

# The study of spatiotemporal patterns integrating temporal uncertainty in late prehistoric settlements in northeastern Spain

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**Abstract** This paper explores the integration of two variables that are typically difficult to use in spatial analysis: time and uncertainty. A framework is constructed to analyse mid- and long-term variation in settlement dynamics during late prehistory in northeastern Spain. Following previous proposals, an aoristic model is built with ceramic dating to feed a Monte Carlo simulation that explores the case study using a discrete time-step approach. At the same time, available radiometric dating is used to validate the accuracy of the simulation results. Departing from the static analysis of spatial variables, the model proposes a new approach by which researchers can address temporal uncertainty. The results show that patterns detected by classical spatial analysis can be produced by artefacts derived from the division of time in chronological units instead of discrete time periods. The model is also used to compare a priori identical variations whose rate of change, when analysed with this approach, is revealed to be completely different.

**Keywords** Spatial temporal analysis · Geographical information systems · Late prehistory in NE Iberian Peninsula

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## Introduction

In archaeological research, medium- to large-scale spatiotemporal data are most typically represented by geographical models using spatial databases (see (Fairén-Jiménez 2004; Pinhasi et al. 2005; Ruestes 2008; García-Sanjúan et al. 2009; Garcia 2013), but while these models have been effective in answering various research questions, they encounter two important obstacles with regard to the concepts of time and uncertainty.

### The study of temporally explicit patterns

Geographical information systems are not designed for working with scenarios depicting temporal and spatial variability. Even though the issue has been previously discussed (Mlekuž 2010; Bailey 2007; Curry 1998), GIS-based tools remain an inadequate means of integrating temporal coordinates in spatial models. They cannot provide a common framework for detecting spatiotemporal patterns, despite the importance of these dynamics in archaeological research. Amongst the approaches explored to remedy this, the most common solution is to apply spatial analysis to different datasets corresponding to the chronologies and to compare their results at the end of the study. This can be combined with an alternative approach that collapses the spatial variable and analyses the different periods statistically to identify temporal patterns.

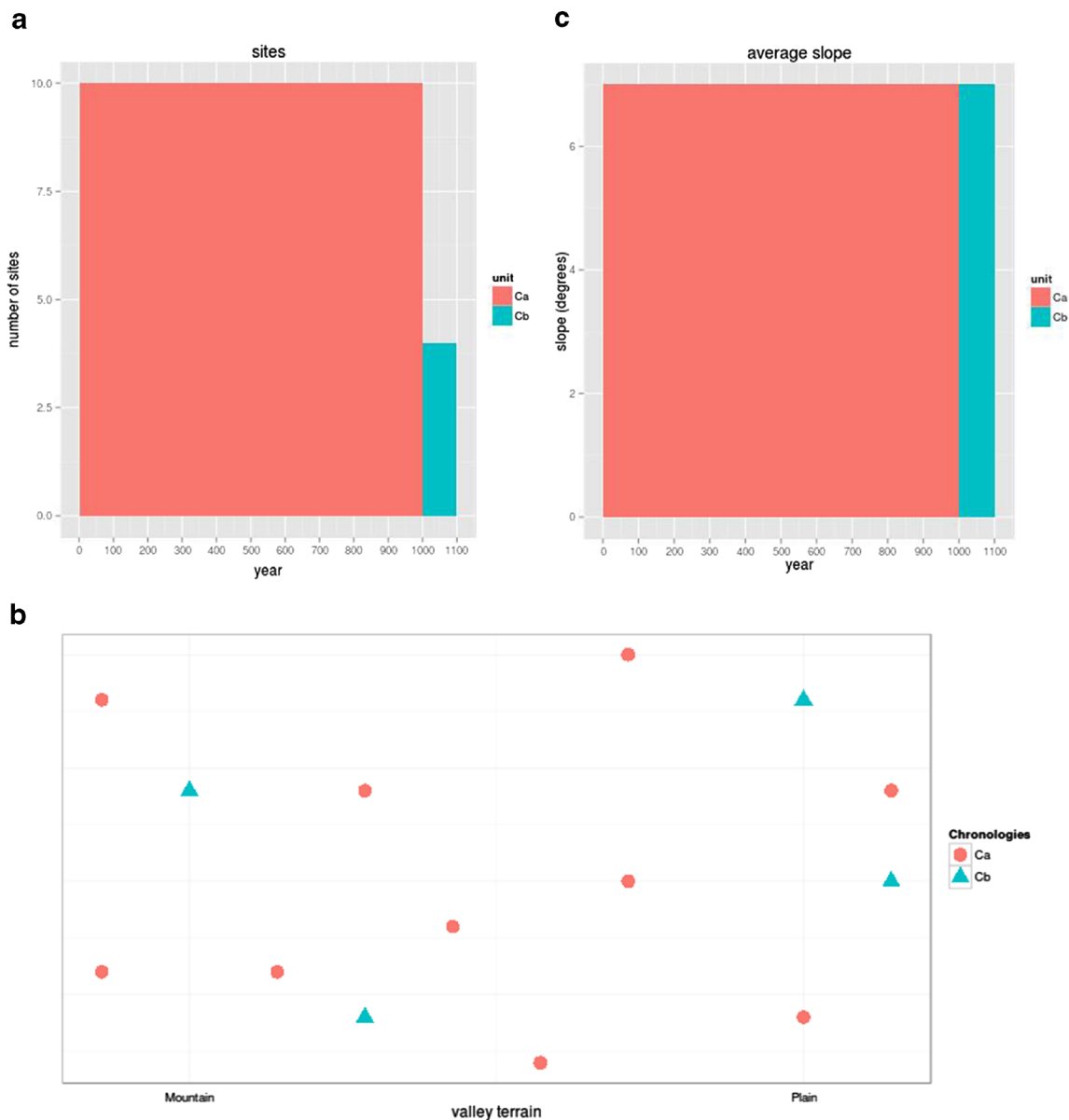
Both approaches are useful, especially when the study combines their results in one interpretation, but they do not solve the problem entirely.

Take two imaginary chronological units of an uneven time span ( $C_a=1000$  years and  $C_b=100$  years) as depicted in Fig. 1a and analyse geographical patterns of site settlements. During  $C_a$ , human populations gradually move

from a mountain to an adjacent plain (fieldwork has located a total of 10 locations that can be analysed). During the second phase (dataset of four sites), the population moves back to the mountains. A spatial analysis (Fig. 1b) does not show the pattern (the movement from mountain to plain in Ca and from plain to mountain in Cb) because it is impossible to split chronologies in smaller parts. Time series visualization (Fig. 1c) is also inadequate because it makes no provision for the site distribution. Although certain hypotheses can be tested using additional techniques (e.g. boxplots, variance in slope), it is impossible to link the statistical approach with additional explicit spatial data (distance between

sites, level of clustering); therefore, it is impossible to detect complex spatial patterns that change over time because spatial and temporal changes are not analysed by the same tool.

Another problem is the difference in time spans. The decrease in height values during Ca could be produced over a time span of 1000 years, 10 times more slowly than in Cb. The identification of different rates of change determines how clearly we can distinguish between gradual and sudden settlement dynamic variation, but cannot be detected with standard GIS-based tools. Archaeological research is therefore unable to apply the entire potential of spatial analysis and geostatistics to its



**Fig. 1** Spatial analysis of an archaeological dataset comprising two imaginary chronological units: **a** number of sites, **b** spatial distribution and **c** time series

data, because the analysis is typically conducted using separate models of spatial and temporal variability. And the time spans are homogenized.

