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

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Highlights

- A classical modelling of time in GIS can generate wrong spatial patterns
- A new method is proposed to apply spatial analysis to uneven archaeological record.
- Mesoscale settlement studies need to integrate temporal uncertainty in order to understand spatial dynamics
- Late Prehistory in Besòs valley presents an unequal quality of archaeological data

1 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 chronologies 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.

2 Introduction

In archaeological research, medium- to large-scale spatiotemporal data are most typically represented by geographical models using spatial databases (see Garcia, 2013; García-Sanjúan et al., 2009; Ruestes, 2008; Fairén-Jiménez, 2004; Pinhasi et al., 2005); 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.

1. The study of temporally explicit patterns

Geographical Information Systems are not designed for working with problems where time variables and spatial variables are equally important; and although the issue has been variously discussed (Bailey, 2007; Curry, 1998; Mlekuž, 2010), GIS-based tools remain an inadequate means of integrating temporal coordinates in spatial models and cannot provide standard analysis of spatiotemporal patterns, despite the importance of this analysis 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 chronologies of an uneven time span (Ca = 1000 years and Cb = 100 years) and analyse these using the variable site height. During Ca, 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 4 sites), the population moves back to the mountains. The first option (Figure 1a) 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 a chronology in smaller parts. The second option (Figure 1b) is also inadequate because it makes no provision for the site distribution. And although certain hypotheses can be tested using additional techniques (e.g., boxplots, variance in height), it is impossible to link the statistical approach with additional explicit spatial data (distance between sites, level of clustering); it is impossible to detect complex spatial patterns that change over time because spatial and temporal changes are not analysed by the same tool.

Figure 1. Spatial analysis of an archaeological dataset comprising two imaginary chronologies: 1a) Spatially explicit study; 1b) Statistical approach to spatial data

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, ten 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 data, because the analysis is split into spatial and temporal variables and the time spans are homogenized.

2. 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, 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: Section 3 describes the case study and reviews the research questions raised by previous spatial analysis. Section 4 specifies the concepts that need to be integrated into the model; Section 5 describes the methodology used to build the model; and Section 6 discusses the results and evaluates the model’s effectiveness in analysing spatiotemporal patterns.

3 The case study: the late prehistoric settlements of the Besós river valley

Our study area was located in the Besós river valley, in the northeast of the Iberian Peninsula (see Figure 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).

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

Located in the Catalan pre-coastal depression, the study area is a natural corridor approximately 200 kilometres 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, 2006, 2005).

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 chronologies, 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 (Martin Cólliga, 2009; Martin Cólliga et al., n.d.; Esteve et al., 2004; Francés Farre, 2005; López Cachero, 2012; Martin Cólliga, 1990; Yubero Gómez and Rubio Campillo, 2010), 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.

Beyond such questions, however, the area does offer a valuable starting point for exploring scenarios where formal spatiotemporal models integrating uncertainty are needed. First of all, recent years have seen the development of a new research project on landscape reconstruction and spatial analysis (López Cachero, 2012; Yubero Gómez and Rubio Campillo, 2010) 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 changes spatial patterns over time.

To study spatiotemporal dynamics in late prehistory our model will also need to address the concept of data uncertainty. This is especially important in the examination of late prehistoric settlements in the northeastern Iberian Peninsula, where the Late Neolithic and Chalcolithic periods are difficult to identify and radiometric dating for Early Iron Age sites is hampered by the Hallstatt Plateau (Barceló, 2007a; López-Cachero and Pons, 2007).

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, 2007b; Barceló et al., 2013).

Period	Absolute dates (approx)
Early Neolithic *cardial*	5500–5000 BCE
Early Neolithic *epicardial*	5000–4400 BCE
Early Neolithic *postcardial*	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

Table 1. Chronological span for each period of late prehistory in the northeastern Iberian Peninsula, after Barceló, 2007b

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 but inadequately served by standard GIS-based models.

Pattern 1: The number of sites decreases from the Late Bronze Age to the Early Iron Age. Note that this pattern had provided the basis for a long-standing hypothesis but 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. In particular, note the substantial variation in the variable slope, which 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.Note that 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 et al., 2012; Bevan and Wilson, 2013).

Finally, a further reason for adopting a spatiotemporal framework was that this could help us detect whether differences in change rate 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.

4 Model concepts

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

4.1 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 Section 3. 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 chronologies of use and radiometric datings.

4.2 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 and Rubio Campillo, 2010; Yubero Gómez et al. (in press) and Yubero-Gómez et al. (forthcoming), where changes in Late Bronze-Early Iron Age mobility patterns are analyzed. The third study defines two variables used again in the new spatiotemporal model: distance from natural corridors, and slope.

The study of the variable slope can help 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 natural corridors is a powerful marker of the importance of good communication at mesoscale levels. 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.

4.3 Temporal uncertainty

Different approaches have been used to integrate the role of temporal uncertainty in archaeology (Lock and Molyneaux, 2007; Lock and Harris, 1997). In our case study we applied the framework proposed by Crema et al. (Crema, 2012; Crema et al., 2010), which uses a probabilistic model to quantify time when high levels of uncertainty hinder spatiotemporal analysis: the aoristic model (Johnson, 2004; Ratcliffe, 2000). This framework provides the researcher with a probabilistic model that can explore potential spatial trajectories over time with a Monte Carlo approach. Moreover, different techniques can be applied to the dataset generated by the simulations, testing a pattern or hypothesis against each run or analysing the percentage of confidences and variation in results

(Bevan et al., 2012).

We applied this 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.

5 Methodology

In order to explore the validity of the patterns described above in Section 3, the spatiotemporal framework was applied as follows.

5.1 Aoristic model

The model was developed with aoristic probabilities based on chronological information collected in the database. A new table was introduced, defining the absolute beginning (*terminus post quem*) and absolute ending (*terminus ante quem*) for each period using the chronologies proposed in Table 1.

The temporal resolution of a step for the aoristic model was defined at 50 years, archaeological evidence indicating that no settlement would be occupied more for longer than this. This temporal resolution also adjusts to the quality of the information we for this case study.

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 ΔT the duration of a time step, β_s the *terminus post quem* of the site, and α_S the *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 Figure 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.

Figure 3a. The sum of aoristic weights for the archaeological sites of the Besós valley in relation to time steps

Figure 3b. Number of sites per time step based on relative dating of pottery phases

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.

5.2 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. Table 2 describes the result for one simulation.

Simulation	**Time steps of 50 years**											
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	...
...	...	...	...	...	...	...	...	...	...	...	...	...

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

The number of executions performed during the simulation was large because the uneven quality of the dataset generated a high level of variation. We therefore performed different sets of simulation runs (100, 1,000, 10,000) to confirm whether the results would be similar. Because the variation in values between the second and third runs was low, the following sections use the results provided by the larger set.

The spatiotemporal model could thus be studied through the testing of hypotheses (examining the validity of patterns) in each of these 10,000 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 Figure 4a (number of sites), 4b (slope) and 4c (distance from natural routes)).

Figure 4a. Number of sites generated by Monte Carlo simulations. The boxplot provides information on average and variation of this variable over the different time steps.

Figure 4b. Slope of existing sites, generated by Monte Carlo simulations. The boxplot provides information on average and variation of this variable over the different time steps.

Figure 4c. Distance of existing sites from natural routes, generated by Monte Carlo simulations. The boxplot provides information on average and variation of this variable over the different time steps.

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

Figure 5a. 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.

Figure 5b. 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.

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, while in the case of the variable distance from natural sites the values decreased from 4250 to 1900 BCE and increased slightly from 1900 BCE to 650 BCE.

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.

5.4 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 Section 3. 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.

a) For each settlement, extract the value of the variables (in our case, slope and distance from natural routes).

b) 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).

c) Apply a window slide of 150 years (3 time steps) to *(b)* above, under the formula:

$WT_n = \frac{\sum_{i=n-1}^{n+1} \overline{WT_i}}{3}$, being WT_n the windowed value of the time step T_n at a given trajectory. The window slide algorithm is applied to avoid distortions provoked by outliers at particular time steps. The technique smoothes the variation, while the relatively narrow width of the window prevents it from removing the underlying pattern.

5.5 Detection of variation

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 Figure 6.

Figure 6a. Variation in number of sites for the chronological model

Figure 6b. Variation in slope for the chronological model

Figure 6c. Variation in distance from natural routes for the chronological model

6 Discussion

The results generated by this model were used to test the validity of the three patterns described above in Section 3. 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 proves that the probability of a new site actually increases. For this reason, this pattern can be discarded as an artefact derived from comparing chronologies with different time spans.

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

Figures 4a and 4c suggest that the geographical traits of Middle Neolithic settlement dynamics are no different to those of other Neolithic chronologies. 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 (Figure 4b) 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 a generally used one. This possibility is supported by the rate of variation (Figure 6b), where the decrease in slope is sudden and is only detected at the beginning of the chronology (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 chronologies studied, with two important exceptions.

The first exception is that Early Neolithic epicardial sites do not follow the pattern, as Figure 4c clearly shows (the pattern of previous and subsequent chronologies 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.

The second exception is the Chalcolithic and Early Iron Age. These chronologies show a slight increase in the distance of sites from natural routes, as observed above. Nevertheless, closer inspection of the rate of variation (Figure 6c) 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 chronologies. 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 times there was movement in the opposite direction.

To summarize, first of all this paper has described how a probabilistic spatiotemporal model can validate or disprove 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 disproved 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), but it is clear that the most advanced solution should be used for case studies with a large amount of radiometric datings.

