The Impacts of Geography and Climate Change on Magdalenian Social Networks

by

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ABSTRACT

This dissertation uses a comparative approach to investigate long-term human-environment interrelationships in times of climate change. It uses Geographical Information Systems and ecological models to reconstruct the Magdalenian (~20,000-14,000 calibrated years ago) environments of the coastal mountainous zone of Cantabria (Northwest Spain) and the interior valleys of the Dordogne (Southwest France) to contextualize the social networks that could have formed during a time of high climate and resource variability. It simulates the formation of such networks in an agent-based model, which documents the processes underlying the formation of archaeological assemblages, and evaluates the potential impacts of climate-topography interactions on cultural transmission. This research then reconstructs the Magdalenian social networks visible through a multivariate statistical analysis of stylistic similarities among portable art objects. As these networks cannot be analyzed directly to infer social behavior, their characteristics are compared to the results of the agent-based model, which provide characteristics estimates of the Magdalenian latent social networks that most likely produced the empirical archaeological assemblage studied.

This research contributes several new results, most of which point to the advantages of using an inter-disciplinary approach to the study of the archaeological record. It demonstrates the benefits of using an agent-based model to parse social data from long-term palimpsests. It shows that geographical and environmental contexts affect the structure of social networks, which in turn affects the transmission of ideas and goods that flow through it. This shows the presence of human-environment interactions that not only affected our ancestors' reaction to resource insecurities, but also led them to innovate and improve the productivity of their own environment. However, it also suggests that such alterations may have reduced the populations' resilience to strong climatic changes, and that the region with diverse resources provided a more stable and resilient environment than the region transformed to satisfy the immediate needs of its population.

Merci maman, papa, et Agathe pour votre soutient

malgré le fait que mes choix me gardent loin de vous. Je vous aime.

Je dédicace cette thèse à Yasmeen Page et à Léa Hétu.

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CHAPTER 1. INTRODUCTION

Introduction

The theoretical framework of this research builds on ethnographic and archaeological research, which has shown that the environmental context in which hunter-gatherers live affects how they construct their social networks (Binford, 1980, 1982; Braun and Plog, 1982; Gamble, 1983; Kelly, 1995, 2013; Whallon, 2006; Wiessner, 1982; Wobst, 1974). Networks used as safety nets to protect against resource fluctuations are usually created between groups living in different environments; therefore, their extent depends on biome diversity and on temporal fluctuations of their resources' availability (Fig. 1.1, Whallon, 2006). This pattern is well accepted for recent and modern populations. However, due to the difficulty of documenting prehistoric social networks, their use as safety nets has not yet been recognized in the Upper Paleolithic. This research combines multi-disciplinary methods to shed light on this question.

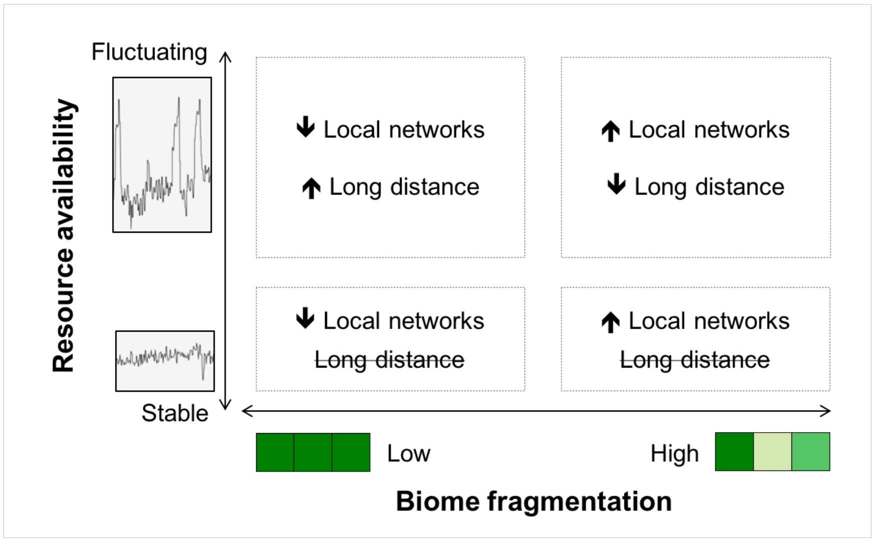


Figure 1.1. Effect of biome fragmentation (x axis) and the level of resource fluctuation (y axis) on the creation of social networks. Simplified version of Whallon's fig 2 (2006).

Prior research has shown that social networks – the composite of social contacts taking place between groups of individuals – may have played an important role in the emergence of large-scale cooperation (Apicella et al., 2012; Boyd and Richerson, 1988; Ohtsuki et al., 2006), which has had important repercussions on our evolution. However, as modern networks are a product of the societal changes that took place during the last millennia, they cannot be easily used to learn about the origins of cooperation (Apicella et al., 2012). Instead, archaeologists and evolutionary anthropologists need to reconstruct the characteristics of prehistoric social networks to better understand when and how cooperation evolved.

Because the practice of reconstructing past social networks through statistical analyses of material culture is relatively new (Brughmans, 2010), it lacks established procedures. Recent research has shown that many widely used social network analysis methods cannot be applied to all types of archaeological data (Gjesfjeld, 2015; Leidwanger et al., 2014; Mills et al., 2013) due to the nature of the archaeological record. This is especially the case when dealing with prehistoric hunter-gatherer social networks because of the sparse nature of the data, their imprecise dating, and the mobility of the agents producing it (Gjesfjeld, 2015). In the absence of defined guidelines, I borrow method elements from studies on cultural transmission (Braun and Plog, 1982; Mills et al., 2013; Plog, 1978; Rautman, 1993) and combine them with experiments using an agent-based model (ABM) to estimate the characteristics of Magdalenian social networks. This innovative methodology can help to reconcile formal social network methods with the networks reconstructed from the incomplete archaeological record, an approach that could be applied to research on the origins of cooperation.