### Uncertainty

The second issue raised in this paper is a long-standing question in archaeological research: how reliable is the data we work with?

First, that data has often been generated by different researchers using varying datasets and degrees of quality. This is particularly true of medium-scale studies, which use reports on sites that have been excavated over time periods of as long as 30 or 40 years and by teams supported by differing budgets. This can even have direct repercussions on the temporal coordinates of sites, specially when and where the quantity and quality of radiometric analysis is concentrated in a small number of sites.

Furthermore, uncertainty remains present in every type of data; however, thoroughly, a site has been researched. Even radiocarbon dates contain uncertainty and for this reason the real chronology of a site is expressed by a probabilistic model that is usually simplified or even discarded as data is progressively integrated from different sites. This has traditionally been applied when researchers work only with the average value, or with the average value plus the standard deviation. Finally, it is also common practice for researchers to discard radiometric datings with large error margins even though they are eliminating data that would be useful if this uncertainty was integrated in the model.

Three major consequences can be expected from this: first, imprecision and uncertainty in the measurements will be inherited in the model, even if they are not made explicit; second, the model will thus be imperfect; and third it will require revisions, which will alter our degree of understanding and our conclusions. These factors will inevitably lead to uncertainties in our evaluation of temporal data, but whether the magnitude of this uncertainty is acceptable will depend on our primary research questions (Crema et al. 2010).

In recent years, there has been some interest in addressing these issues, which are clearly linked because any formal geographical model that successfully deals with them will need to correctly model both time and uncertainty. This paper uses a spatiotemporal model integrating uncertainty to answer various questions about the uses of classical spatial analysis, and the remainder of the paper is organized as follows: “**Case study**” section describes the case study and reviews the research questions raised by previous spatial analysis. “**Model concepts**” section specifies the concepts that need to be integrated into the model; “**Methodology**” section describes the procedures used to build the model; and “**Discussion**” section interprets the results and evaluates the model’s effectiveness in analysing spatiotemporal patterns.

### The case study: the late prehistoric settlements of the Besòs river valley

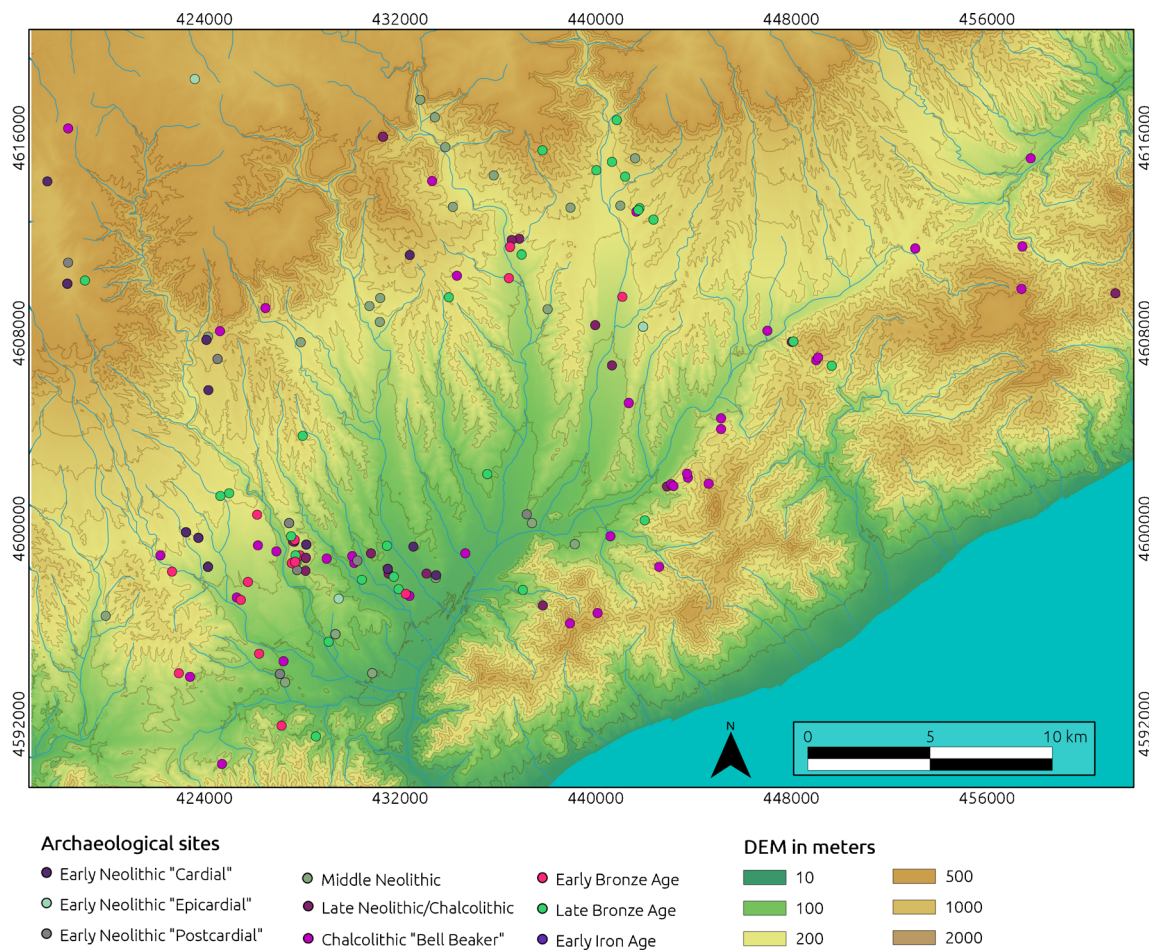
Our study area was located in the Besòs river valley, in the northeast of the Iberian Peninsula (see Fig. 2). During recent prehistory, the geographical, physical and environmental characteristics of this river valley made it an ideal territory for the survival of human groups and its archaeological sites show chronologies from the Palaeolithic period to the present day (Carlús i Martín and Terrats Jiménez 2003).

Located in the Catalan pre-coastal depression, the study area is a natural corridor approximately 200-km long and bears numerous traces of human occupation including evidence of houses, mills, canals, orchards, water wells, ice wells, roads, industries in nineteenth- and twentieth-century buildings, water supplies and archaeological and paleontological features (Carlús i Martín and Terrats Jiménez 2003; López Cachero 2005, 2007)

The area’s highly varied geography comprises a number of hills and mountains, a river basin and plain territories. On the one hand, this variety becomes valuable to researchers because they can study the human uses of each type of geography during different chronological units, from the Neolithic period to the Early Iron Age, and because a large number of sites straddle ancient prehistory and the modern age; on the other hand, the fact that their particular location has attracted successive periods of human occupation in different eras (Coll et al. 1993) has also made it more difficult to efficiently detect and analyse settlement patterns or to detect real occupation phases of sites.

Extensive research has been conducted on late prehistoric settlements (Esteve et al. 2004; Francés Farre 2005; Martín Còlliga 2009; Yubero Gómez and Rubio Campillo 2010; López Cachero 2012), but these studies have focused on specific periods or sites (Can Roqueta, Pla de la Bruguera, Camí de Can Grau) and have addressed questions at a local rather than global scale. For this reason, it is still difficult for us to compare and understand the spatiotemporal dynamics of the zone during the entire period of late prehistory. Moreover, in recent decades, the area has undergone large-scale urban development and most sites have been excavated, documented and subsequently destroyed. Researchers therefore have plenty of material evidence at their disposal, but the unequal nature of the fieldwork completed to date has created a high degree of uncertainty. The result, then, is that the set of late prehistoric sites that define the area constitutes an extremely fragmented aggregate, and the area as a whole has not been thoroughly studied.