Third, we have proposed that the study of the rate of variation is extremely useful from an evolutionary point of view. Once we move from a comparison between chronologies to 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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Table1

Period	**Absolute dates (approx)**
Early Neolithic *cardial*	5500–5000 BCE
Early Neolithic *epicardial*	5000–4400 BCE
Early Neolithic *postcardial*	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

Table2

Simulation					
Archaeological site	...	1050	1000	950	900
Can Piteu-Can Roqueta	...	0	1	0	0
Can Gambús-1	...	0	0	0	0
Pla de la Bruguera	...	0	0	0	0
...	...	...	...	...	...

Figure

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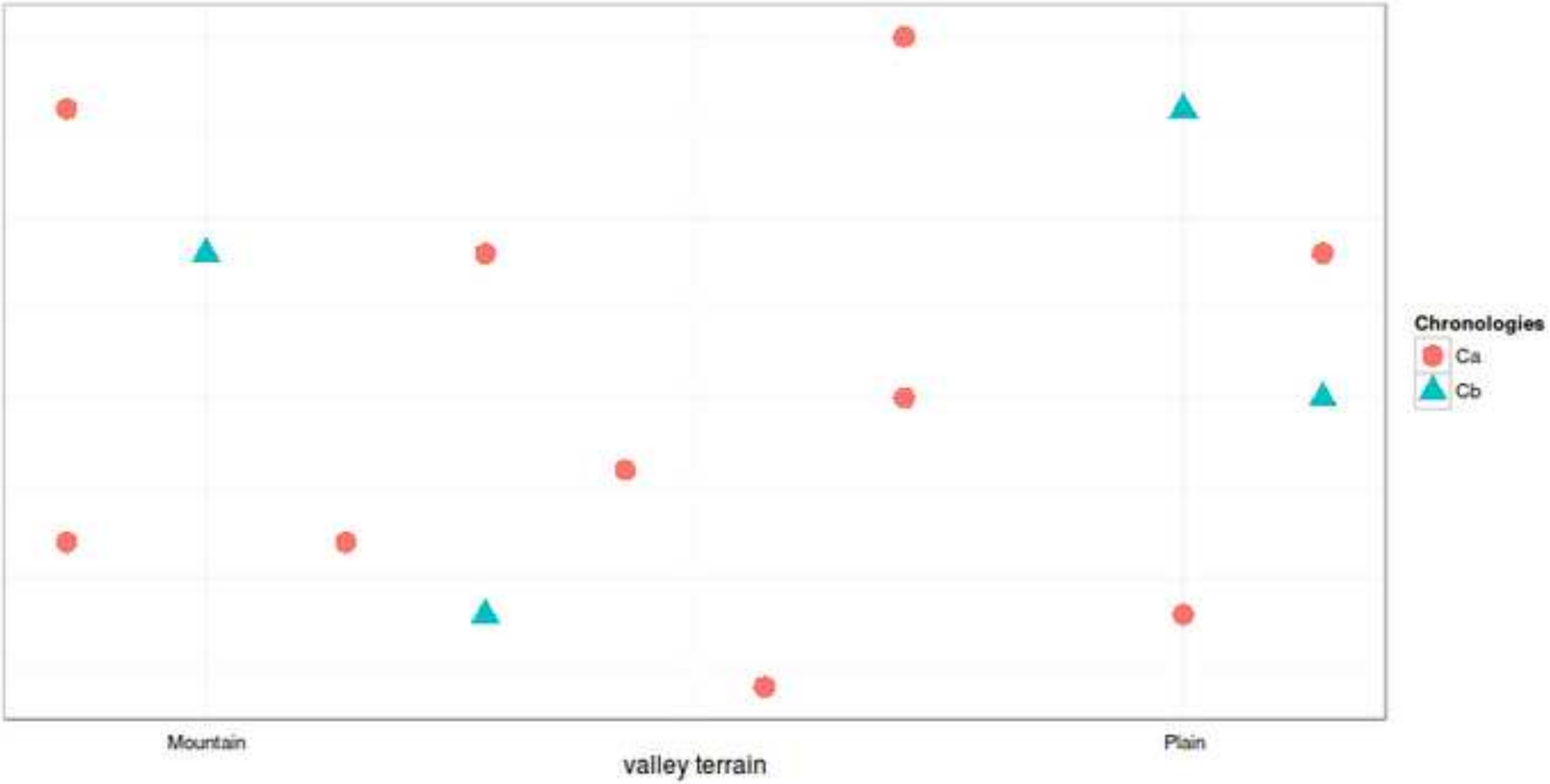
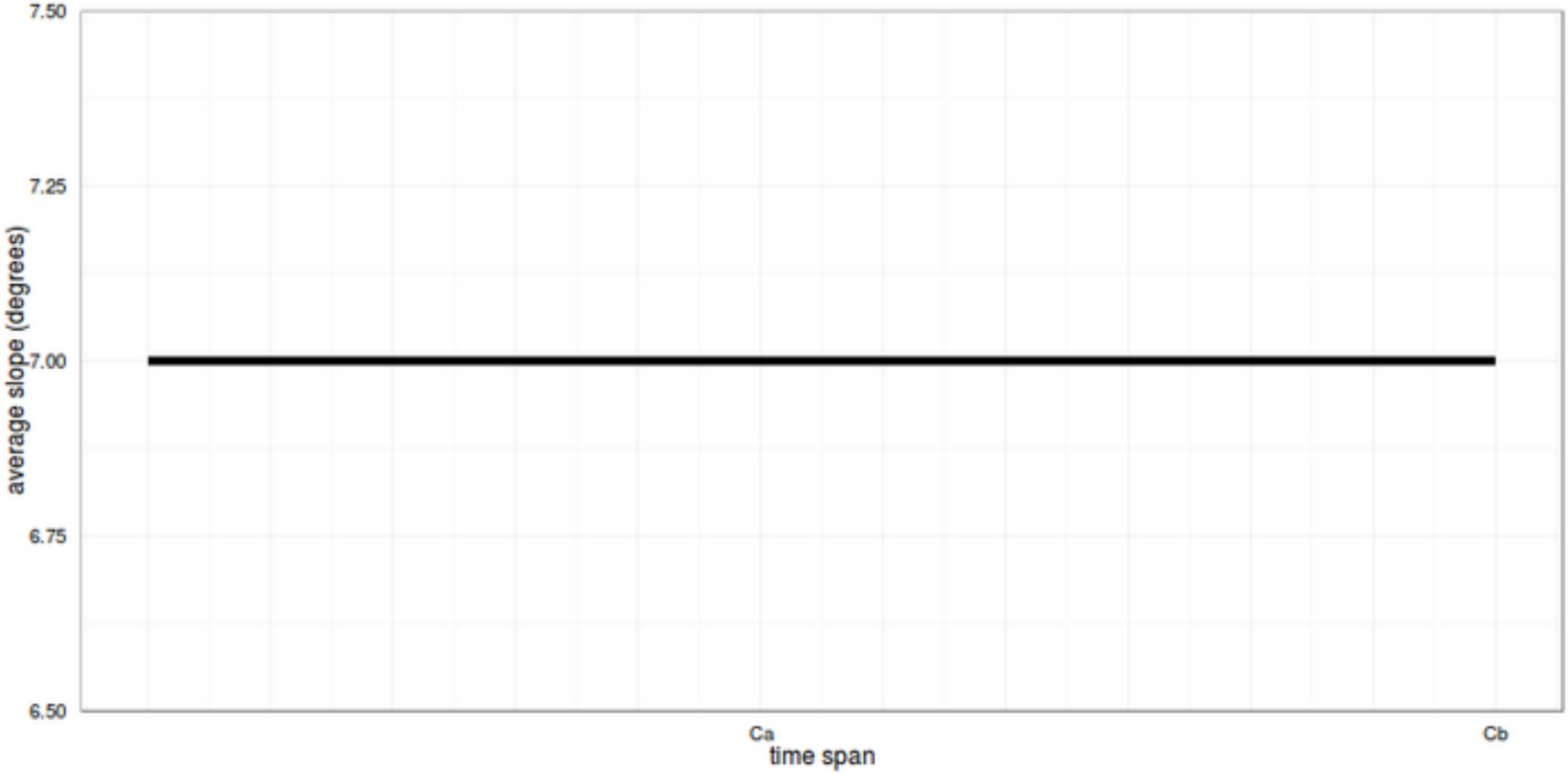
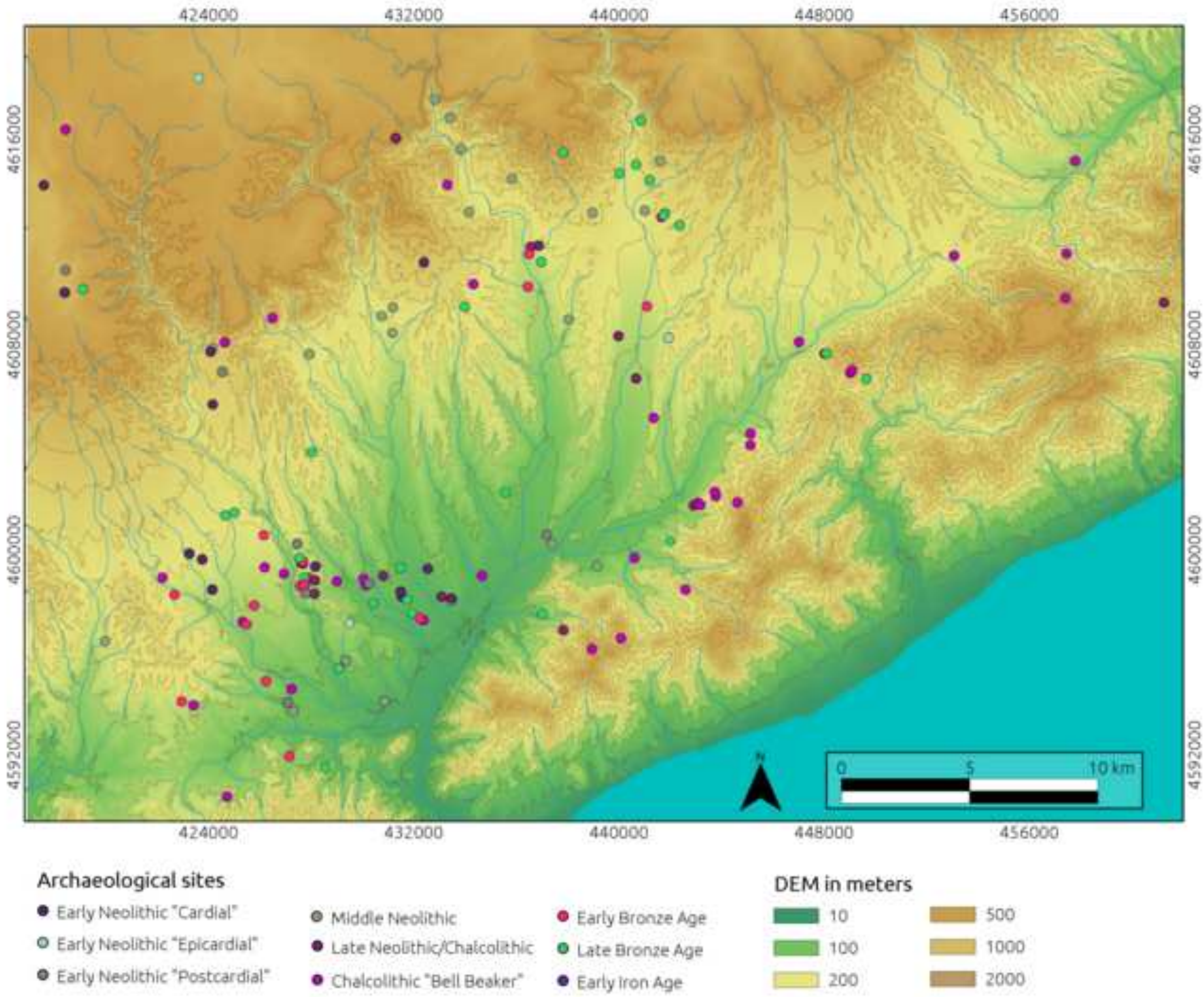
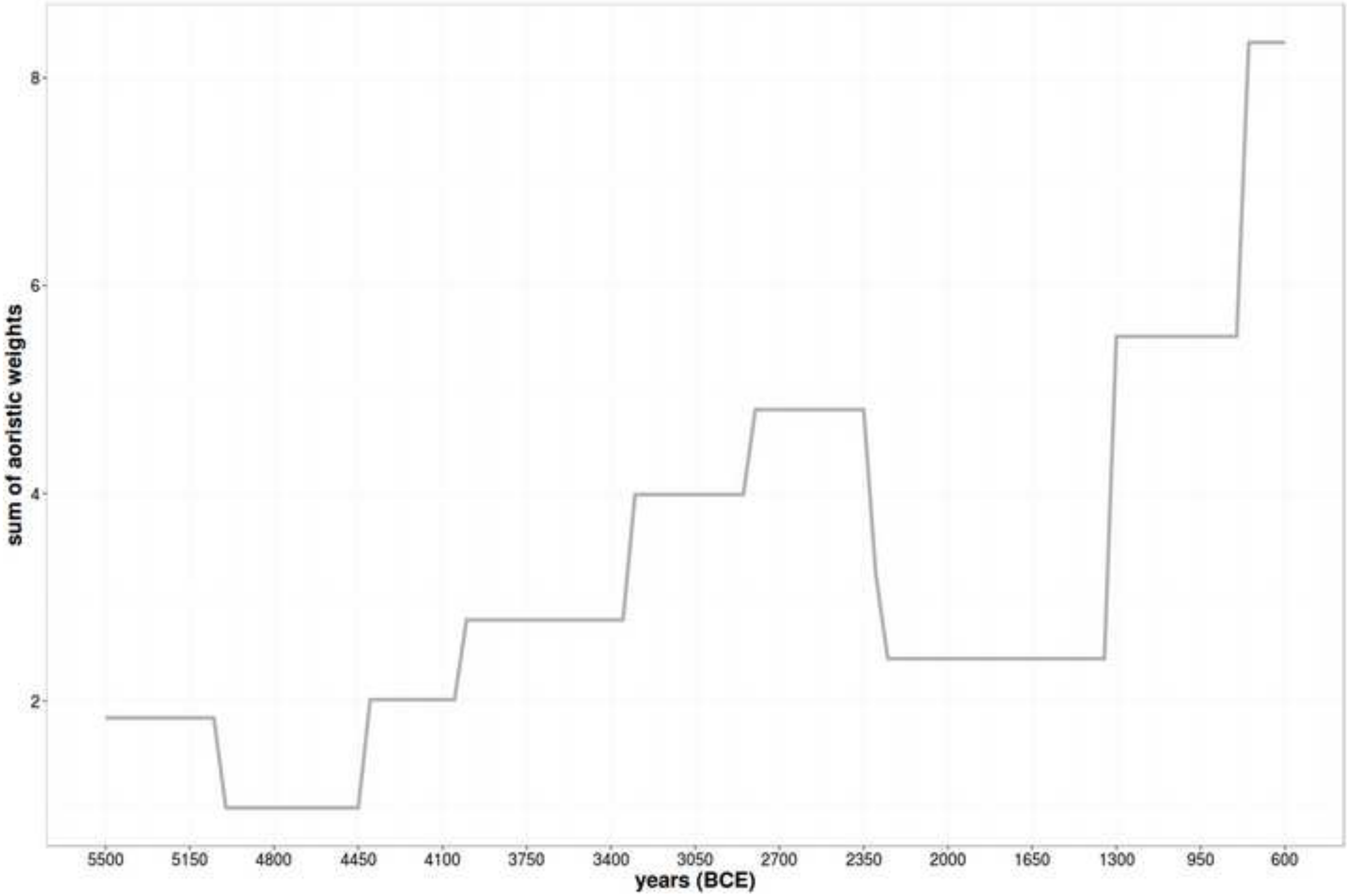



