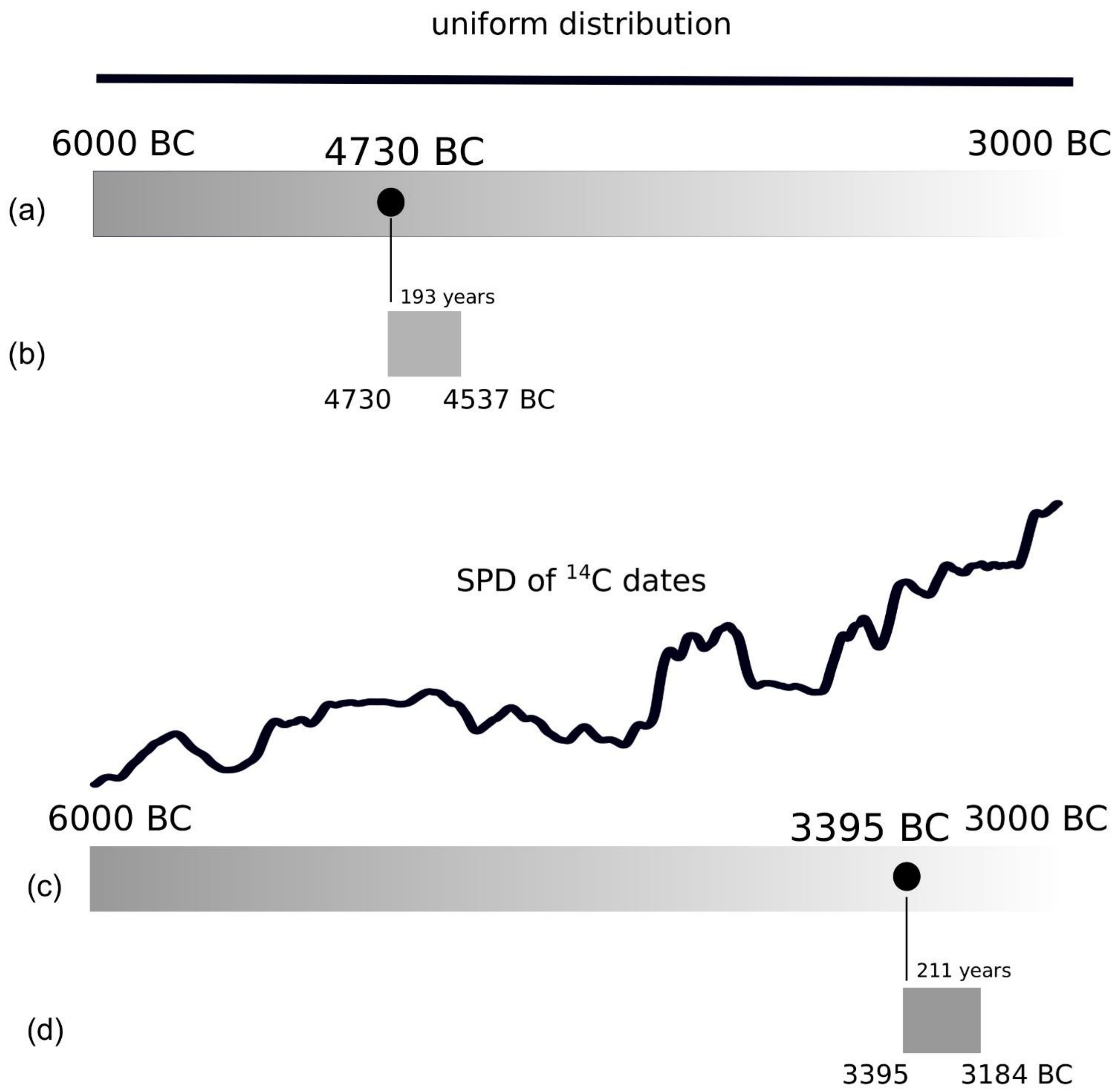

Figure 4. Randomised start date of sites: **a)** a date is randomly drawn within the time-span of a given site-phase with a uniform probability distribution or **c)** with a probability weighted by the SPD of radiocarbon dates, and **b-d)** a sites duration randomly generated from a normal distribution with a mean of 200 years and a standard deviations of 50 years is added to the drawn date.