Agent-based models have recently grown in popularity amongst archaeologists because, similarly to experimental archaeology, they allow researchers to document the processes that produced the studied archaeological record, and bridge different archaeological scales (Costopoulos, 2010; Kohler et al., 2005; Lake, 2010; White, 2012). Agent-based models are appropriate tools to study complex systems where agents interact with each other, and where those interactions produce emergent patterns that cannot be inferred from studying the individual interactions alone (Axelrod and Tesfatsion, 2005). An agent-based model can be used to produce a transparent and systematic understanding of systems, as well as to improve the toolset available to researchers (Axelrod, 2006; Axelrod and Tesfatsion, 2005). In this research, I use one as a heuristic method to document the underlying processes behind the studied archaeological record.

Archaeologically, social networks are analyzed at the site level, where they represent long-term palimpsests of individual interactions. Research done on lithic and shell raw material, as well as stylistic similarities in artistic representations have shown that local and long-distance contacts occurred throughout the Magdalenian (Álvarez-Fernández, 2002, 2009; Aubry et al., 2012; Bahn, 1982; Fullola et al., 2012; Gravel-Miguel, 2011; Langlais et al., 2012; Miller, 2012; Rensink, 1995; Schwendler, 2004, 2012; Taborin, 1993). However, most of this research has described the networks reconstructed from those proxies without analyzing them in their environmental context. It did not consider the impact of topography and natural barriers on hunter-gatherers' mobility and thus on inter-group contacts. Furthermore, prior research often relied on the untested assumption that networks reconstructed through archaeological proxies are good representations of the underlying social processes that created them. The present research uses a multi-disciplinary toolkit to test and question that assumption, which has important repercussions for archaeological studies of social networks. It then presents a new and more robust method to estimate prehistoric social behavior from networks reconstructed through archaeological proxies.

Summary of the Research

This dissertation uses a comparative approach to investigate the recursive interactions of climate, ecosystems, and social behavior in small-scale societies, and to evaluate if social networks were already used as safety nets in the Upper Paleolithic. I use GIS and ecological models to reconstruct the Magdalenian environments of the coastal mountainous zone of Cantabria (NW Spain) and the interior valleys of the Dordogne (SW France) to contextualize the types of social networks that could have formed during a time of high climate and resource variability, and compare their temporal and spatial characteristics. I simulate these networks in an agent-based model, which I use to 1) document the processes underlying the formation of archaeological assemblages, in ways similar to experimental archaeology, and 2) evaluate the potential impacts of climate-topography interactions on cultural transmission. I compare the modeled networks to archaeological signatures of Magdalenian social networks derived from multivariate statistical analyses of stylistic similarities among portable art objects. This allows estimating the characteristics of the Magdalenian latent social networks that most likely produced the empirical archaeological assemblage studied, characteristics that cannot be estimated from the archaeological record alone. This research is the first to look at Magdalenian social networks' extent and structure through least-cost paths, which provides a more realistic understanding of mobility than the straight lines between sites used in previous studies (Bahn, 1982; Schwendler, 2004, 2012). It is also the first to demonstrate the impact of climate change and topography on the structure and extent of social contact between groups of Magdalenian hunter-gatherers.

Research Hypotheses

In this research, I test the hypothesis that networks were created to safeguard against the resource fluctuations of the Upper Paleolithic. I use an agent-based model to study the complex system that emerged from interactions between hunter-gatherers set in reconstructed Magdalenian environments of Cantabria and the Dordogne. In the model, agents create alliances between camps, and campers share cultural information. I use the model outputs as a bridge connecting the modeled and the empirical networks and to demonstrate the impacts of environmental resources and topography on the structure of created social networks. This allows me to test the following theory-informed hypotheses:

1. Magdalenian social networks were more extensive in the Dordogne than in Cantabria.
2. The Magdalenian sites in the Dordogne were ‘homogeneously connected’ whereas the sites in Cantabria were ‘heterogeneously connected’.
3. The intensity of use of the social networks in the Dordogne varied more over time than in Cantabria.

Organization of the Dissertation

The dissertation is separated into 7 chapters, including the introduction and the discussion. In Chapter 2, I present background information on the Magdalenian climatic and cultural characteristics, with a focus on the two regions studied. In Chapter 3, I use an ecological model to reconstruct the biome distribution of the different Magdalenian subperiods. These reconstructed environmental maps allow me to gather information on the temporal and geographical changes in biome diversity and fragmentation, and evaluate how those may have affected the structure and extent of Magdalenian social networks. I use these reconstructed maps in an agent-based model discussed in Chapter 4. The characteristics of the model, as well as the results of its simulations are described in that chapter. In Chapter 5, I present the statistical study of Magdalenian portable art objects found in sites from the Dordogne and Cantabria. I discuss the methods followed to collect and analyze the stylistic data to ultimately reconstruct the Magdalenian networks that represent shared stylistic conventions. In Chapter 6, I compare the characteristics of the Magdalenian social networks reconstructed through the portable art analysis to the outputs of the agent-based model to estimate the characteristics of the latent Magdalenian networks underlying the studied artifacts. I use these estimated networks to test the hypotheses mentioned above. I close that chapter by evaluating how the results compare with other research on the Magdalenian. Finally, I use Chapter 7 to summarize and discuss the important contributions of the dissertation.