7.50
7.25
7.00
6.75
6.50
average slope (degrees)
Ca
Cb
time span

Figure


424000
432000
440000
448000
456000
4616000
4608000
4600000
4592000
N
0
5
10 km
Archaeological sites
● Early Neolithic "Cardial"
○ Early Neolithic "Epicardial"
● Early Neolithic "Postcardial"
● Middle Neolithic
● Late Neolithic/Chalcolithic
● Chalcolithic "Bell Beaker"
● Early Bronze Age
● Late Bronze Age
● Early Iron Age
DEM in meters
10
100
200
500
1000
2000


sum of aoristic weights
8
6
4
2
5500
5150
4800
4450
4100
3750
3400
3050
2700
2350
2000
1650
1300
950
600
years (BCE)

Figure

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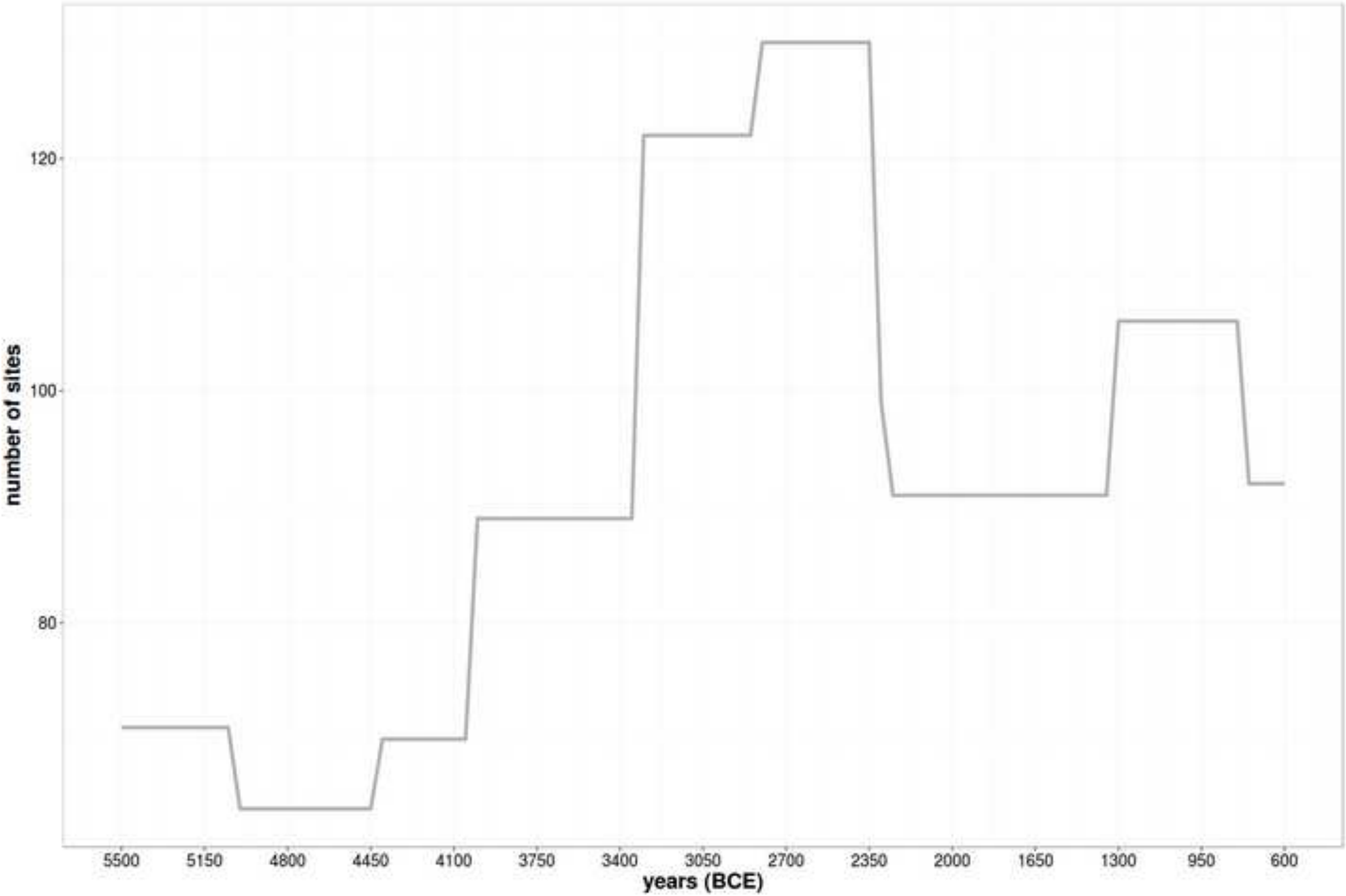