Despite such issues, the area does offer a valuable starting point for exploring scenarios where formal spatiotemporal models integrating uncertainty are needed. First of all, recent



**Fig. 2** Late prehistoric archaeological sites located in the study area, depicted over a Digital Elevation Model raster map

years have seen the development of a new research project on landscape reconstruction and spatial analysis (Yubero Gómez and Rubio Campillo 2010; López Cachero 2012) and the creation of a geographical model to be used as the basic framework for exploring this kind of archaeological record from a mesoscale late prehistoric perspective. In this context, although geographical information systems have been powerful enough to organize and analyse all these data and although their capabilities have been used in previous studies, we must now acknowledge their inadequacy for integrating time in our analyses and consider that additional research techniques will be required if we wish to extend our studies to understand changing spatial patterns over time. Basically, our model needs to address the concept of data uncertainty. Previous works such as Crema et al. (2010), Bevan and Wilson (2013) and Bevan et al. (2012) integrating archaeological spatial and temporal date have been reference works in this field.

Table 1 describes the time span we are dealing with. The relative and radiometric datings have provided an interesting but challenging scenario for various papers (Barceló 2007a; Barceló et al. 2013).

As explained above, our case study analysed not only short-term settlement dynamics but also mid- and long-term issues. In particular, we considered the validity of three patterns proposed by previous studies (Yubero Gómez and Rubio Campillo 2010; Yubero et al. Forthcoming) but inadequately served by standard GIS-based models.

**Table 1** Chronological span for each chronological unit of late prehistory in the northeastern Iberian Peninsula, after Barceló (2007b)

Chronological unit	Absolute dates (approx.)
Early Neolithic <i>cardial</i>	5500–5000 BCE
Early Neolithic <i>epicardial</i>	5000–4400 BCE
Early Neolithic <i>postcardial</i>	4400–4000 BCE
Middle Neolithic	4000–3300 BCE
Late Neolithic/Chalcolithic	3300–2300 BCE
Chalcolithic "Bell Beaker"	2800–2200 BCE
Early Bronze Age	2300–1300 BCE
Late Bronze Age	1300–750 BCE
Early Iron Age	750–550 BCE

*Pattern 1: the number of sites decreases from the Late Bronze Age to the Early Iron Age* This pattern required further examination before it could be properly validated or identified as an artefact deriving from the comparison of different time spans.

*Pattern 2: Middle Neolithic sites depict different geographical traits to Early and Late Neolithic sites* The substantial variation in the variable slope suggests that during 4000–3300 BCE, the population was concentrated on the plains.

*Pattern 3: In all the periods of late prehistory except the Chalcolithic period and the Early Iron Age, the distance from sites to natural routes slowly decreased* If this pattern was validated, it would confirm that human populations constantly moved to strategic locations, but that there was a noteworthy variation on this trend in the case of the two periods described. Classical hypotheses propose that Chalcolithic populations are defined by small sites far away from the plains, and this is validated by spatial analysis (Yubero Gómez and Rubio Campillo 2010); on the other hand, the same study contradicts the long-standing hypothesis that the emergence of trade during the First Iron Age prompted populations to seek strategically located settlements, arguing that only a small number of sites offer the geographical data to corroborate this.

It was clear that an exclusively geographical approach would be an inadequate means of testing the validity of these three patterns, and that new paradigms were needed to create a spatiotemporal model that could integrate explicit uncertainty variables (Bevan and Wilson 2013; Bevan et al. 2012).

Finally, a further reason for adopting a spatiotemporal framework was that this could help us detect whether differences in the rate of change were more or less sudden or gradual. The three variables (number of archaeological sites, slope, distance from natural corridors) were thus analysed within a long-term perspective.

## Model concepts

This section examines the concepts that played an important role in our model: settlement location and chronologies, and geographical and temporal data.

### Spatial site database

In previous research, our spatial database was specifically designed for the needs of the case study and was based on an entity-relation model that could integrate existing data from different sources and be extended for further testing of the validity of the three patterns described above in “**Model**

**concepts**” section. The design allowed us to store, search and execute queries as needed. Moreover, it was flexible enough to accept changes without our having to modify the entire design and structure of the database (Yubero Gómez and Rubio Campillo 2010).

The database had 237 entries and contained all the relevant information about the sites in the study area, including a geo-referenced location, a list of chronological units of use and radiometric datings.

### Geographical variables

A geographical model of the study area was needed to test the validity of the three patterns. The basic information is collected in previous or forthcoming papers, especially in (Yubero Gómez et al. *In press*; Yubero Gómez et al. *Forthcoming*; Yubero Gómez and Rubio Campillo 2010), where changes in Late Bronze-Early Iron Age mobility patterns are analysed. The third study defines two variables used again in the new spatiotemporal model: slope and distance to natural corridors.

Slope is the degree of inclination of a given location in relation to its neighbouring space (defined using Moore neighbourhood). The study of this variable helps to detect changes in settlement locations, from mountains to plains, and was particularly useful in the case of our study area, where there appears to be a direct link between the pattern of sites with high slope values and periods of high conflictivity. In these cases, steep slopes usually define locations with high control of the surrounding area combined with low accessibility.

On the other hand, the variable distance from archaeological sites to natural corridors is a powerful marker of the importance of good communication at mesoscale levels (Murrieta-Flores 2012). In order to calculate this, we defined a perimeter of points at a distance of 25 km from the study area at a resolution of 10 km. Then, we calculated the least-cost routes from each point on the perimeter to all the other points, while quantifying how many of the routes pass through each cell of the original raster map. The routes with the highest value (for example, taking the quartile with the highest number of routes) define the natural corridors according to the geography of the area. Studying this relationship by chronology and area enables us to see the extent to which this variable is significant and place it in relation to the archaeological contexts. Sites closer to the natural corridors of an area offer clear advantages for external trading and control of the territory, while settlements located further away from these routes are easier to defend in times of conflict because of their remote and inaccessible position.

### Temporal uncertainty

Different approaches have been used to integrate the role of temporal uncertainty in archaeology (Lock and Harris 1997;

Lock and Molyneaux 2006). In our case study, we applied the framework proposed by Crema et al. (2010; Crema 2012), which uses a probabilistic model to quantify time when high levels of uncertainty hinder spatiotemporal analysis: the aoristic model (Ratcliffe 2000; Johnson 2003). This framework provides the researcher with a probabilistic model that can be combined with a Monte Carlo approach to explore potential spatial trajectories over time. Moreover, different techniques can be applied to the dataset generated by the simulations, testing a pattern or hypothesis against each run or performing risk analysis techniques in results (Bevan et al. 2012).

## Methodology

We applied the described spatiotemporal framework to our data. Our intentions were to solve the problems in our geographical model and, as explained above, to quantify uncertainty in order to improve our understanding of mid-term settlement dynamics like those detected in the three patterns described above.

In order to explore the validity of the patterns described above in “Model concepts” section, the following steps were applied to the data of our case study.

### Aoristic model

An aoristic model defines for each event a probability distribution of absence over discrete time steps. This probability is 0 outside the span comprised between by the absolute beginning (*terminus post quem*) and absolute ending (*terminus ante quem*) of the event, and equal probability of presence for all the time steps between these dates (this value is defined as *aoristic weight*).