CHAPTER 2. MAGDALENIAN BACKGROUND

Introduction

The Magdalenian is a techno-complex dated to 20-14 cal. kya. It is found in several western European countries, with an intensive occupation in France and the Iberian Peninsula. It is well known for its impressive parietal and portable art, as well as its invention of barbed harpoons. In this chapter, I summarize the current state of knowledge on Magdalenian demography, technology, subsistence, symbolic activities, and social networks, with a focus on Cantabria and the Dordogne. It should be noted that the region I call Cantabria in this research encompasses both political regions of Asturias and Cantabria (see Fig. 2.1). Similarly, the Dordogne includes both political regions of the Dordogne and the Gironde (Fig. 2.2)

Geographical Context

At the height of the Last Glacial Maximum (LGM) ~22,000 years ago, glaciers extending over the northern continents lowered the sea level by about 120m (Peltier and Fairbanks, 2006). This affected the landscape of the two regions studied; it increased the altitude of the Cantabria Mountains, and extended considerably the coastal shelf near the Dordogne, thus changing their biome distribution. Cantabria is located on the northern edge of the Iberian Peninsula, sandwiched between the Cantabrian Mountains and the Atlantic Ocean. The rugged topography of this region means that even at the height of the LGM, the width of land strip between sea and mountains would have been no more than 35km. The steep gradient of the mountain range – the Picos de Europa measures ~ 2,650m – would have created a condensed mosaic of biotopes that would have welcomed a varied range of resources (Carrion et al., 2010; Straus, 1986, 1991). Simple environmental reconstructions suggest that during the LGM and at the start of the Late Glacial, montane glaciers covered the mountain ranges, while the intermontane valleys harbored temperate, forested microbiomes (Straus, 1986).

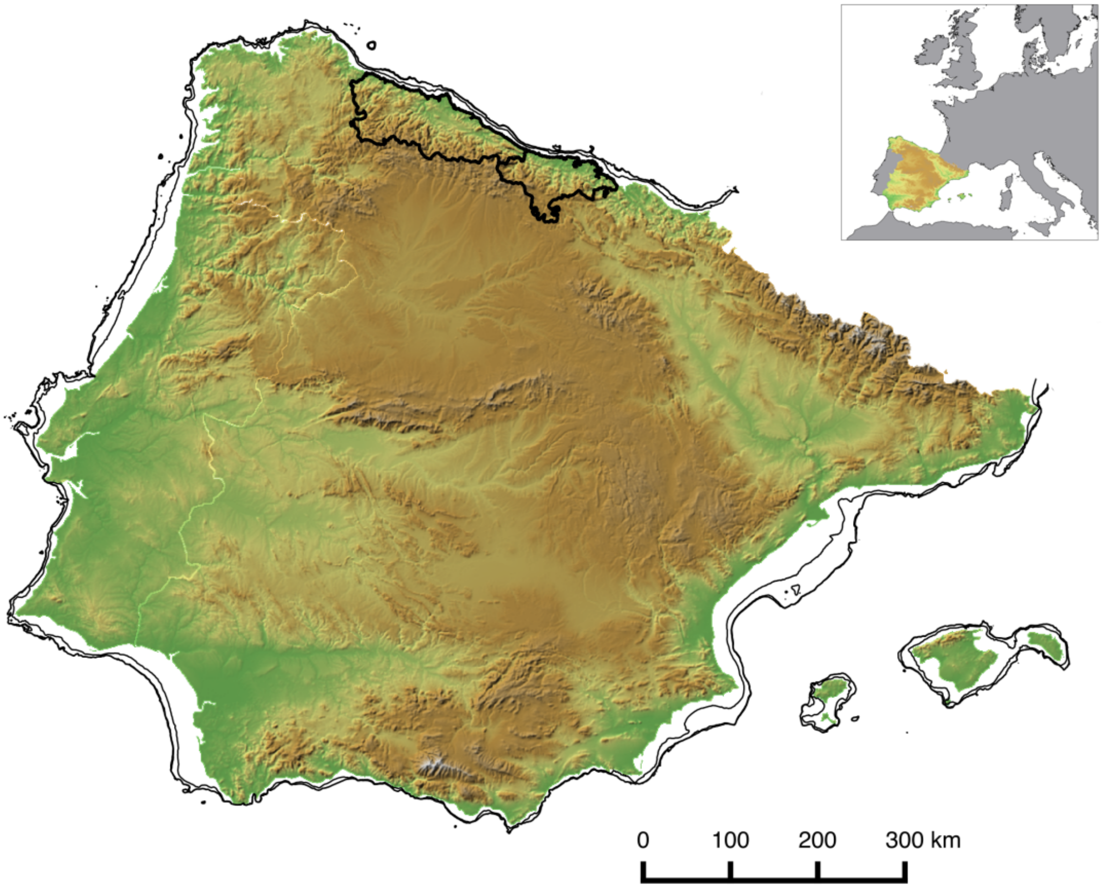


Figure 2.1. Geographical location of the Spanish region studied, which encompasses the political regions of Asturias (left bold contour) and Cantabria (right bold contour). The lines around the land show the position of the seashore during the Magdalenian.

The Dordogne is located in Western France and is characterized by an East-to-West decreasing relief accompanied by a few major river valleys flowing from the Massif Central to the Atlantic Ocean. The landscape of the Dordogne is gentler than the Cantabrian one. While high plateaus and steep limestone cliffs surround parts of the major river valleys (Jones, 2007), most of the region is covered with gentle rolling hills and accessible river valleys. The different biotopes of the river valleys and plateaus would have hosted a varied set of resources, influencing Late Glacial Magdalenian hunter-gatherers' behavior (Delpech, 1990; Jones, 2007). I discuss the environmental characteristics of the two regions further in Chapter 3.