Figure

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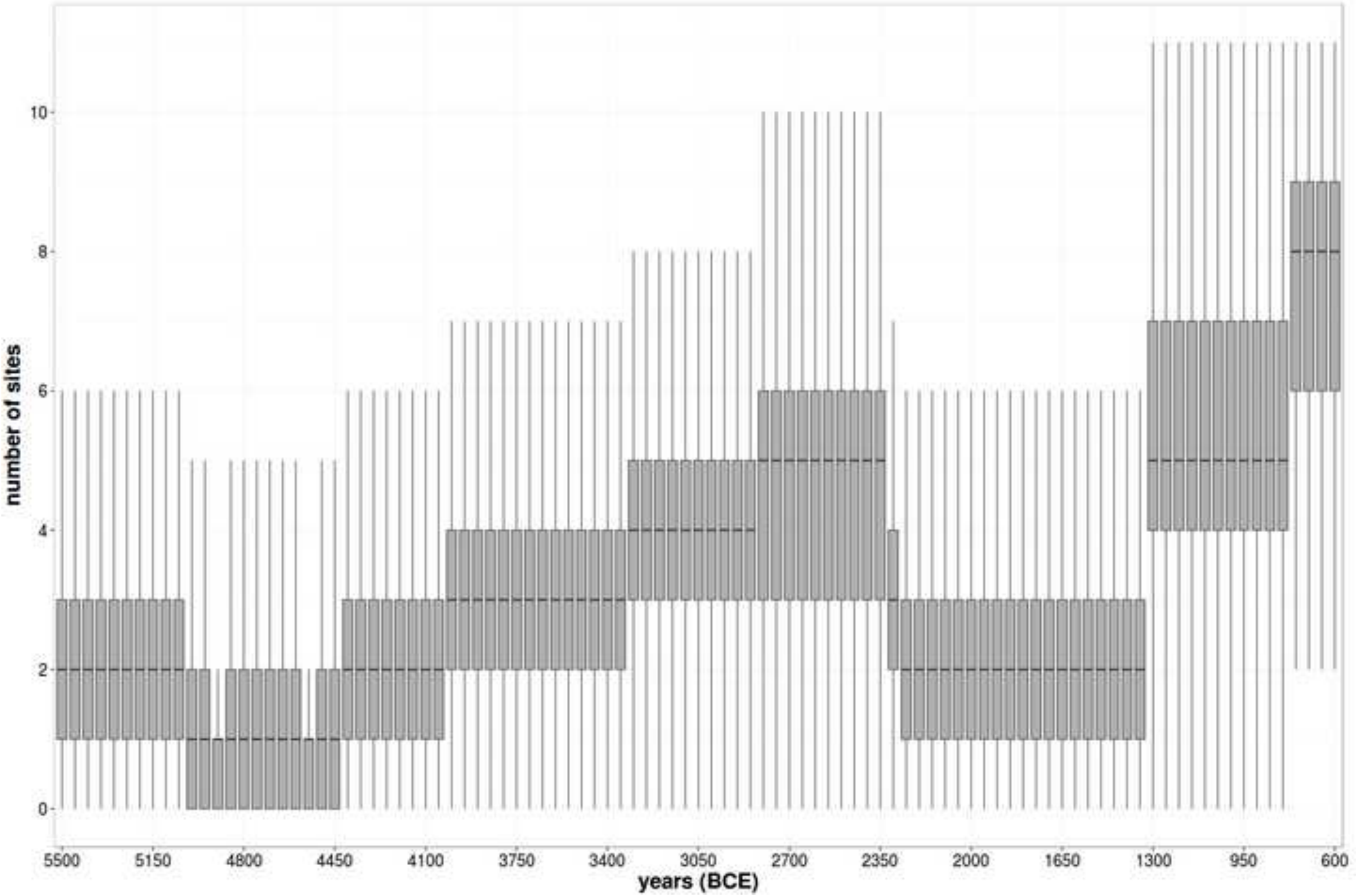

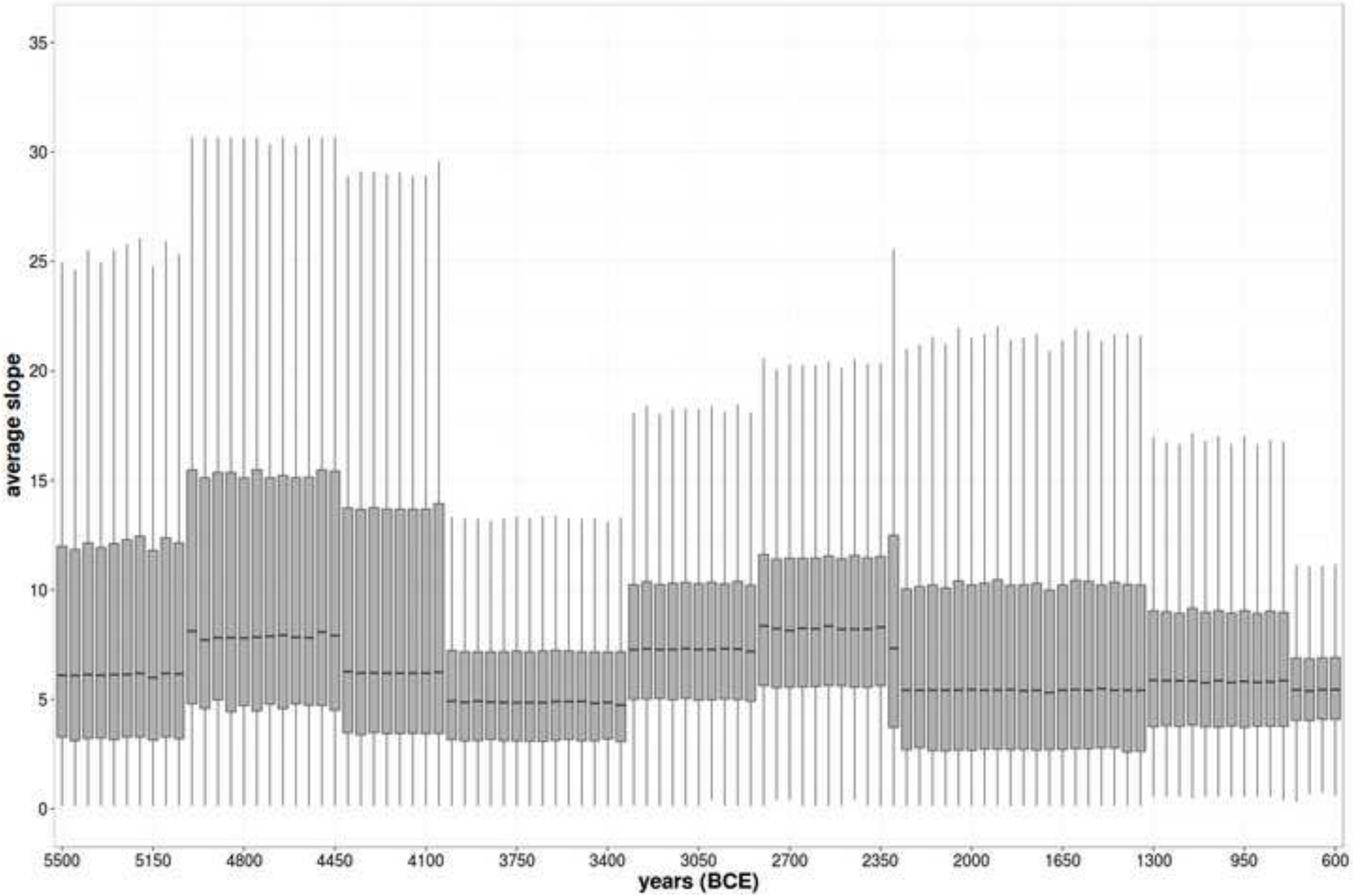
average slope
35
30
25
20
15
10
5
0
5500
5150
4800
4450
4100
3750
3400
3050
2700
2350
2000
1650
1300
950
600
years (BCE)