Each event of our case study is the creation or reoccupation of a settlement through a chronological unit, and *t.p.q.* and *t.a.q.* are defined as the chronological units proposed in Table 1. The sum of the aoristic weights for a site in a given chronological unit is always 1, but there is no consensus about duration and number of occupations of each site within a given chronological unit. For this reason, the time step of the aoristic model has been defined at 50 years, as resolution adjusts to the quality of the information we have in this case study and the spans of the temporal units. Finally, each settlement can exist multiple time steps during each chronological unit.

The aoristic weight  $W$  of a settlement  $S$  for a given time step  $T_N$  is defined as

$W_{S,T_N} = \frac{\Delta T}{\beta_S - \alpha_S}$ , being  $\Delta T$  the duration of a time step,  $\beta_S$  the *terminus post quem* of the chronological unit, and  $\alpha_S$  its *terminus ante quem*.

Figure 3a shows the sum of aoristic weights for the case study. If we compare the global trends of the figure with the sum of sites per pottery phase (defined in Fig. 3b), the value of the aoristic model becomes clear in that it allows us to question pattern 1 and to identify the supposed decrease in the number of sites during the transition from Late Bronze Age to Early Iron Age as an artefact produced by the differences in time span between the two periods (550 to 200 years). The simple move from a model based on pottery to an aoristic model shows how the number of sites actually increased.

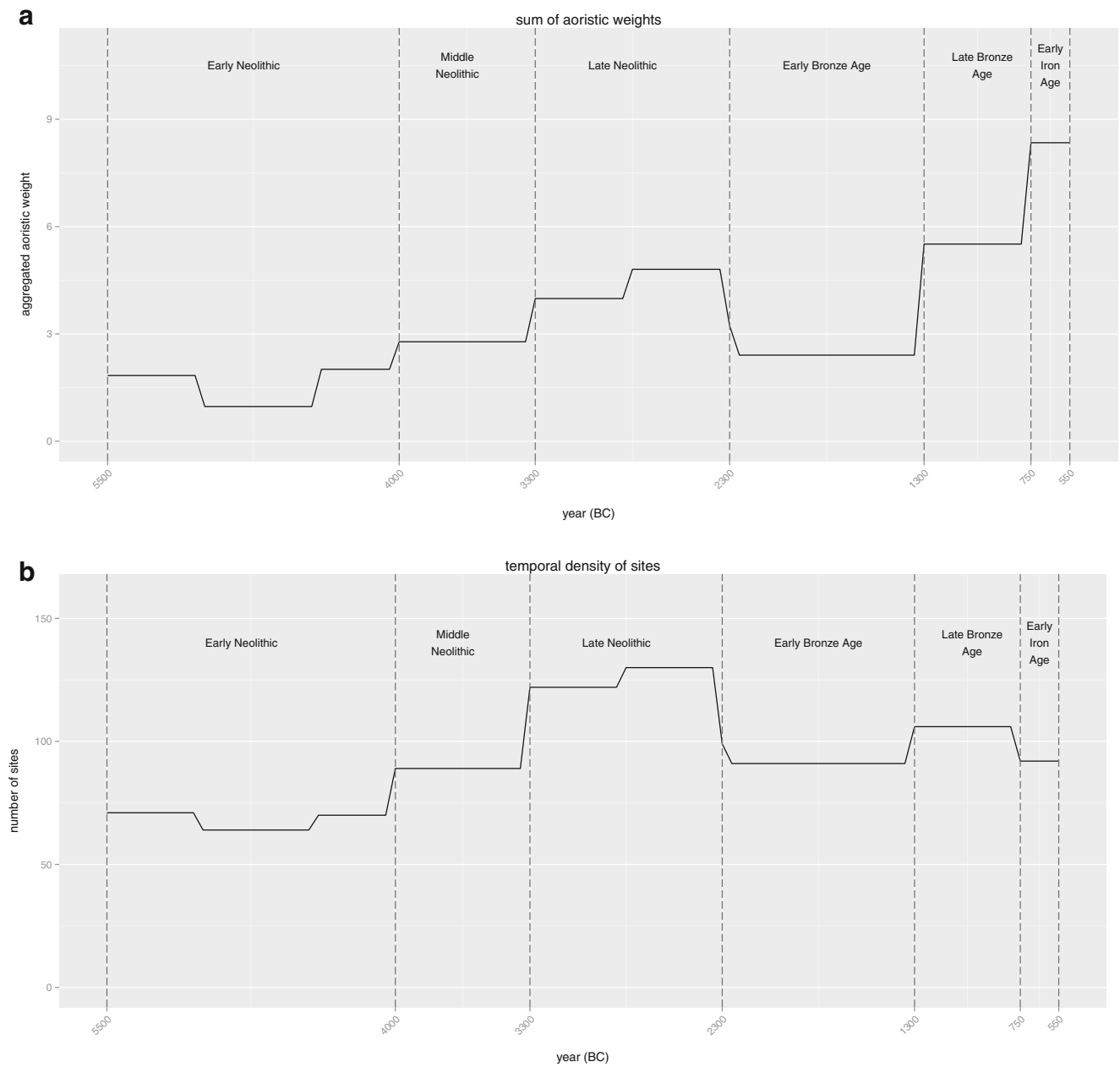
Although this comparison is valuable, the aoristic model alone cannot be used to test hypotheses on the subject of spatiotemporal patterns because the model’s probabilistic basis is difficult to translate to spatial coordinates, even though certain proposals have been made (Crema 2011). For this reason, to gather information related to spatial change over time, we designed an experiment based on Monte Carlo simulations.

### Monte Carlo simulations

The approach we used is proposed by Crema et al. (Crema 2012; Crema et al. 2010). The idea was to use the probabilities of site existence defined in the aoristic model as an input for a Monte Carlo simulation. This technique is suited for exploring stochastic models where the number of probabilistic combinations is too high to be explored in the standard manner (by studying all the possible combinations of settlement occupation/abandonment for each time step). We simulated different historical trajectories using the aoristic weight of a site for a given time step as the probability of existence of a Bernoulli distribution. Each run computes, for each site and time step, absence/presence based on the aoristic weights for each chronological unit. Considering the high level of reoccupations, presence of a site during time step is independent, and each site can be abandoned and reoccupied several times during one chronological unit.

This created different trajectories for each run where we can identify settlement patterns. As an example, Table 2 describes the result for one of these runs.

The number of executions performed during the simulation was large because the uneven quality of the dataset generated a high level of variation. To use an appropriate (and at the same time minimum) number of runs a convergence test was designed. Figure 4 shows the density plots of standard deviations during time step for different number of runs (100, 1000 and 10,000). A Kolmogorov-Smirnov test was performed, considering that the density plot showed nonparametric shapes for the different sample sizes (results: (a) KS test between 100 and 1 k produced a  $p$  value of 0.36 and (b) the test between 1 and 10 k produced a  $p$  value of 0.96). Considering that the 1 and 10 k distributions were indistinguishable, we therefore chose 1 k as the sample size of the different analysis.