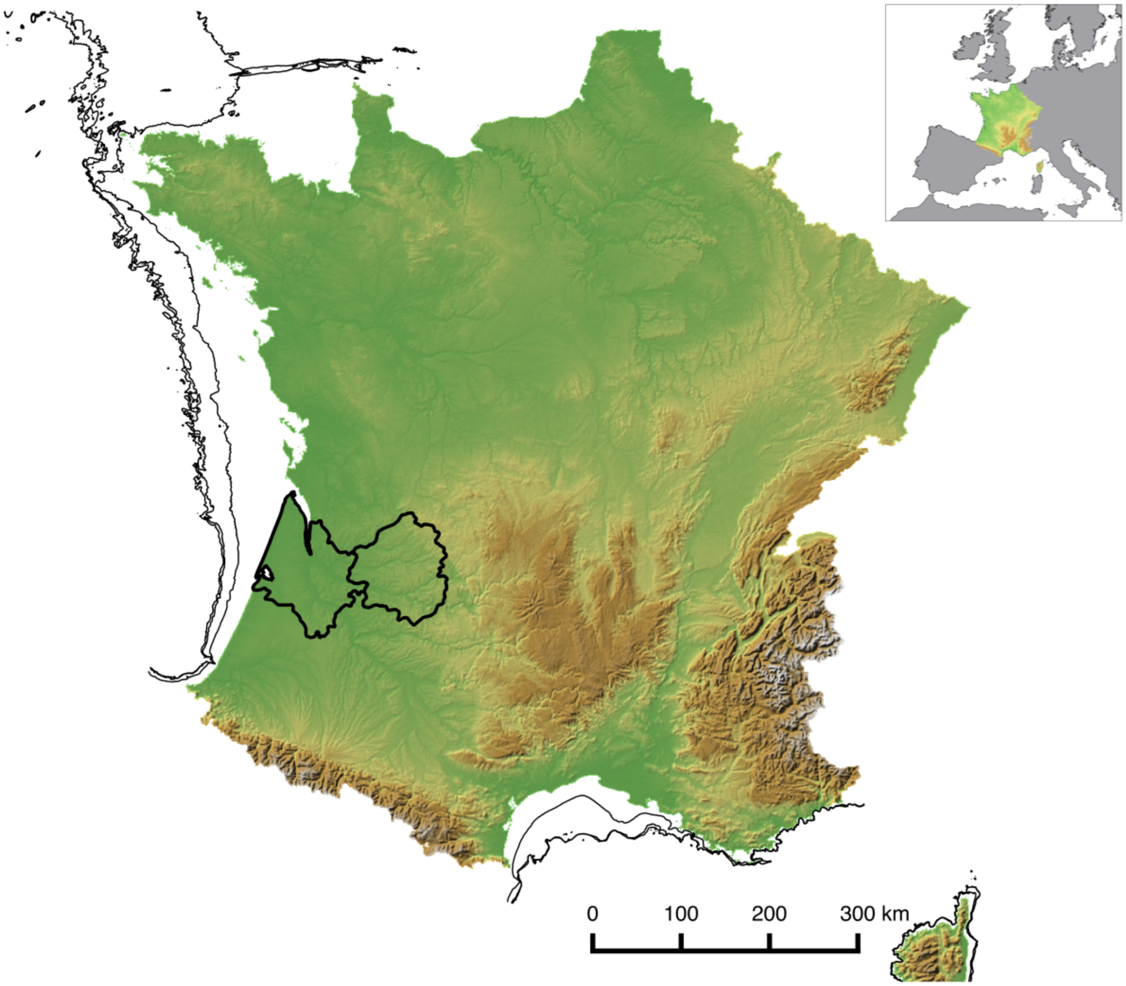


Figure 2.2. Geographical location of the French region studied, which encompasses the political regions of Gironde (left bold contour) and Dordogne (right bold contour). The lines surrounding the land show the position of the seashore during the Magdalenian.

Magdalenian Chronology

The long history of Magdalenian excavation has left us with 3 technology-informed subperiods that are not synched perfectly between the two regions (Langlais et al., 2016; Utrilla et al., 2012) (see Fig. 2.3).

Based on the timing of harpoons' appearance in the archaeological record, the Cantabrian Magdalenian has been divided into two main periods (Initial Magdalenian and Recent Magdalenian, or pre- and post-harpoons), each of which is also divided in two subperiods (Álvarez Alonso et al., 2016). The first part of the Initial Magdalenian – dated to 22.3-19.5 cal kya – is called the Archaic Magdalenian or Badegoulian. It is followed by the Cantabrian Lower Magdalenian, dated to 19.5-17.5 cal. kya (Álvarez Alonso et al., 2016; Rivero, 2010; Sauvet, 2008). The appearance of harpoons marks the beginning of the Recent Magdalenian (Álvarez Alonso et al., 2016), and especially the beginning of its Middle Magdalenian subperiod, dated to 17.5-16 cal kya. The last subperiod, the Upper Magdalenian, dates to 16-13.2 cal kya (Rivero, 2010).

The chronology of the Dordogne differs slightly. There, the Lower Magdalenian starts earlier, around 20.8 cal kya and ends around 18.8 cal kya. Recent dates suggest that the Middle Magdalenian started earlier than previously thought, with dates ranging from 18.8-16.3 cal. kya (Barshay-Szmidt et al., 2016). In the Dordogne, the Middle Magdalenian can be divided into old (18.8-17.5 cal. kya) and recent (17.5-16.3 cal. kya). The Upper Magdalenian – defined by the appearance of harpoons (de Sonneville-Bordes, 1960), which occurred slightly later than in Cantabria – is also divided into old (16.3-15.3 cal. kya) and recent (15.3-14 cal. kya).