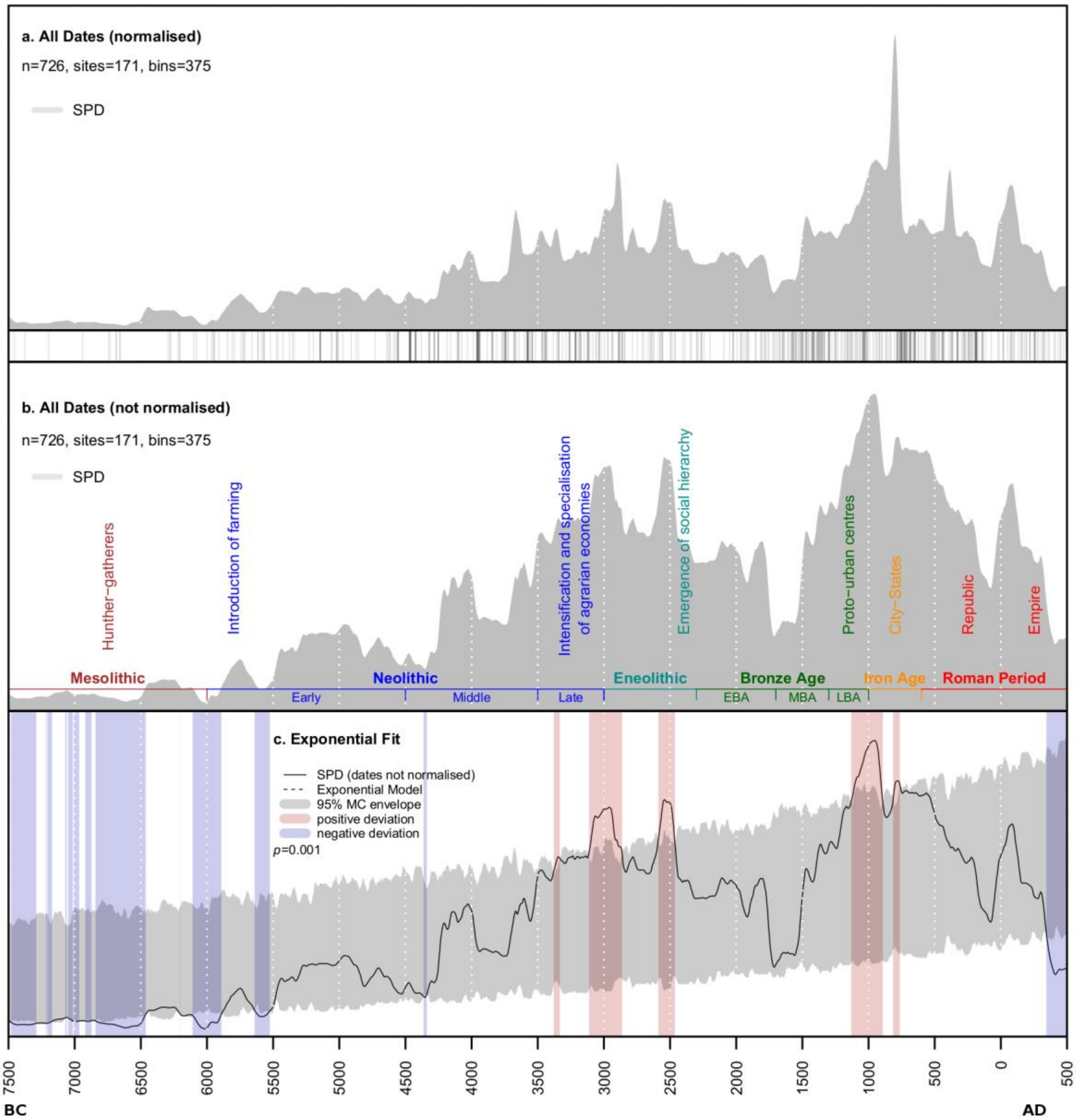

Figure 5. Summed Probability Distribution (SPD) of a) normalised and b) unnormalised calibrated radiocarbon dates, and (c) unnormalised (solid line) vs. a fitted exponential (95 % confidence grey envelope). Blue and red vertical bands indicate respectively chronological ranges within the observed SPD deviates negatively and positively from the null model.