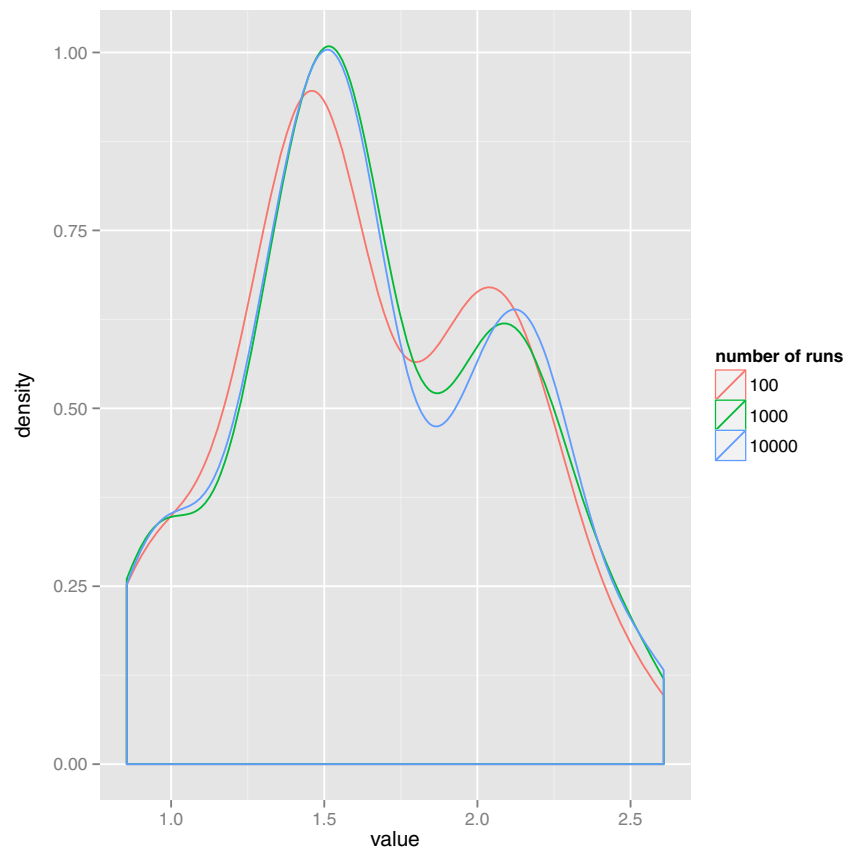


**Fig. 3** **a** The sum of aoristic weights for the archaeological sites of the Besòs valley in relation to time steps. **b** Number of sites per time step based on relative dating of pottery phases

**Table 2** A single Monte Carlo execution of our case study recording the existence (1) or nonexistence (0) of different sites for the period 1050–600 BCE

Simulation	Time steps of 50 years											
	...	1050	1000	950	900	850	800	750	700	650	600	...
Archaeological site	...	1050	1000	950	900	850	800	750	700	650	600	...
Can Piteu-Can Roqueta	...	0	1	0	0	0	0	0	0	1	0	...
Can Gambús-1	...	0	0	0	0	0	0	0	0	0	1	...
Pla de la Bruguera	...	0	0	0	0	0	0	1	0	0	0	...
...	...	...	...	...	...	...	...	...	...	...	...	...

**Fig. 4** Density plots for standard deviations of 100, 1 and 10 k sample sizes of the Monte Carlo distributions



The spatiotemporal model could thus be studied through the testing of hypotheses (examining the validity of patterns) in each of these 1000 trajectories, which provides the researcher with a global approach to the data where temporal uncertainty has already been taken into account. Results for each variable are shown in Fig. 5a (number of sites), 5b (slope) and 5c (distance from natural routes).

Cross-validation of the aoristic model with radiocarbon dates

The framework combines the aoristic approach to temporal uncertainty with Monte Carlo simulations for integrating archaeological and spatial data. Unfortunately, it is difficult to use multiple data sources without breaking the coherence of the probabilistic model.

This is extremely important where radiometric datings are available for some of the sites. This data should be combined with the general temporal information provided by pottery dating but the aoristic model cannot integrate different time spans for the same event. Lock and Harris suggest an alternative approach in which each dating technique has an associated weight and the final value of each site is computed as the sum of the different values for each time step and site (Lock and Harris 1997). This approach is incompatible with Monte Carlo simulations because weights are chosen by the

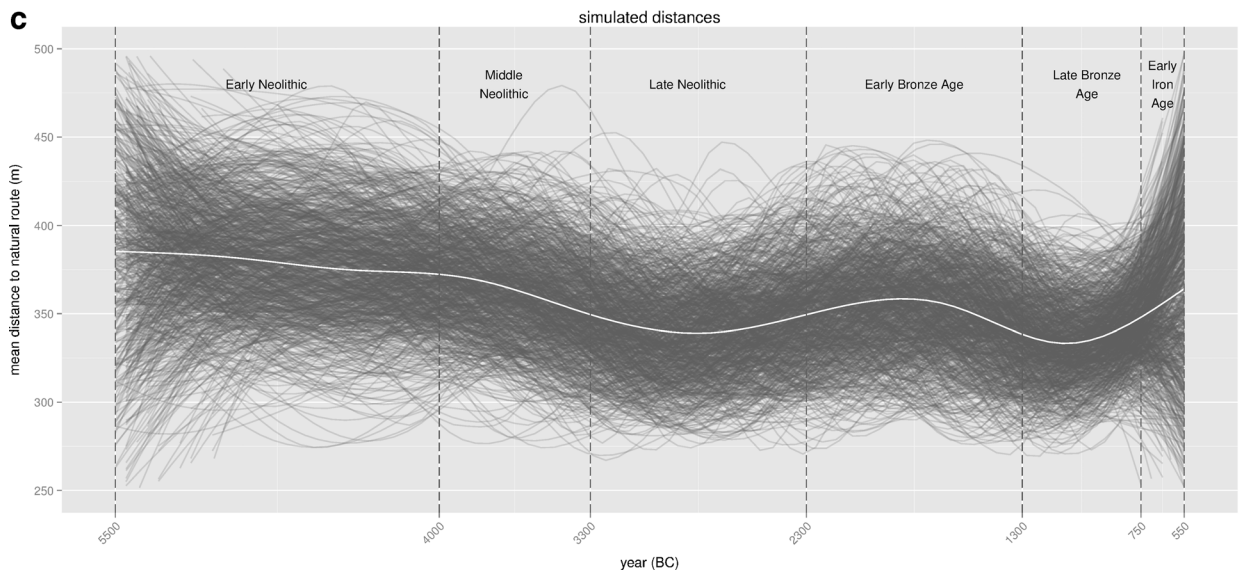
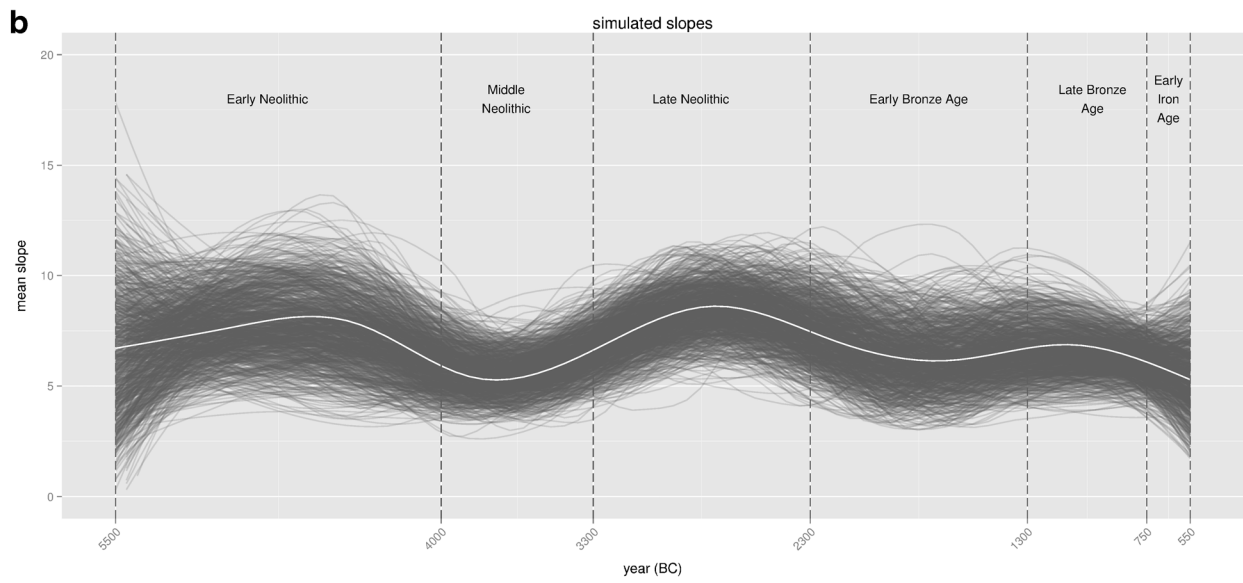
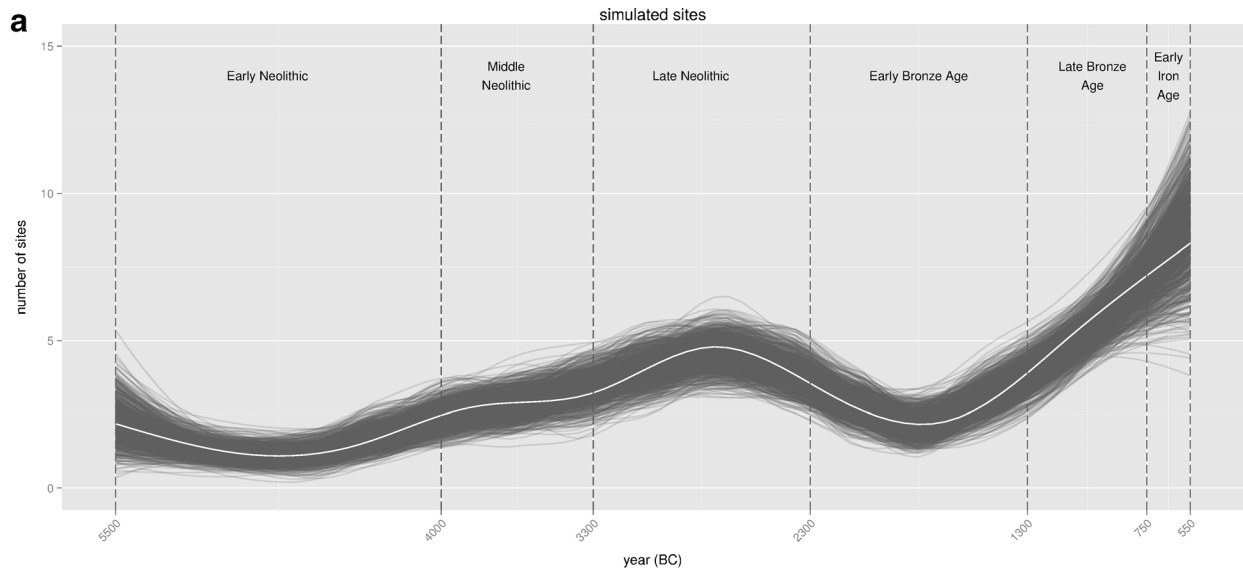
researcher and the final value cannot be used as a probability between 0 and 1.