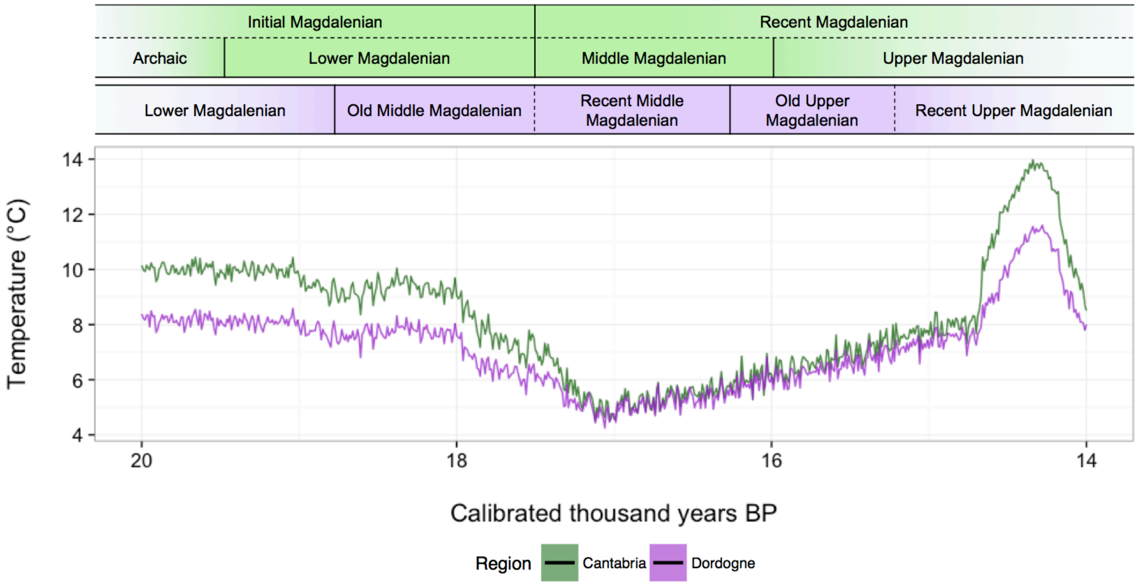


Figure 2.3. Comparative chronology of the Magdalenian in both regions, placed in its broad climatic context. Based on Álvarez Alonso et al., 2016; Debout et al., 2012, Kuntz et al., 2016, and Rivero, 2010. The climate data comes from the TraCE-21ka project.

Despite the lack of perfect synchronicity between the general subdivisions of the two regions – and the problems it creates when comparing their 'contemporary' archaeological patterns – I still use the Lower, Middle, and Upper classifications when describing the general characteristics of this techno-complex, since most publications and archaeological reports relate the timing of techno-complex milestones to this chronological scale. In the remaining part of this chapter – and dissertation – I rely on the literature's chronological attribution to the 3 periods to summarize the temporal characteristics of the Magdalenian.

Magdalenian Demography

The Magdalenian techno-complex, while known mostly from France, has also been found in Germany, Britain, Belgium, Switzerland, and Portugal (Albrecht, 1989; Bicho and Haws, 2012; Leesch et al., 2012; Miller, 2012; Poltowicz-Bobak, 2012; Straus, 1991;

Straus et al., 2012; see also Fig. 2.4). However, due to the advance of glaciers during the Last Glacial Maximum, most northern occupations date to the Upper Magdalenian (Leesch et al., 2012; Miller, 2012; Poltowicz-Bobak, 2012; Straus, 1991). Most Lower Magdalenian sites are found in Southwest France and Cantabria, which have been identified as temperate refugia (Conkey and Redman, 1978; Jochim, 1987; Schwendler, 2012; Straus, 1991). However, demographic estimates suggest that even those refugia – as well as the nearby Pyrenees – were sparsely occupied (Barshay-Szmidt et al., 2016; Dachary, 2002; Fontana, 1999; Otte, 2012; Straus, 2005). In the Dordogne, Lower Magdalenian sites were found on the banks of the main rivers (Jones, 2007; Lenoir, 1992; Rensink, 1995).

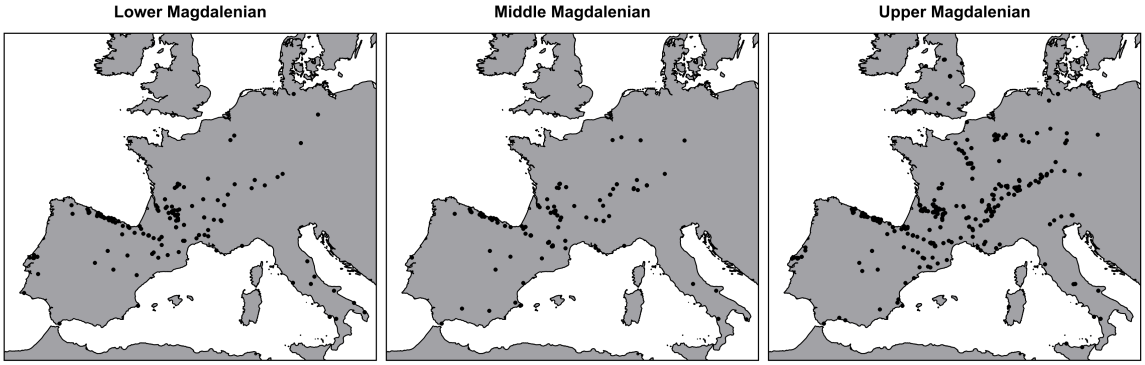


Figure 2.4. Geographical position of radiocarbon dated Magdalenian. The data comes mostly from the Radiocarbon Palaeolithic Europe Database v. 20 (2016), and was cleaned following methods described in Chapter 3.

While the relatively warm and stable temperature of the post-LGM would have facilitated the northern population expansion that began during the Lower Magdalenian, the advent of the Oldest Dryas, caused by Heinrich Event 1, led to an abrupt decrease in temperature and humidity that probably disrupted this demographic change. This period coincides with the Middle Magdalenian, which saw changes in population distribution, including an important reduction in the occupation of the Dordogne (Barshay-Szmidt et al., 2016; White, 1987) and the reoccupation of the northern Pyrenees (Clottes, 1989; Delpech, 1983; Schwendler, 2012; Straus, 1991, 1995). Some have argued that these two demographic changes were related, and represented the movement of Dordogne populations to the sheltered Pyrenees to cope with the arid climate of the Middle Magdalenian (Barshay-Szmidt et al., 2016; Dachary, 2006).

The temperature and humidity increase of the Upper Magdalenian allowed populations to expand northward permanently (Audouze, 2006; Debout et al., 2012; Miller, 2012; Otte, 2012; Sacchi, 1988; Straus, 1991) and to settle higher altitudes of the Pyrenees (Montes and Utrilla, 2008; Sacchi, 1988; Schwendler, 2012). In both Cantabria and the Dordogne, site density and occupation intensity increased (Álvarez Alonso et al., 2016; Straus, 2005) which led hunter-gatherers to broaden their territories; a few Cantabrian sites were now located on high altitudes mountain flanks recently freed from glaciers (Straus, 2005), whereas Dordogne sites could now be found beyond the main river valleys (Jones, 2007).