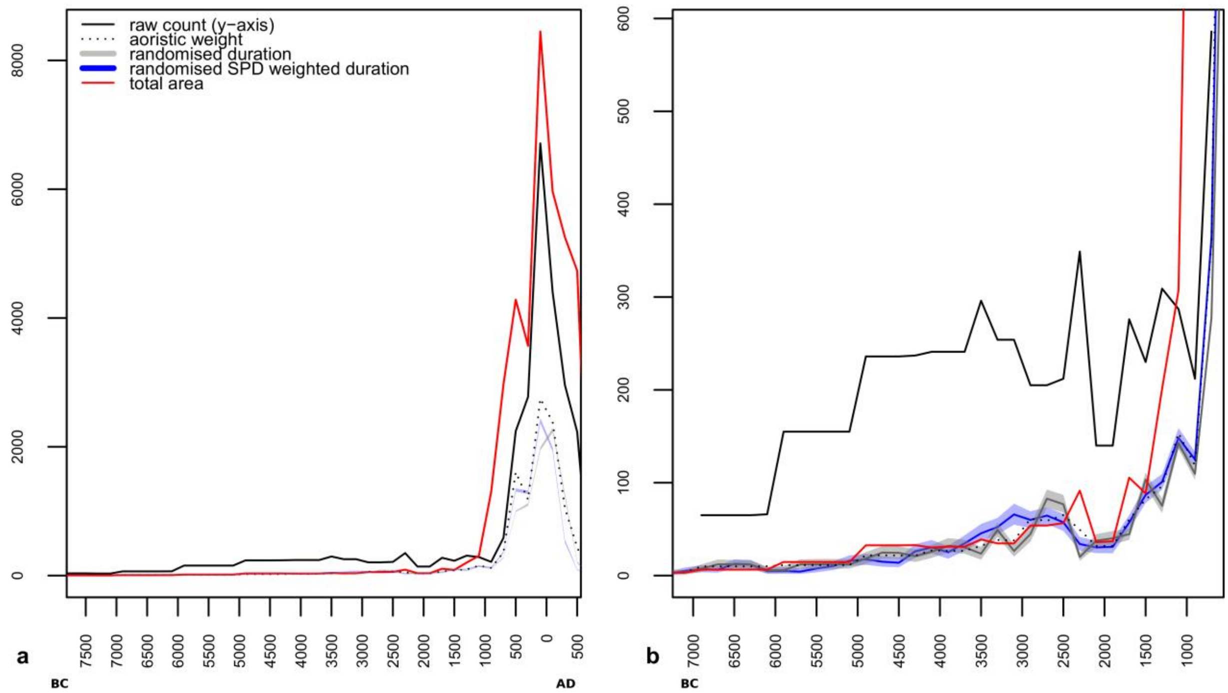

Figure 6. a) Comparison of sites raw count (solid line), summed estimated settlement size (red line), aoristic sum (dashed line), randomised start date of sites (grey envelope), and SPD weighted randomised start date of sites (blue envelope) from 7.5 ka BC to 500 AD. **b)** Inset of population change between 7.0 and 0.8 ka BC.