In addition, in our case study, radiocarbon dates were concentrated in a small number of sites (e.g. Bòbila Madurell, Cova del Frare and Can Roqueta) and were either scarce or nonexistent in the majority. For this reason, any integration of radiocarbon datings into the aoristic model would distort the results and introduce a clear bias towards the most documented sites.

We propose an alternative method for radiometric dating in spatiotemporal models which we believe can be useful when researchers have a low number of datings, as we did in this case study. The method consists in validating the model for the most well-represented time steps instead of integrating radiocarbon datings into the model. The comparison of the average geographical values should provide insight about the degree of correctness of our aoristic model built from pottery datings.

**Fig. 5** **a** Number of sites generated by Monte Carlo simulations. Each *grey line* shows the results for a different run, and the *white shape* is the average trajectory. **b** Slope of existing sites, generated by Monte Carlo simulations. Each *grey line* shows the results for a different run, and the *white shape* is the average trajectory. **c** Distance of existing sites from natural routes, generated by Monte Carlo simulations. Each *grey line* shows the results for a different run, and the *white shape* is the average trajectory



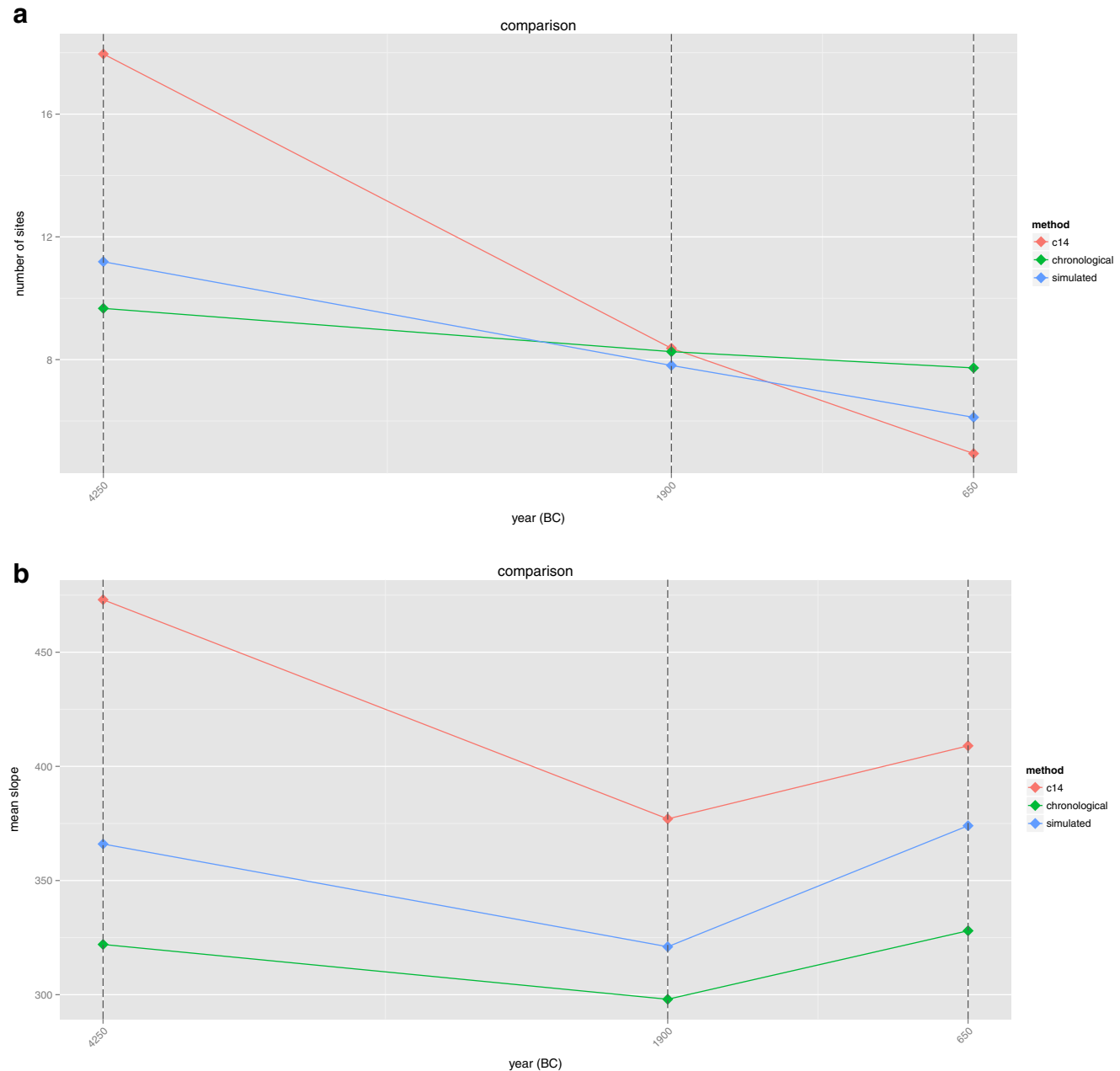


This cross-validation is shown for slope and for distance from natural routes in Fig. 5a, b over three different time steps: 4250, 1900 and 650 BCE.