Figure

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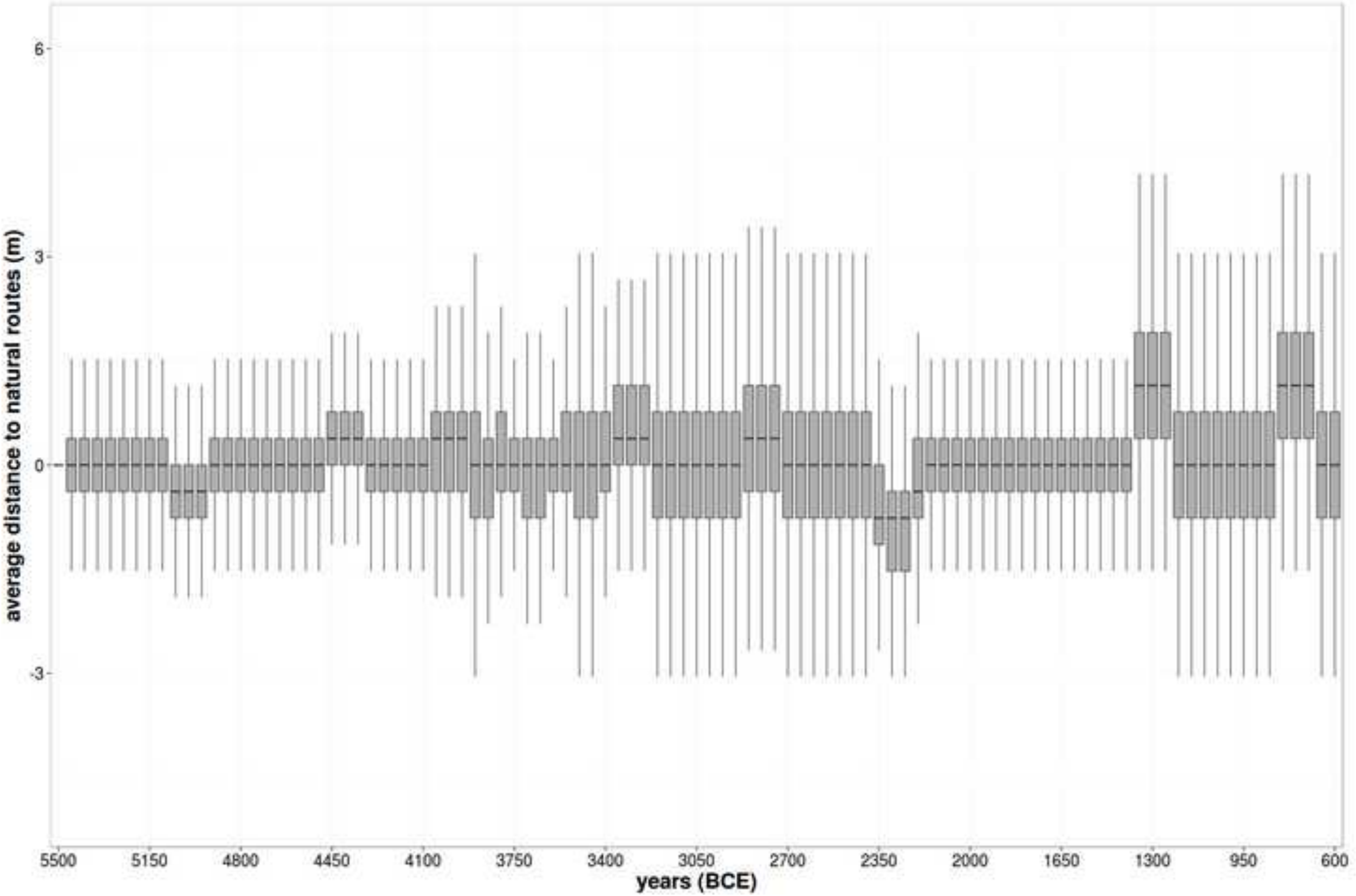

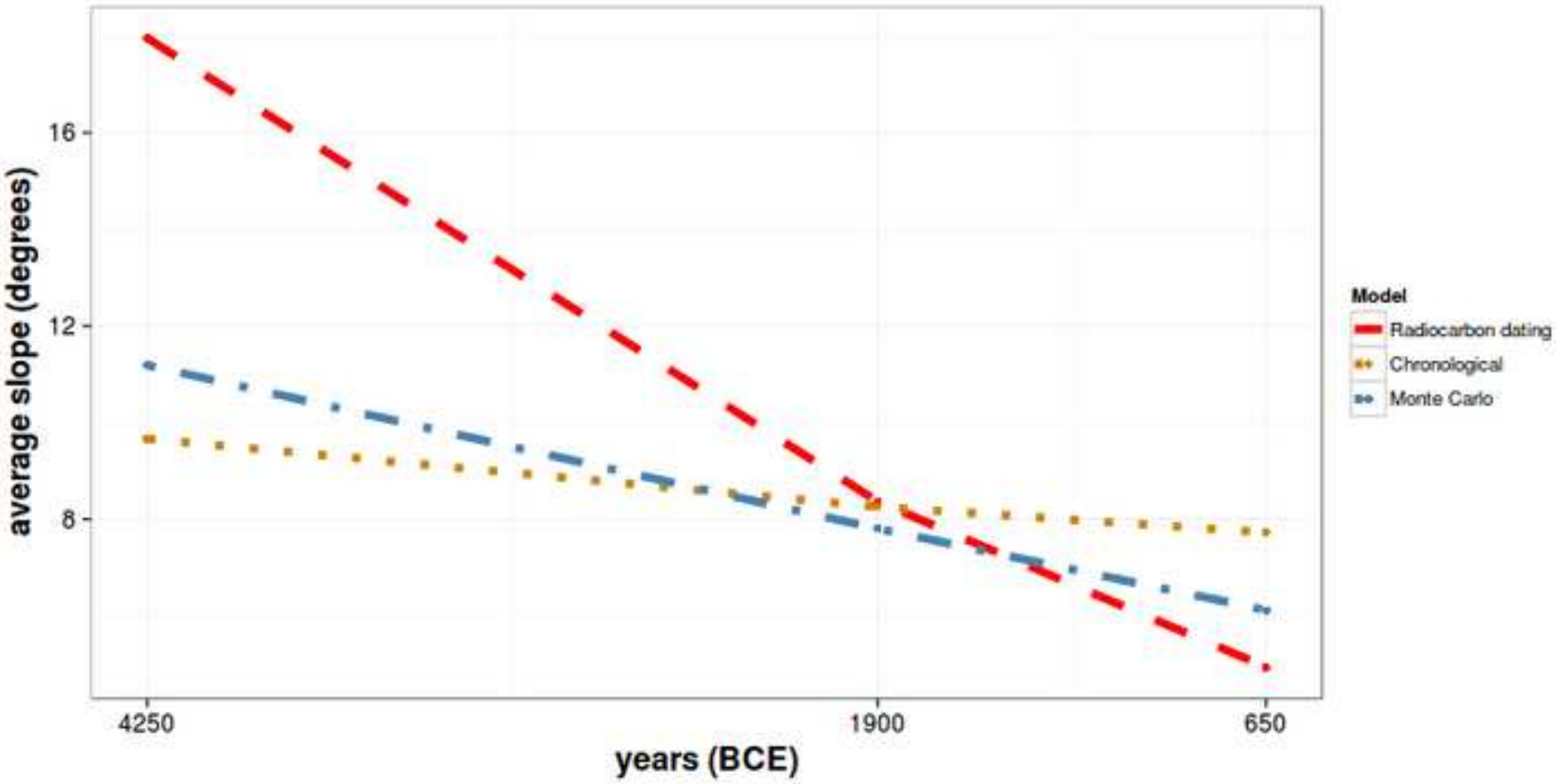
average slope (degrees)
16
12
8
4250
1900
650
years (BCE)
Model
Radiocarbon dating
Chronological
Monte Carlo

Figure

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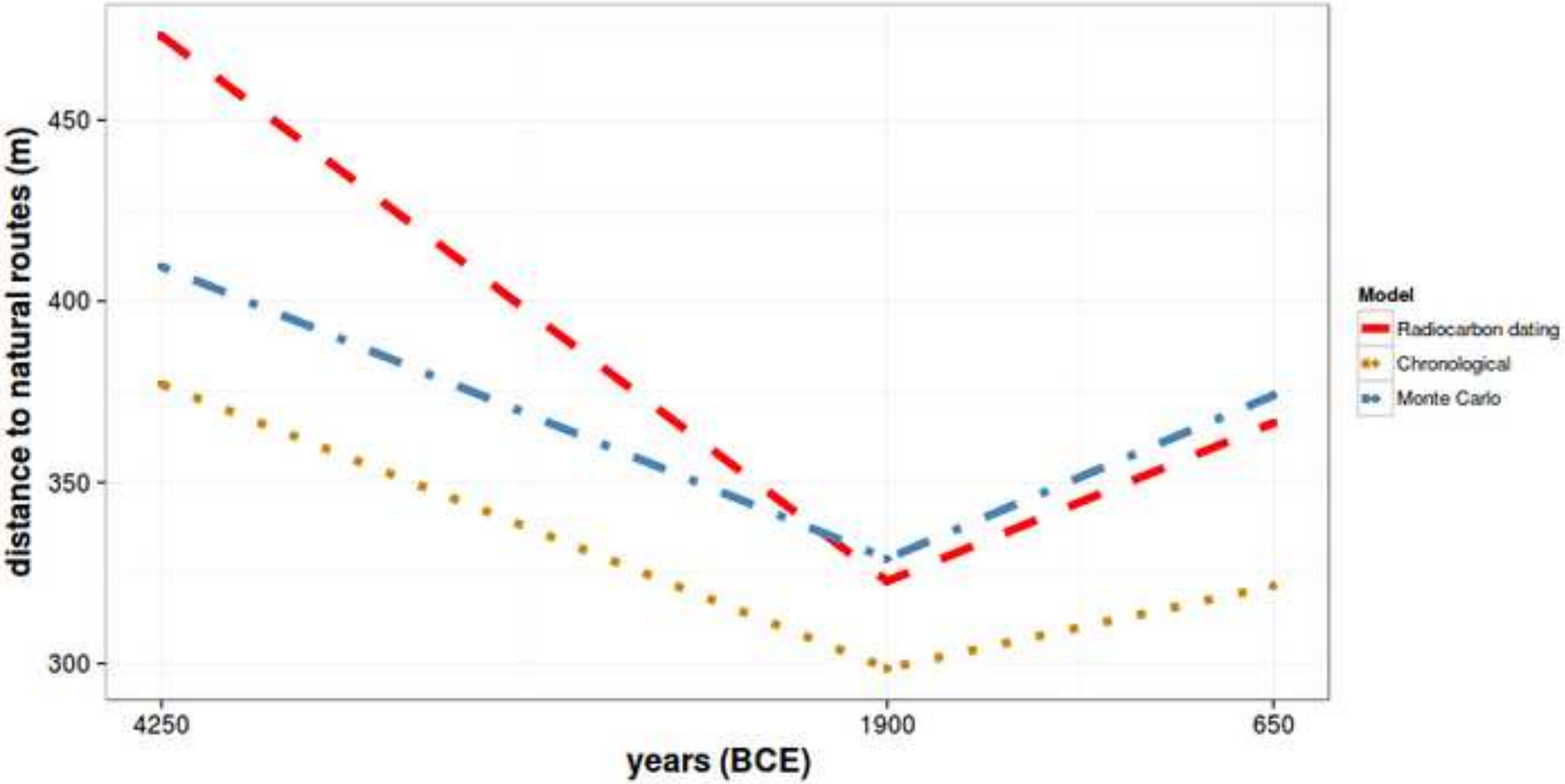