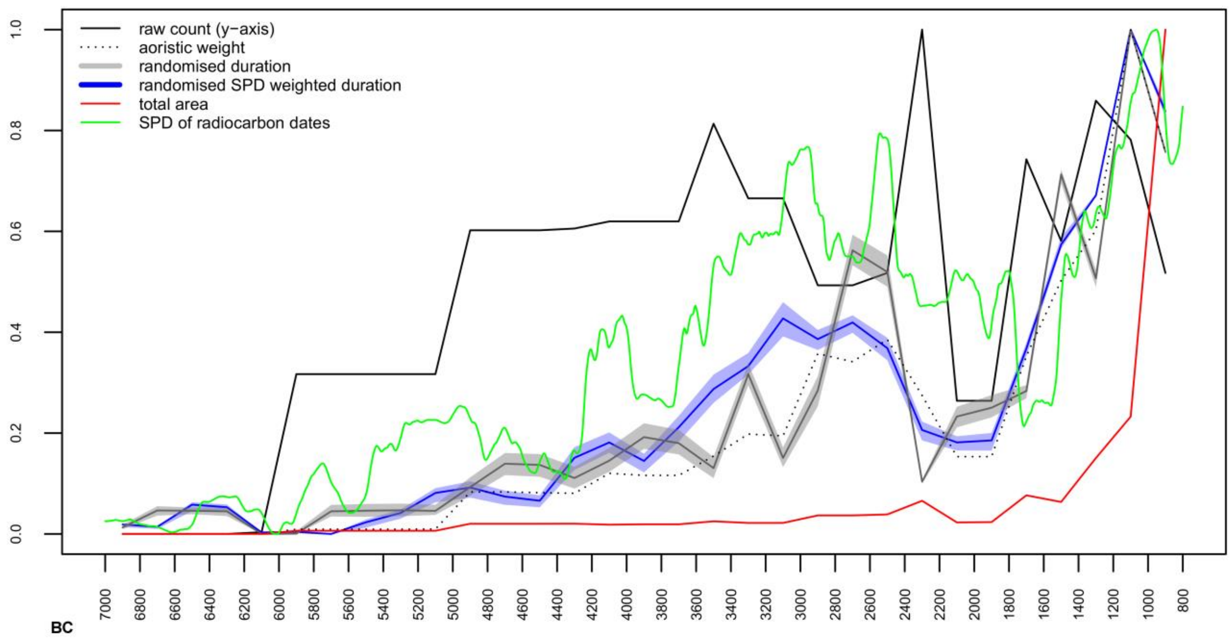

Figure 7. Comparison of all archaeological proxies: sites raw count (solid line), summed estimated settlement size (red line), aoristic sum (dashed line), randomised duration of sites with uniform probability (grey envelope), SPD weighted randomised duration of sites weighted (blue envelope), and SPD of radiocarbon dates (green line) from 7.0 ka BC to 800 BC. All values have been normalised between 0 and 1.

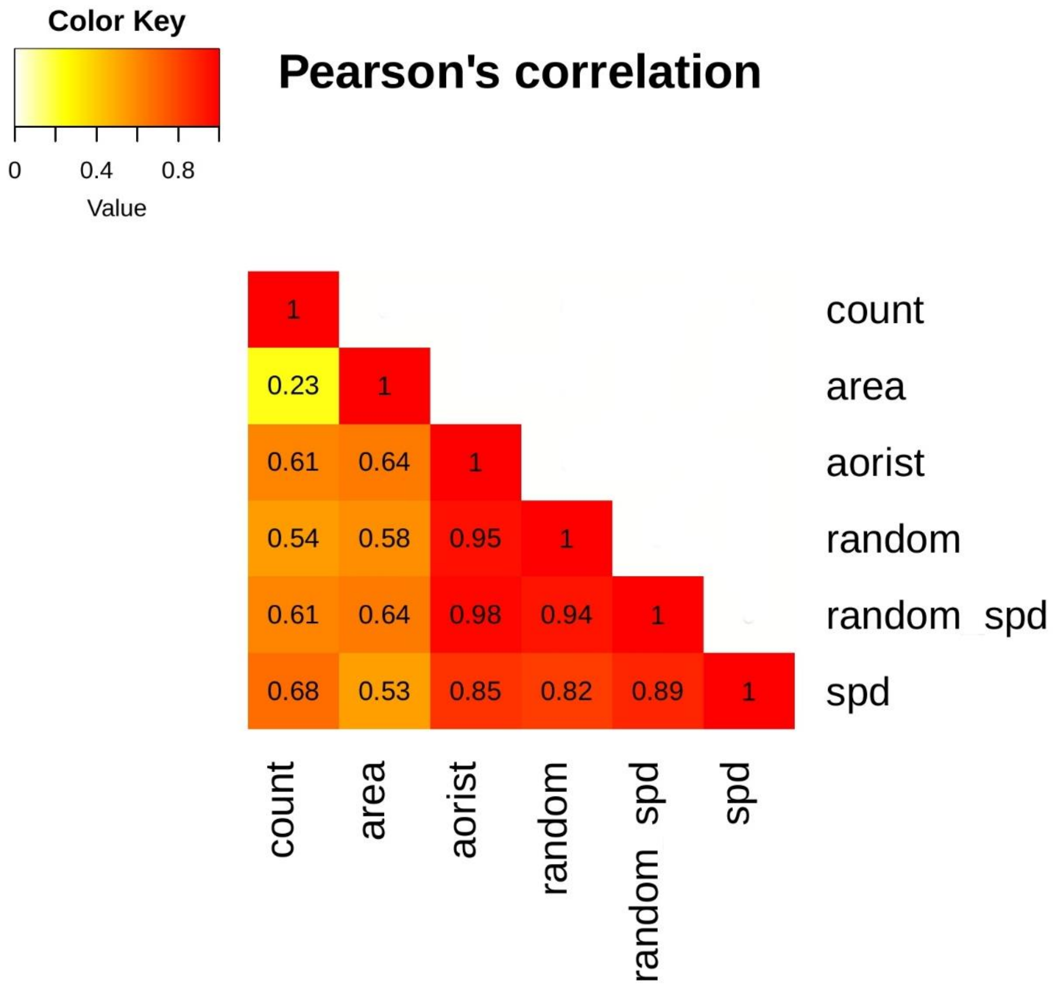

Figure 8. Pairwise Pearson's correlations between all archaeological proxies. The red-yellow scale values represent correlation values, with dark red representing the better fit and yellow the worse fit results.