In our case study, these were the sites that offered the highest number of radiocarbon dates, so the information provided by this average was the most reliable information we could retrieve from the data available. Additional research and analysis could improve the picture, but even with such scarce data, we could confirm that the patterns detected using the aoristic model were

reproduced using just the sites dated during these time steps with radiometry.

Given the sample of sites with radiocarbon dates (5–10), validation remained difficult. However, the comparison of tendencies could still provide us with information about the spatiotemporal patterns: in all cases, we observed a constant decrease of the mean value for slope (Fig. 6a), while in the case of the variable distance from natural sites, the values decreased from 4250 to 1900 BCE and increased slightly from 1900 to 650 BCE (Fig. 6b).



**Fig. 6 a** The average for the variable slope described for the different models at time steps 4250, 1900 and 650 BCE. The value was computed from the collection of sites existing in these time steps. C14 values are taken from the mean value of the probabilistic distribution. **b** The average

for the variable distance from natural routes described for the different models at time steps 4250, 1900 and 650 BCE. The value was computed from the collection of sites existing in these time steps. C14 values are taken from the mean value of the probabilistic distribution.

To sum up, in the cases where radiometric datings are available in small numbers, we suggest using these datings to cross-validate the model. The comparison of the spatial trends detected in the Monte Carlo simulations against the sites with radiometric datings for a particular time step can be used to test whether detected patterns are consistent. Naturally, the only drawback is that this technique cannot be used to examine the variable number of sites.

#### Calculation of spatial values

The next step was a computation of the variables needed to test the validity of the three patterns described above in “Model concepts” section. In our case study, we wanted to understand the temporal differences in the changes in settlement dynamics detected with classical spatial analysis.

In order to do this the pace of change must be calculated for every time step as follows.

- For each settlement, extract the value of the variables (in our case, slope and distance from natural routes).
- For each time step and simulated trajectory, calculate the average value of (a) above (i.e. compute the average for the set of sites that exist during each time step).
- Apply a temporal kernel of 150 years (3 time steps) to (b) above, under the following formula:

$$WT_n = \frac{\sum_{i=n-1}^{n+1} \overline{WT}_i}{3},$$

being  $WT_n$  the value of the time step  $T_n$  at a given trajectory. The temporal kernel algorithm is applied to avoid distortions provoked by outliers at particular time steps. The technique smooths the variation, while the relatively narrow width of the kernel prevents it from removing the underlying pattern.

#### Detection of variation

The rate of variation is also a relevant variable while analysing settlement dynamics. In order to explore this concept, relative variation was computed from absolute values provided by Monte Carlo simulation. For each time step, the rate of variation was computed as an angle, using the Pythagorean theorem.

The sign of the variation shows whether the change is an increase or a decrease, while its value provides the rate of change (0 being the value when consecutive time steps have identical absolute values). The results can be seen in Fig. 7a–c.

## Discussion

The results generated by this model were used to test the validity of the three patterns described above in “Model concepts” section. In particular, our intention was to examine whether a pattern that had been observed by classical spatial analysis could still be detected when the temporal variable was incorporated. Our results were as follows:

Pattern 1 (the number of sites decreases from the Late Bronze Age to the Early Iron Age)

Figure 3b shows that the absolute number of sites decreases in this transition. In contrast, the aoristic model shown in Fig. 3a proves that the probability of a new site actually increases. For this reason, this pattern can be discarded as an artefact derived from comparing chronological units with different time spans.

Pattern 2 (Middle Neolithic sites depict different geographical traits to Early and Late Neolithic sites)