Magdalenian Subsistence

Subsistence was specialized for most of the Magdalenian (Altuna and Mariezkurrena, 1995); it focused on the largest locally available species such as mammoth in Germany (Albrecht, 1989), reindeer in France (Fontana, 1999; Kuntz and Costamagno, 2011; Sacchi, 1988), and mountain goats and red deer in Cantabria (Altuna, 1992; Marín Arroyo and González Morales, 2007; Marín, 2004; Straus, 1977 amongst others).

Cantabria was a refugium for hunter-gatherer population and large-bodied mammals fleeing the arid climate of the northern latitudes (Altuna, 1979; Freeman, 1973, 1981; Straus, 1991). In this context, the sheltered river valleys at the foot of the Cantabrian mountain range favored the distribution of a wide range of animal taxa that could be hunted yearlong and complemented with the marine resources of the nearby ocean (Álvarez Alonso et al., 2016; Álvarez-Fernández, 2002; Mellars, 1985; Straus, 1986, 1991). The reduced mobility of Cantabrian hunted species – red deer and ibex – prevented the need for large-scale residential movements, which in turn led to site specialization seen in faunal assemblages (Marín Arroyo, 2009; Straus, 1991; Yravedra, 2010). This led Straus and González Morales (2012) to hypothesize that the Cantabrian populations were socially organized in small bands, with territories confined to a specific valley.

Following the logistical mobility system, residential camps were located in the mountains during the summer and near the ocean during the winter (Clark and Barton, 2017; Marín Arroyo, 2009; Schwendler, 2012; Straus, 1986). From those camps, 'task-specific' individuals moved to hunting locations to take advantage of the diverse resources available, including ocean mollusks, small mammals, and river fish (Álvarez-Fernández, 2008; Álvarez-Fernández et al., 2011; Álvarez Alonso et al., 2016; Clark and Barton, 2017; Dachary, 2002; Freeman, 1973; Straus, 1977, 1991, 1992).

The faunal records dated to the Lower and Middle Magdalenian (Fig. 2.5) show the importance of red deer in most faunal assemblages. Only a few sites located in the mountain valleys focused on mountain goat. During the Middle Magdalenian, the reliance on horses increased slightly, especially in sites located in the eastern part of the region. This shows that tree coverage decreased substantially during this period, which may have resulted from the aridity of the climate, as well as the impact of human occupation (see Chapter 3).

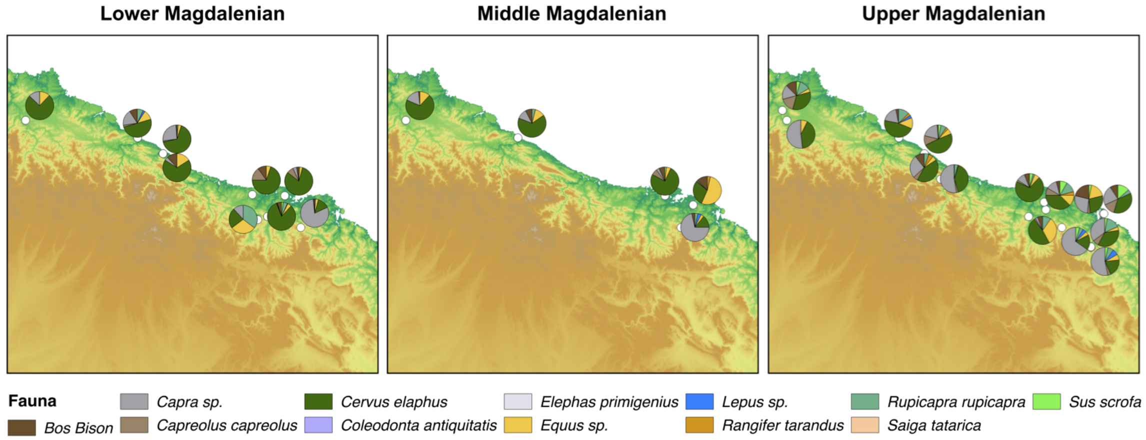


Figure 2.5. Cantabria faunal records attributed to each period. The data represents MNI when available, and NISP in other cases.

As a response to climate and environmental changes and/or to the overexploitation of large mammals (Otte, 2012), Upper Magdalenian Cantabrian populations diversified their subsistence by including small mammals and mollusks (Altuna, 1985, 1995; Dachary, 2002; Straus et al., 1981). This significant change is visible in the calculated inverse Simpson diversity indices of individual faunal assemblages (Fig. 2.6, data available in Appendix A).

Reindeer was the main source of subsistence in the Dordogne until the end of the Middle Magdalenian, when their proportion diminished (Delpech, 1990; Kuntz and Costamagno, 2011) only to disappear from the region ~ 14 cal. kya (Costamagno et al., 2016). Only a few sites relied heavily on other species – such as bison, horse, and saïga – during the Lower and Middle Magdalenian (Fig. 2.7). The highly productive Dordogne environment prevented the need for extensive migrations and storage (Kuntz and

Costamagno, 2011). Instead, Dordogne occupants followed a residential mobility pattern, and moved their camps regularly to follow resources (Straus, 1986). Some data suggests the use of short-distance hunting trips towards the Massif Central (Kuntz and Costamagno, 2011).