Figure

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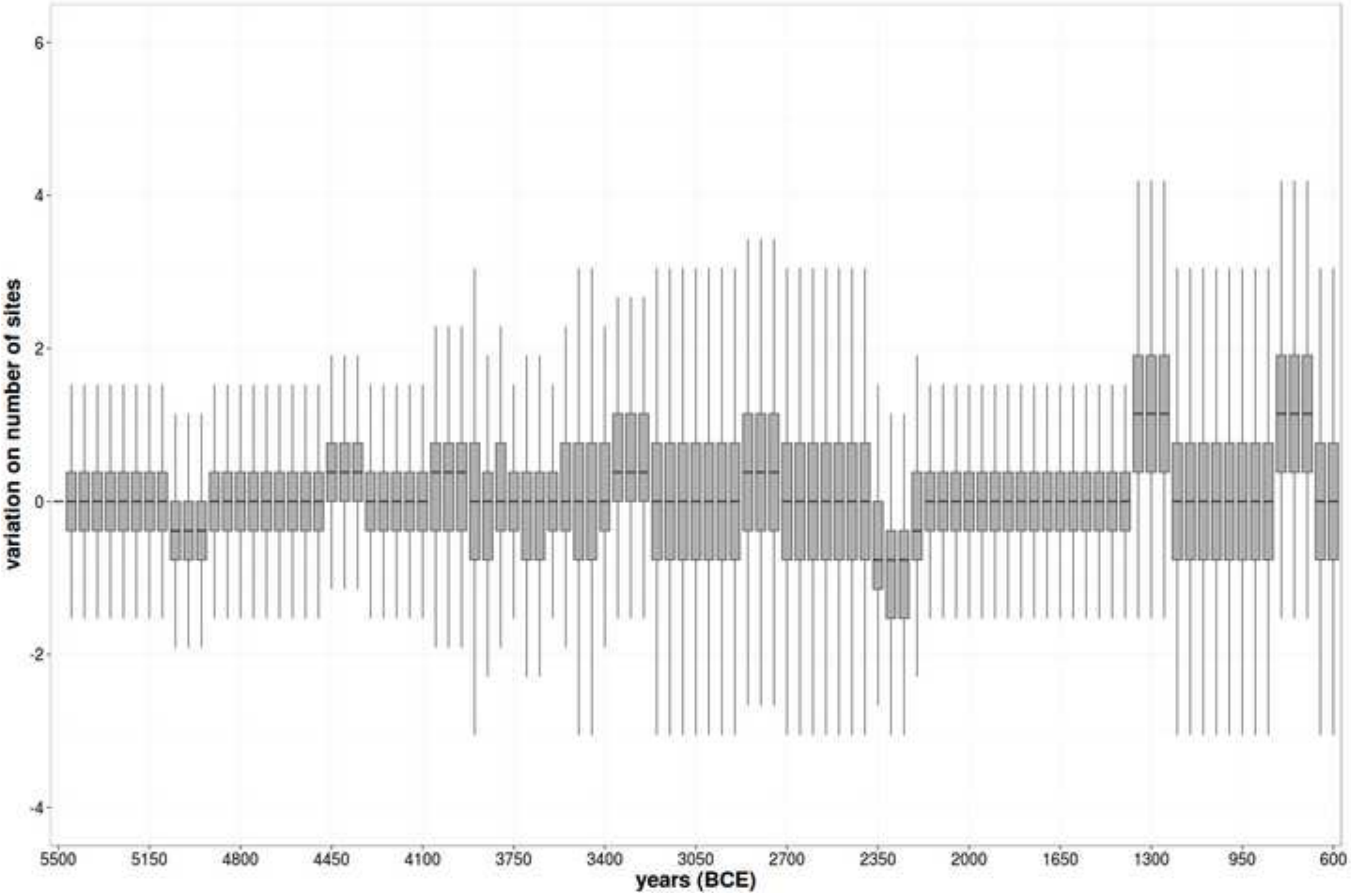

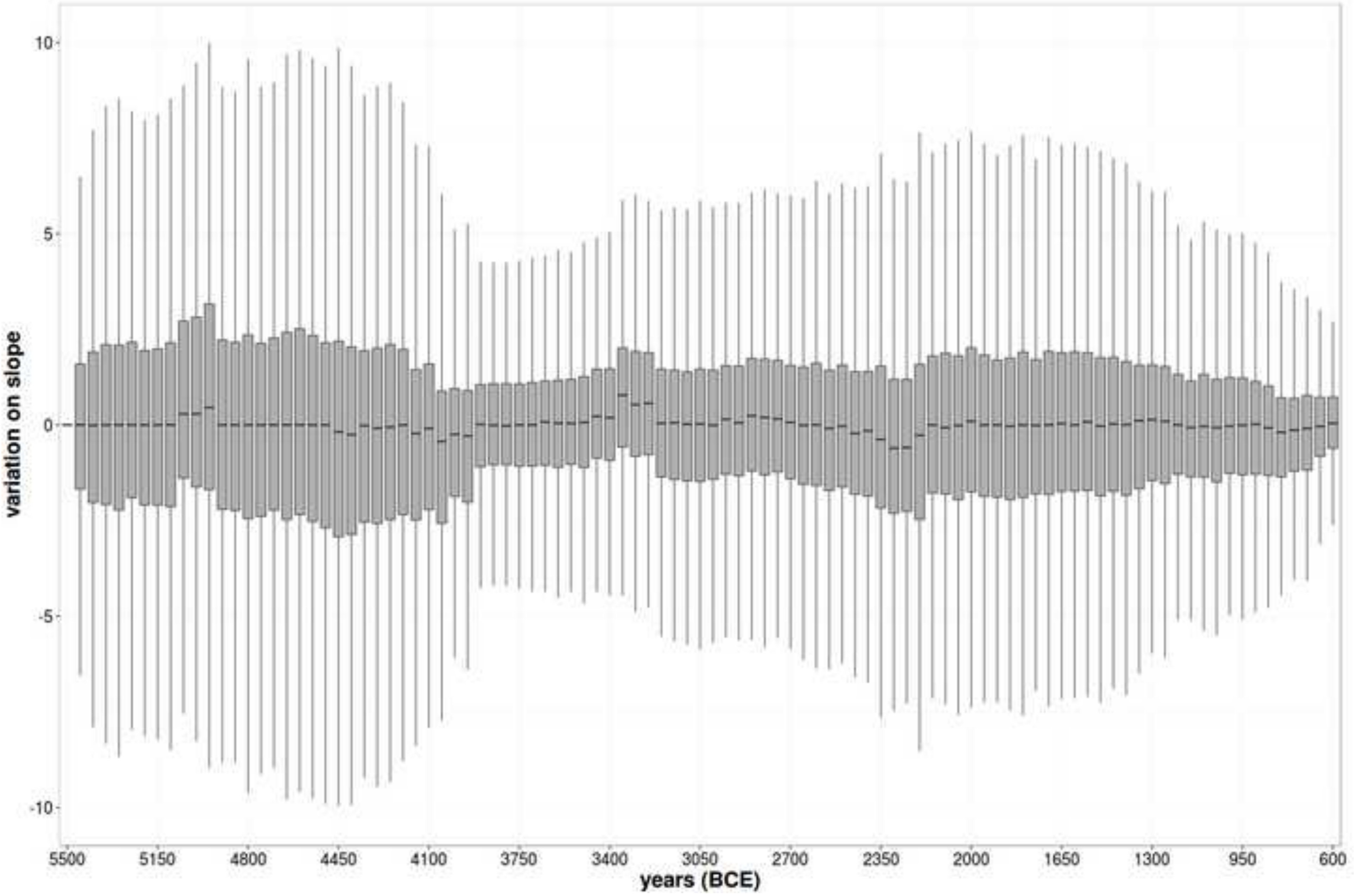
10
5
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-5
-10
variation on slope
5500
5150
4800
4450
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3750
3400
3050
2700
2350
2000
1650
1300
950
600
years (BCE)