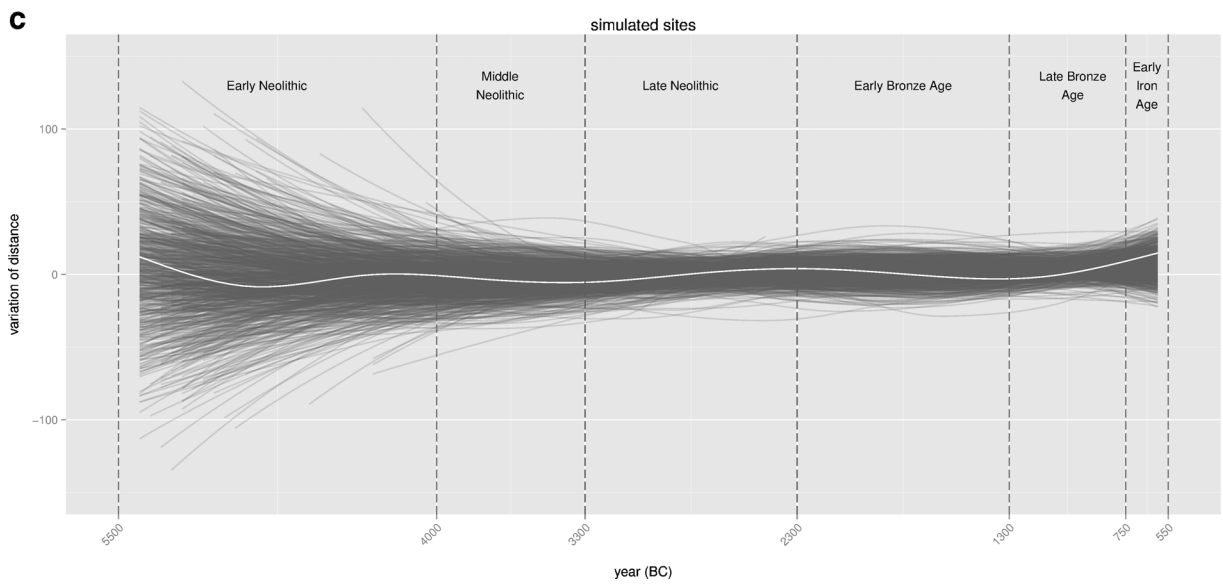
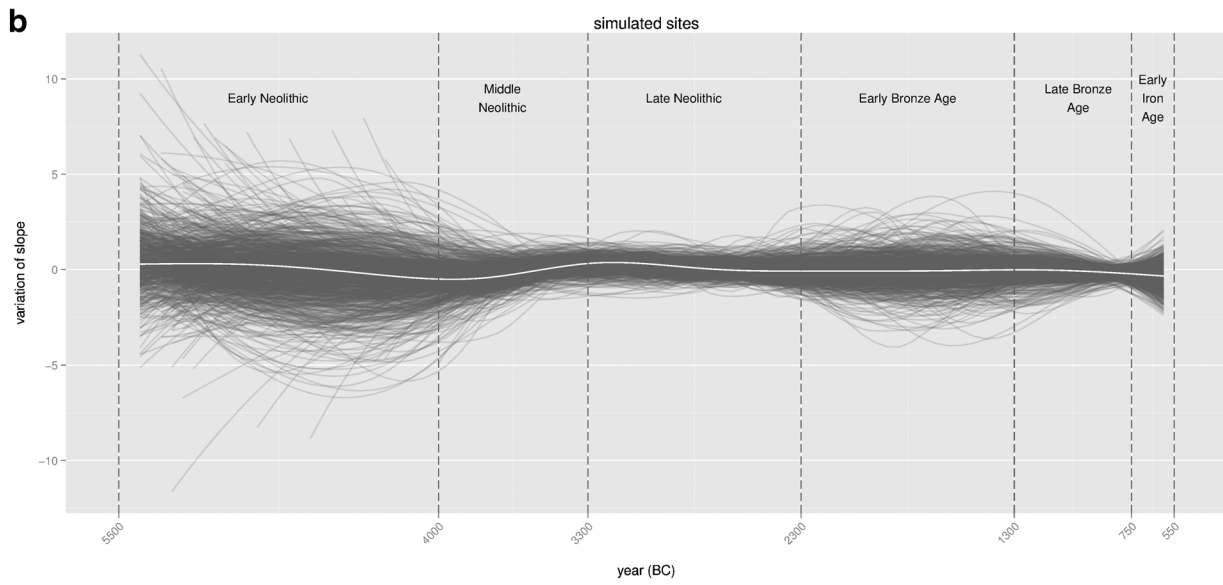
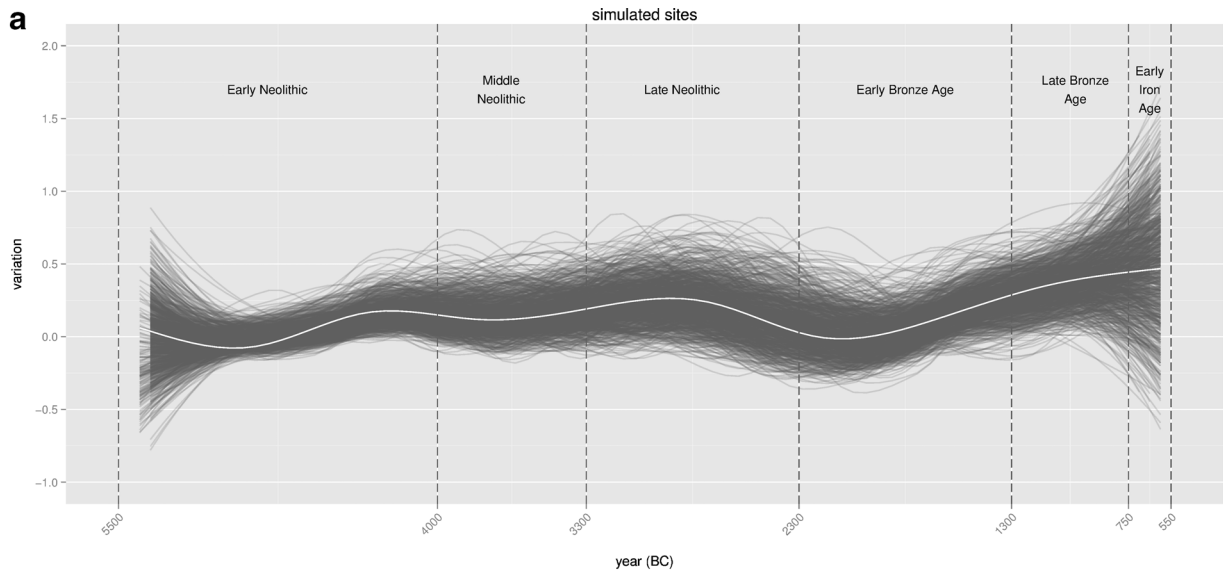
Figure 5a, c suggests that the geographical traits of Middle Neolithic settlement dynamics are no different to those of other Neolithic chronological units. In the evolution of both variables (number of sites and distance from natural routes), the Middle Neolithic continues the trend of Early Neolithic and Late Neolithic: an increase in the number of sites, and a decrease in the distance from natural routes.

On the other hand, a different pattern was notable for the variable slope. In the aoristic model (Fig. 5b), this trend is confirmed and Middle Neolithic behaviour appears closer to later periods such as the Bronze Age or First Iron Age than it is to the Neolithic. The explanation may be that during the Middle Neolithic human populations emigrated from other areas to the area of our study. The settlers’ priorities would have differed to the priorities of previous occupants of the area, so that the niche they occupied (plains without great strategic value) was not previously used. This possibility is supported by the rate of variation (Fig. 7b), where the decrease in slope is sudden and is only detected at the beginning of the chronological unit (in contrast to variations like the increase produced at the end of the Middle Neolithic).

Pattern 3 (in all the periods of late prehistory except the Chalcolithic period and the Early Iron Age, the distance from sites to natural routes slowly decreased)

This pattern is validated in most of the chronological units studied, with two important exceptions.

The first exception is that Early Neolithic epicardial sites do not follow the pattern, as Fig. 5c clearly shows (the pattern of previous and subsequent chronological units is completely different). This difference (almost half the distance from natural routes than in the other periods) can be understood as an artefact generated by a low sample. In fact, this is the period with a lowest number of sites, so the results will have to be considered inconclusive until new data can validate this pattern.



◀ **Fig. 7** **a** Variation in number of sites for the chronological model. **b** Variation in slope for the chronological model. **c** Variation in distance from natural routes for the chronological model

The second exception is the Chalcolithic and Early Iron Age. These chronological units show a slight increase in the distance of sites from natural routes, as observed above. Nevertheless, closer inspection of the rate of variation (Fig. 7c) reveals that this perspective is distorted: in both cases, the trend is not a sudden change but a gradual increase that was already present during previous chronological units. We can therefore conclude that the supposed pattern of gradual movement from heights towards natural routes is not real, and that during long periods of time, there was movement in the opposite direction.

To summarize, first of all, this paper has described how a probabilistic spatiotemporal model can validate the existence of changes in settlement dynamics observed with classical spatial analysis. In particular, the trends are verified when periods have similar time spans and highly unlikely when this is not the case (as repeatedly shown with Late Bronze Age and Early Iron Age data).

Second, our study has integrated radiometric dating to the point where it can be useful but does not create a strong bias of the results towards the most well-known sites. In other words, our work suggests that the synchronic comparison of variables can validate the diachronic approach of the aoristic model whenever this is allowed by the number of radiometric datings for a particular time. This is useful when the dataset is uneven (as in our study). However, in case studies where a large amount of available radiometric datings, it would be desirable to create the aoristic model exclusively based on this high-quality datasets.

Third, we have proposed that the study of the rate of variation is extremely useful for exploring long-term settlement dynamics. Once we move from a comparison between chronologies and a more continuous study, temporal differences between changes must be studied, and this paper has offered a simple algorithm capable of dealing with this variable on top of the aoristic model.

Finally, we propose that any comparison of geographical variables for different chronologies should address temporal uncertainty. Temporal uncertainty plays a crucial role in our understanding of the relationship between archaeological sites and their environment, and if we are to fully understand spatiotemporal change, then archaeological research must begin to consider this issue.

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