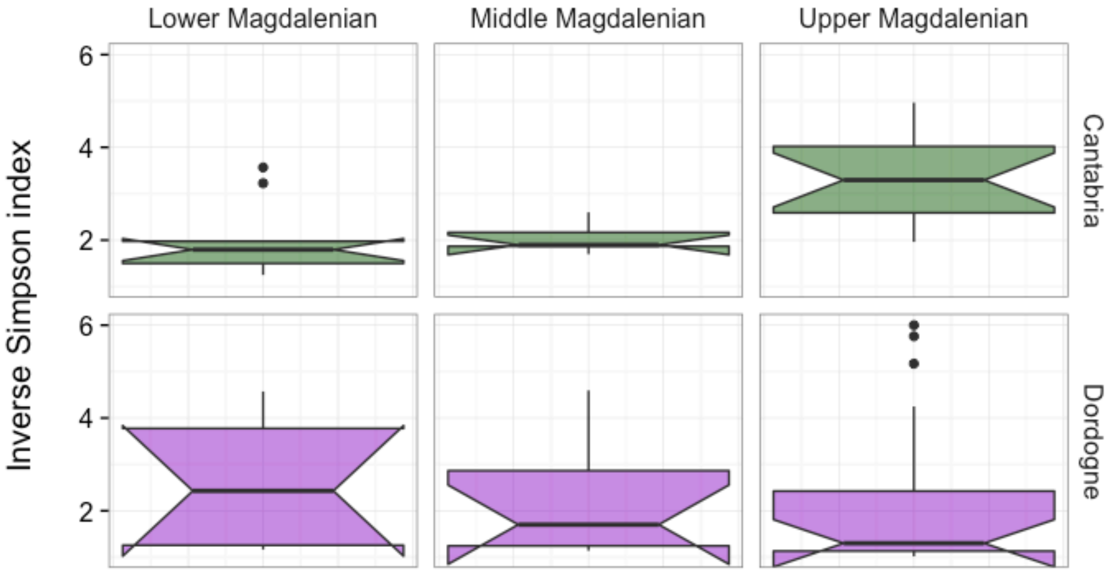


Figure 2.6. Inverse Simpson diversity indices of individual faunal assemblages.

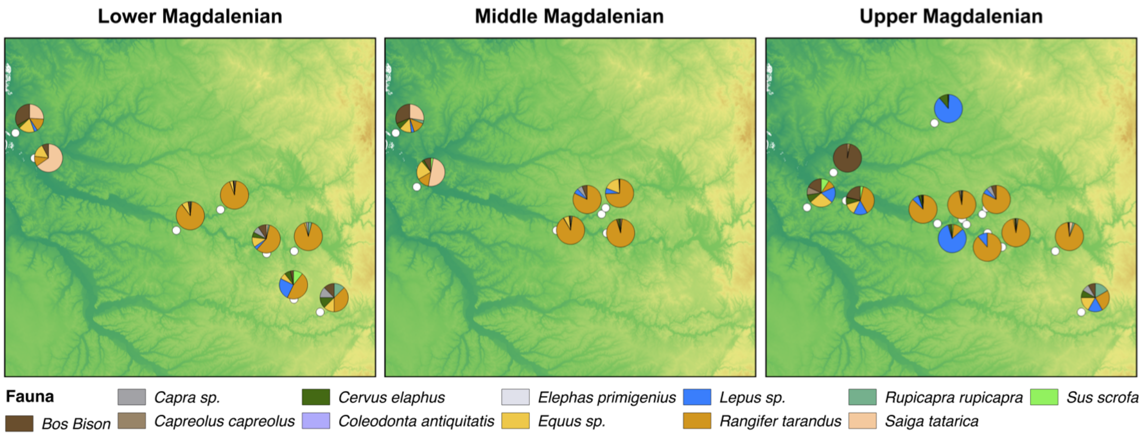


Figure 2.7. Dordogne faunal assemblages attributed to each period. The data represents MNI when available, and NISP in other cases. See Appendix A for data.

Practices changed considerably during the Upper Magdalenian, as the warmer temperature and increased humidity favored the growth of forested environments, which probably contributed to the increased reliance on small forest fauna, seen in Figure 2.7 (Costamagno et al., 2016; deSonneville-Bordes, 1960; Dachary, 2002; Delpech, 1983, 1992; Jones, 2007; Langlais et al., 2012; Sacchi, 1988). Figure 2.6 shows that, while these changes appear to have been important, they are not statistically significant.

Magdalenian Technology

The Magdalenian technology is generally characterized by the abundance of burins, scrapers, antler points, backed bladelets, an important bone industry (Dachary, 2002; Montes and Utrilla, 2008; Rozoy, 1988; Straus, 1991), and the appearance of harpoons made on antler during the Middle-Upper Magdalenian (Fullola et al., 2012; Julien, 1982; Sacchi, 1988). In most places, bone and antler tools were made from the animals that were already hunted as food source (Fullola et al., 2012; Julien, 1982).

At the start of the Lower Magdalenian, hunters of both Cantabria and the Dordogne made their tools on local material. In Cantabrian regions with poor-quality flint, tools were made on non-flint material (Straus, 2013). In contrast, the Dordogne had several local high-quality flint sources that were used throughout the Magdalenian (Demars, 1998; Lenoir, 1992). Cantabrian lithic styles differed by sites (Utrilla, 1981), interpreted as a result of low mobility and small territory (Straus, 2012).

Tools were reconfigured during the Middle Magdalenian, with the appearance of harpoons in Cantabria (Álvarez Alonso et al., 2016; Corchón Rodriguez, 1986), and tool decorations (Blanchard, 1972; Capitan and Peyrony, 1928; Dachary, 2002; Langlais et al., 2012; Sacchi, 1988). In the Dordogne, most lithic raw material remained local (Langlais et al., 2016; Lenoir, 1992), whereas Cantabrian hunters increased their reliance on exotic lithic raw material (Álvarez Alonso et al., 2016; Corchón Rodríguez, 1986, 1995, 2005; Corchón Rodríguez and Rivero, 2008; Corchón et al., 2008), suggesting a broadening of overall mobility or an increase in the exchange of raw material.