Figure

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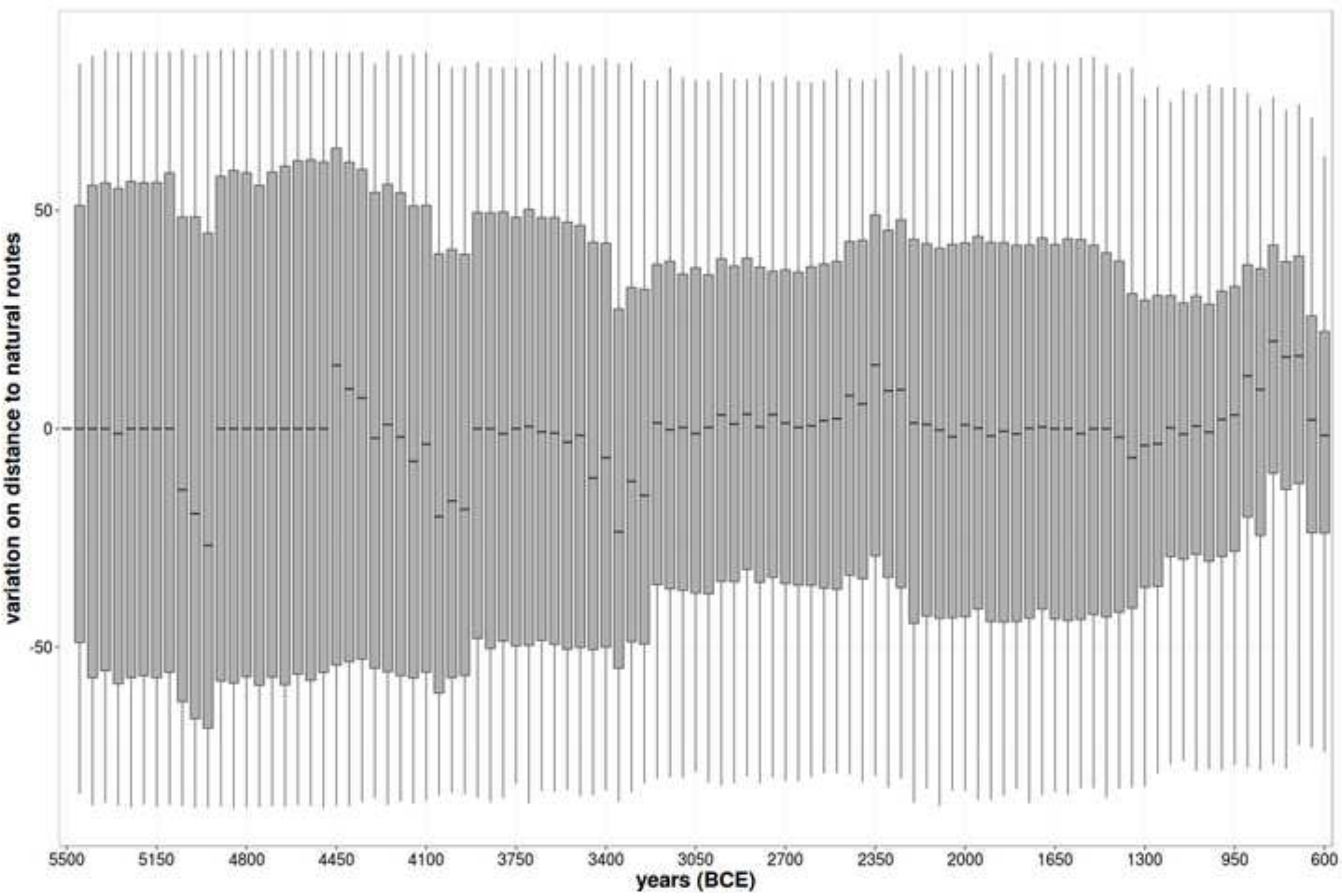

Figure

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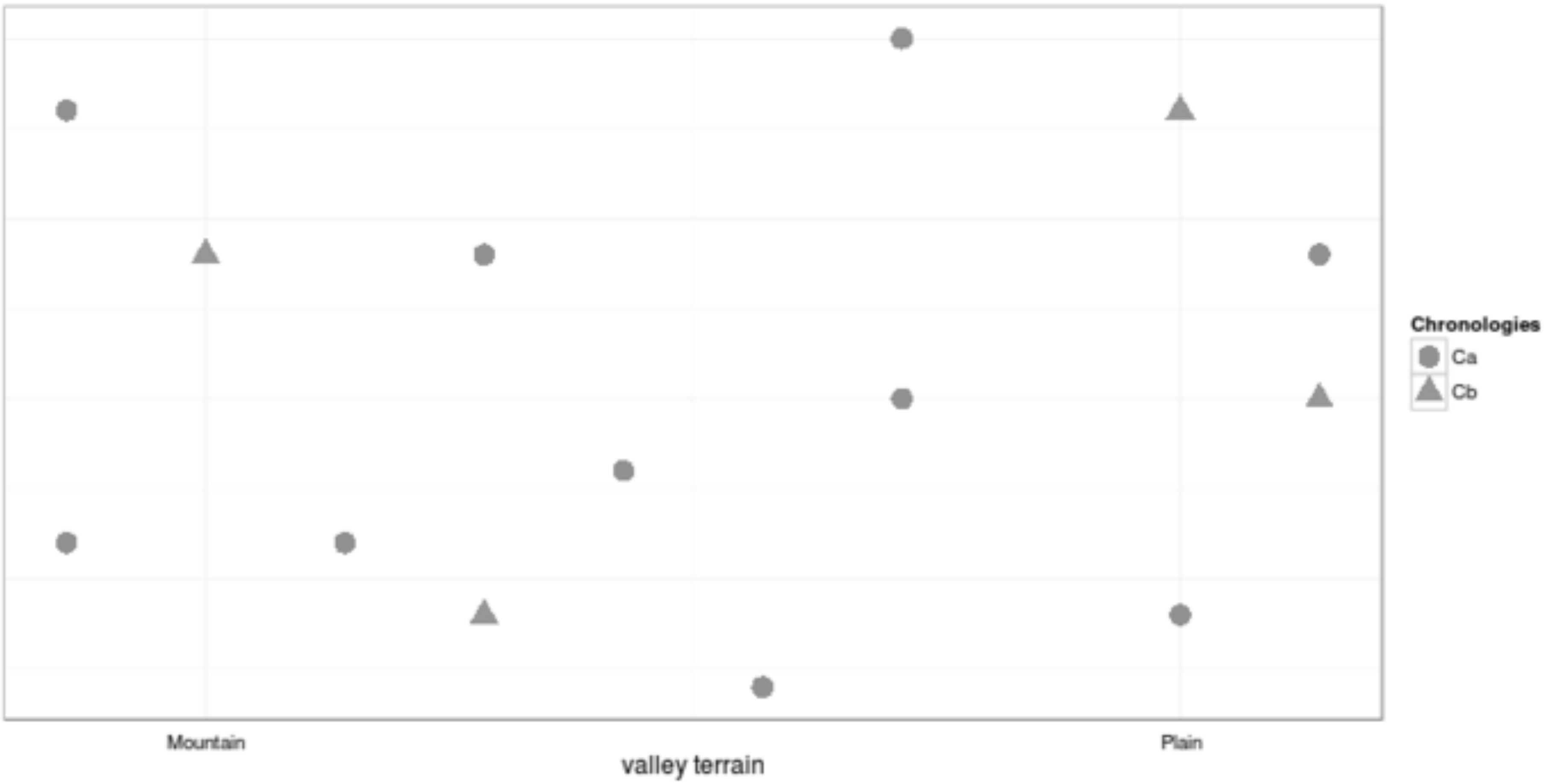