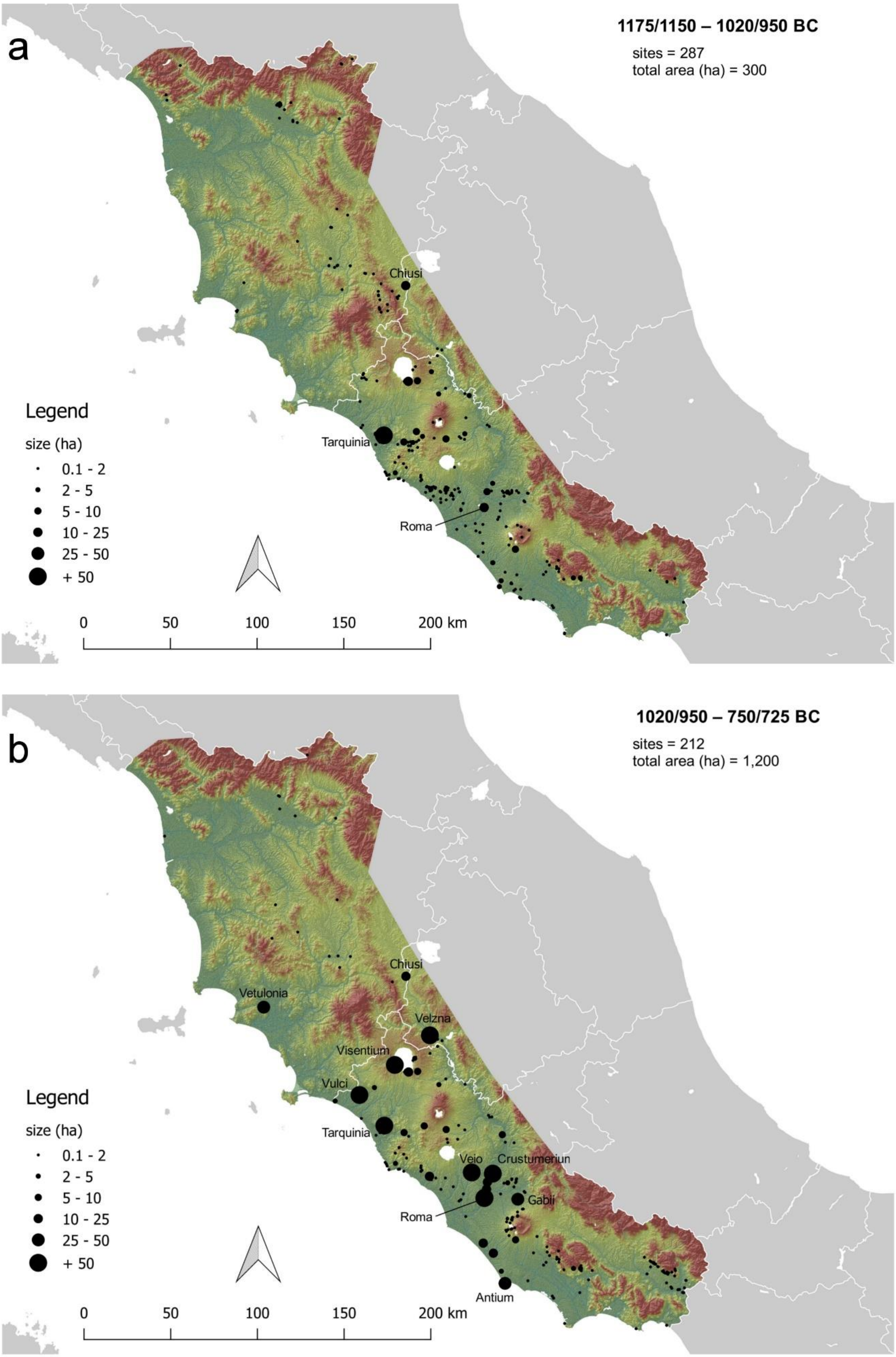

Fig. 9. Settlements distribution and estimated size during the Final Bronze Age (a) and the Early Iron Age (b).

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