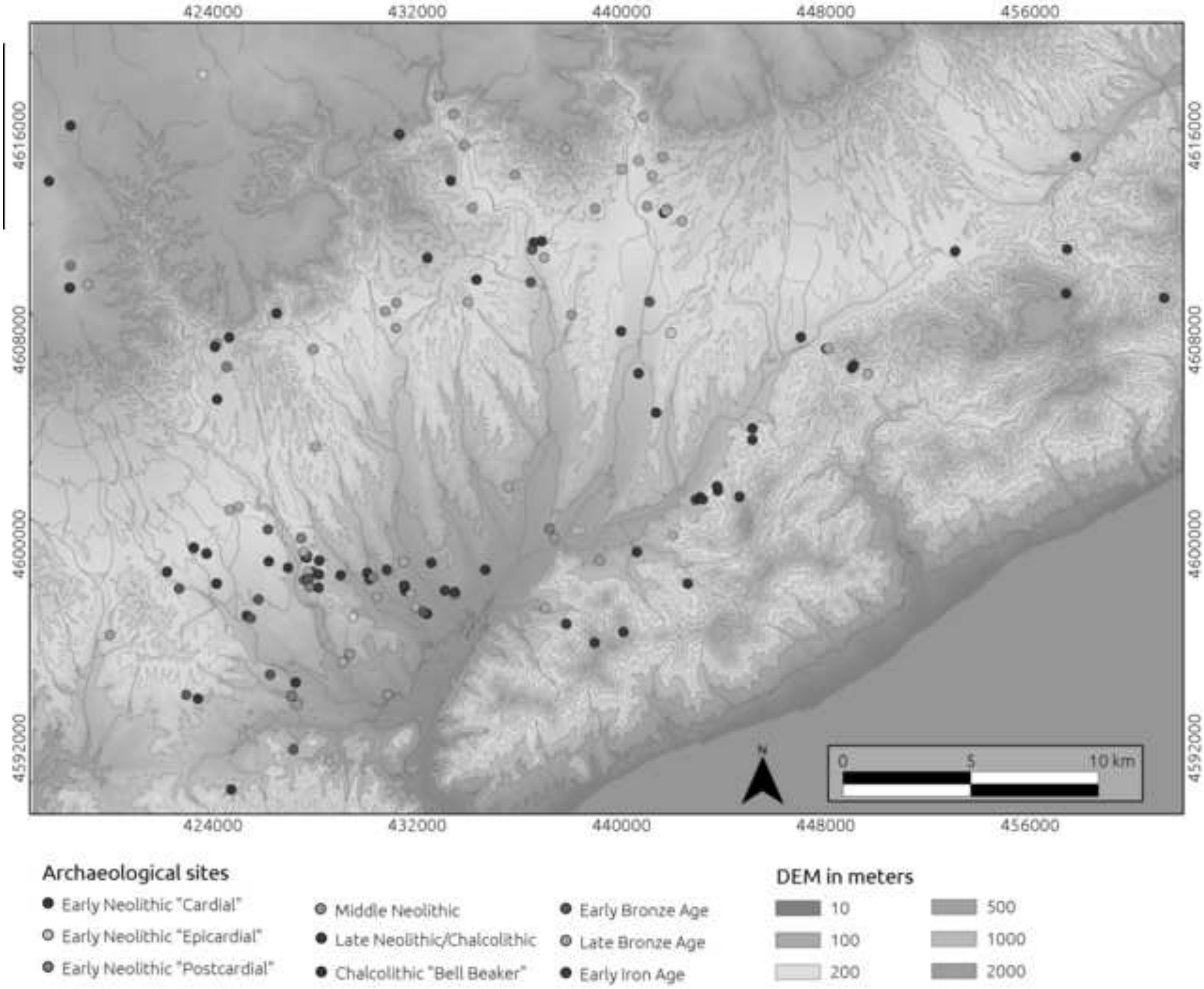
424000
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4616000
4608000
4600000
4592000
N
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5
10 km
Archaeological sites
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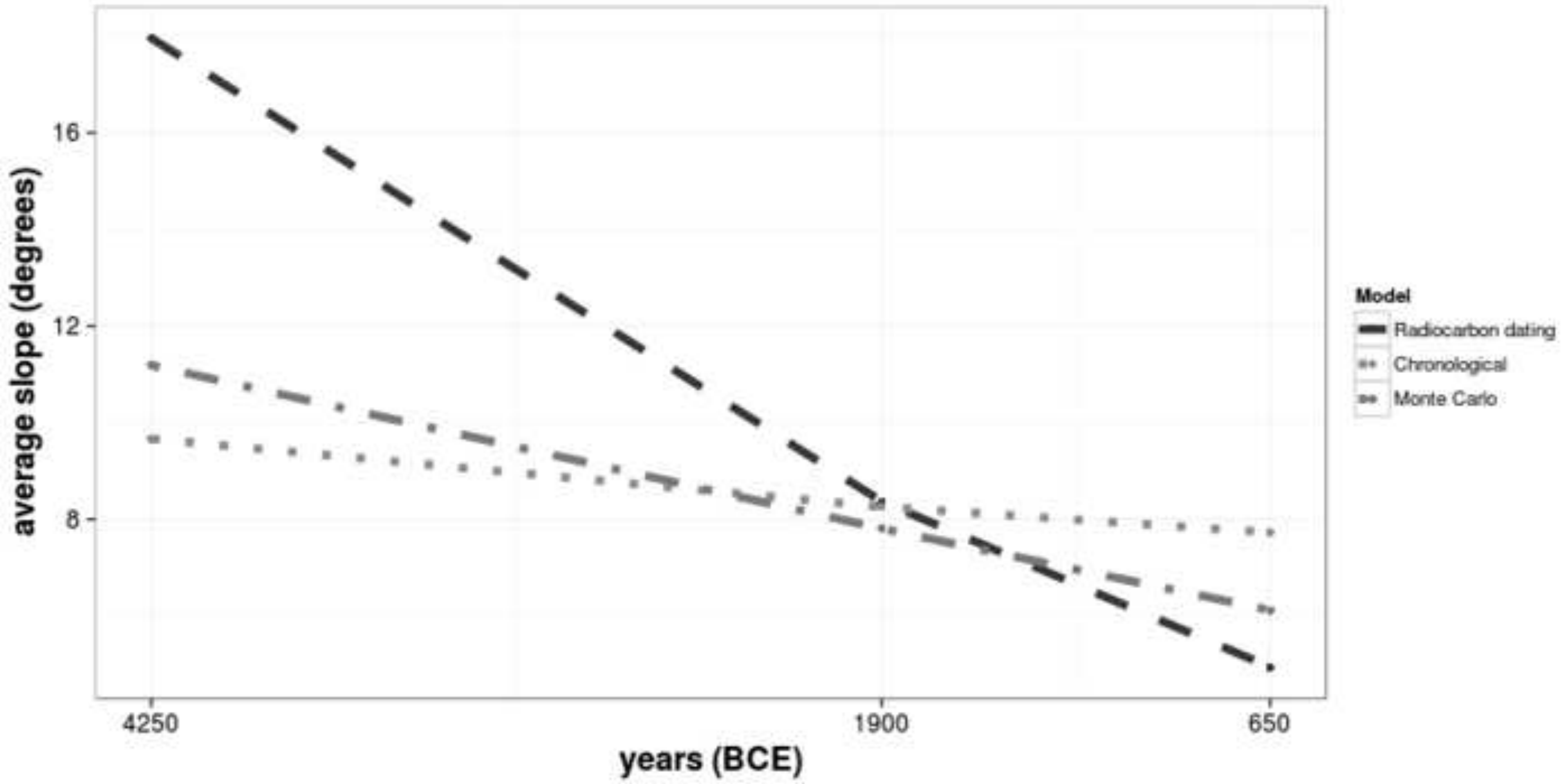
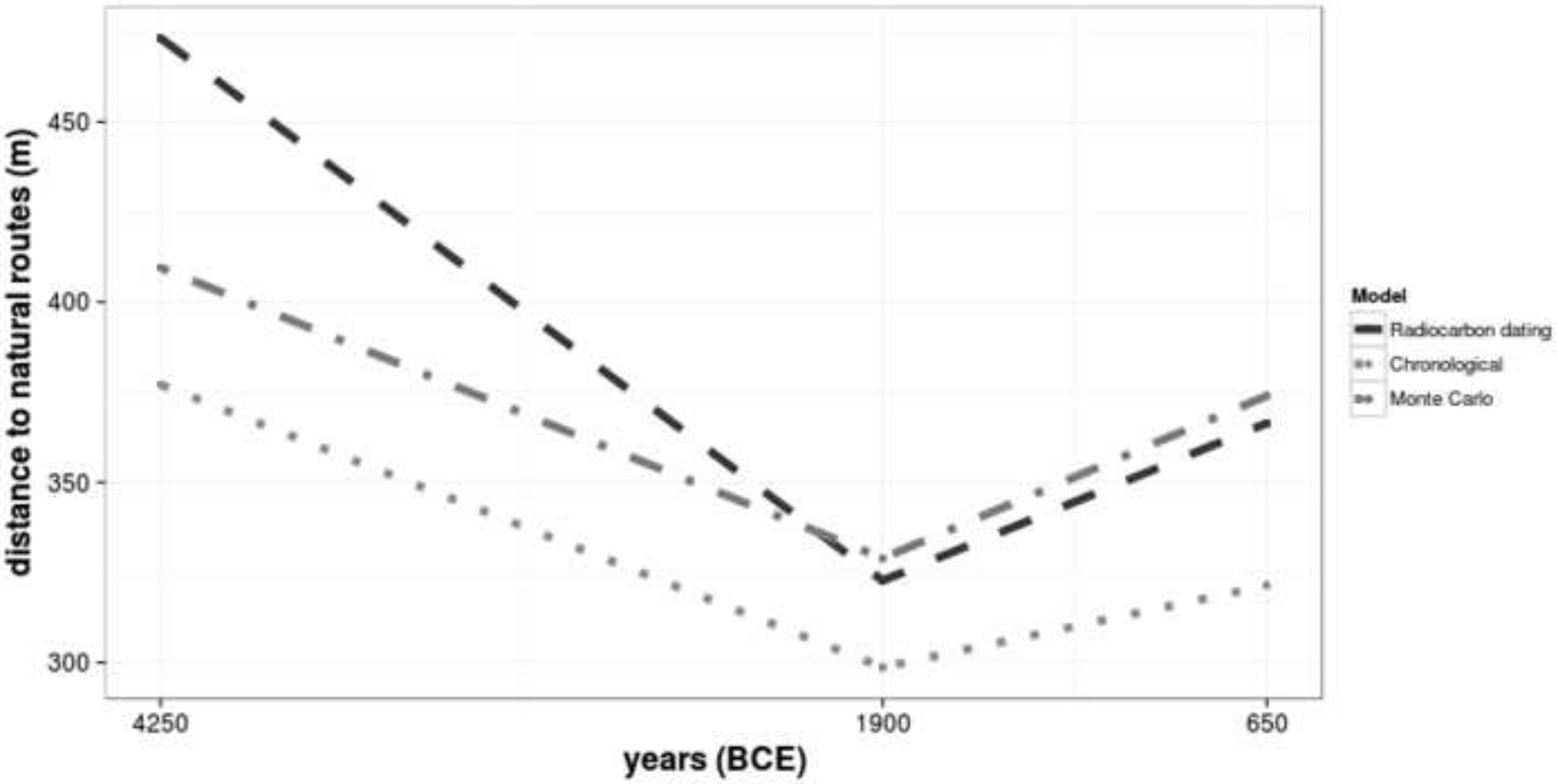
● Chalcolithic "Bell Beaker"
● Early Bronze Age
● Late Bronze Age
● Early Iron Age
DEM in meters
10
100
200
500
1000
2000


average slope (degrees)
16
12
8
4250
1900
650
years (BCE)
Model
Radiocarbon dating
Chronological
Monte Carlo


distance to natural routes (m)
450
400
350
300
4250
1900
650
years (BCE)
Model
Radiocarbon dating
Chronological
Monte Carlo