During the Upper Magdalenian, populations of both regions optimized their use of local raw material, leading to a reduction in tool size and quality, as well as their overall simplification (Álvarez Alonso et al., 2016; Dachary, 2002; Fullola et al., 2012; Langlais et al., 2012; Sacchi, 1988). These technological innovations, in addition to the appearance of light shouldered points and new hafting techniques, coincided with a change in subsistence practices targeting smaller taxa living in local forested environments (Costamagno and Laroulandie, 2004; Langlais et al., 2012; Otte, 2012). Harpoons appeared in the Dordogne (deSonneville-Bordes, 1960; Julien, 1982; Peterkin, 1993), following the trend started in Cantabria a few centuries earlier. The northern expansion of populations led to the creation of more heterogeneous industries, with tool characteristics confined to specific regions (Langlais et al., 2012; Langley and Street, 2013).

Magdalenian Symbolic Activities

The Magdalenian is known for its impressive rock art paintings and its detailed engraved portable art. The increase of parietal art at the peak of the LGM hints at its use to communicate group affiliation and ownership to cope with the demographic pressure brought by climate change, a practice that could have carried on during the Late Glacial under the form of portable art objects (Barton et al., 1994). In addition to art, the extensive diffusion of ornaments made on marine and fossil shells, as well as animal teeth, demonstrate the importance of non-utilitarian objects (Álvarez-Fernández, 2006, 2009; Schwendler, 2012), as well as the ubiquity of symbolic intra-group exchange of that period (Culley, 2016). Ornaments have been found in all regions encompassed by the Magdalenian techno-complex (Álvarez-Fernández, 2006; Gravel-Miguel, 2011; Schwendler, 2012). In most cases, they were made from local available material (Álvarez-Fernández, 2009); however, pierced red deer canines – a popular raw material to make ornaments – have been found in several sites located in environments that would not have been occupied by red deer. The distance traveled to collect raw material was significantly higher at the end of the Lower Magdalenian and the beginning of the Middle Magdalenian than in more recent periods (Gravel-Miguel, 2011).

Parietal and portable art became widespread during the Magdalenian, and recognized similarities in themes and stylistic concepts throughout the Magdalenian territory (Barandiarán, 1994; Dachary, 2002; Montes and Utrilla, 2008; Otte, 2012; Pigeaud, 2007; Rivero, 2010; Rivero and Sauvet, 2014; Schwendler, 2004, 2012) hint at the presence of widespread social contacts through which cultural transmission occurred. In this perspective, it has been hypothesized that population aggregation and expansion were closely linked to symbolic behavior and style conventions (Audouze, 2006; Bahn, 1982; Conkey, 1980, 1992; Schwendler, 2012; White, 1987). For example, archaeologists have quantified the variability of artistic styles and lithic raw material in archaeological assemblages to identify aggregation sites such as Isturitz, Mas d'Azil, Laugerie-Basse, Gazel, and Altamira (Conkey, 1992; see for example Bourdier, 2013; Rivero, 2010; Sacchi, 1988). In the social and climatic context of the Magdalenian, regular population aggregation could have been a way to mitigate – or maintain – the social institutionalization that was taking place (Bahn, 1982; Schwendler, 2012).

The Magdalenian art 'conventions' changed through time (Fortea Pérez et al., 2004). Portable art dated to the Lower Magdalenian was somewhat schematic using repeated hatchings (Aparicio Pérez, 1987), as seen on the engraved scapulae found at Altamira, El Castillo, El Miron, and El Cierro (Fig. 2.8), which were clearly made by artists sharing the same cultural background (Almagro-Basch, 1976; Corchón Rodríguez, 1986; Freeman and González, 2001; González Morales et al., 2007).

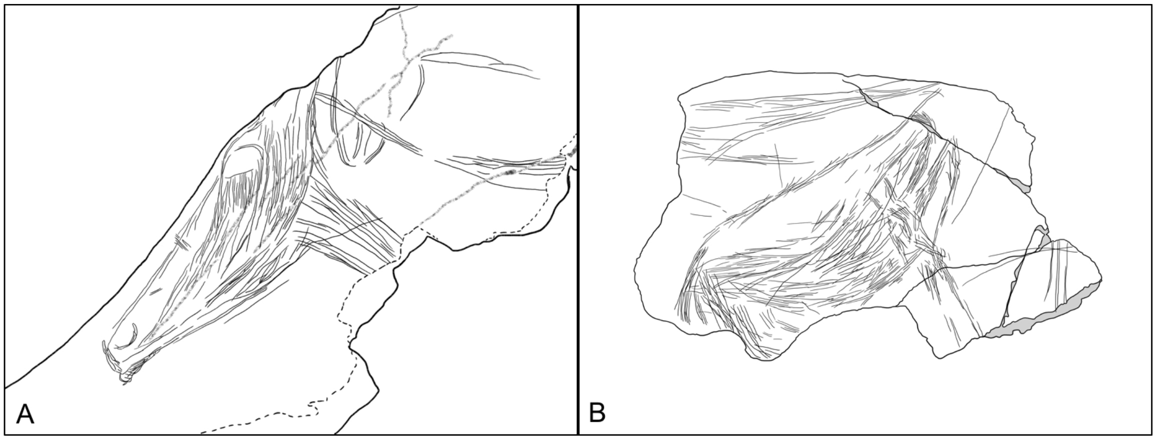


Figure 2.8. Tracing of the Lower Magdalenian engraved scapula from A. El Miron and B. Altamira (tracing by the author).

Representations became more detailed and naturalistic during the Middle Magdalenian (Fig. 2.9). The homogeneity of complex designs suggests the cultural transmission of artistic conventions between specialized artists (Bahn, 1982; Buisson et al., 1996), exemplified by the spiral rods and ibex contours découpés found throughout the European Southwest (see Álvarez Alonso et al., 2016; Buisson et al., 1996; Fritz et al., 2007; Sauvet et al., 2008a, 2008b; Schwendler, 2012). Studies show that some of those designs originated from a specific location and were transmitted to other regions by successive contacts (Buisson et al., 1996; Dachary, 2002), creating the homogeneous artistic record we know of today (Fullola et al., 2012). In addition to bones and antlers, slabs of stone – also called *plaquettes* – became popular supports for artistic representations during this period, as seen at La Garma (Ontañón and Arias, 2012).

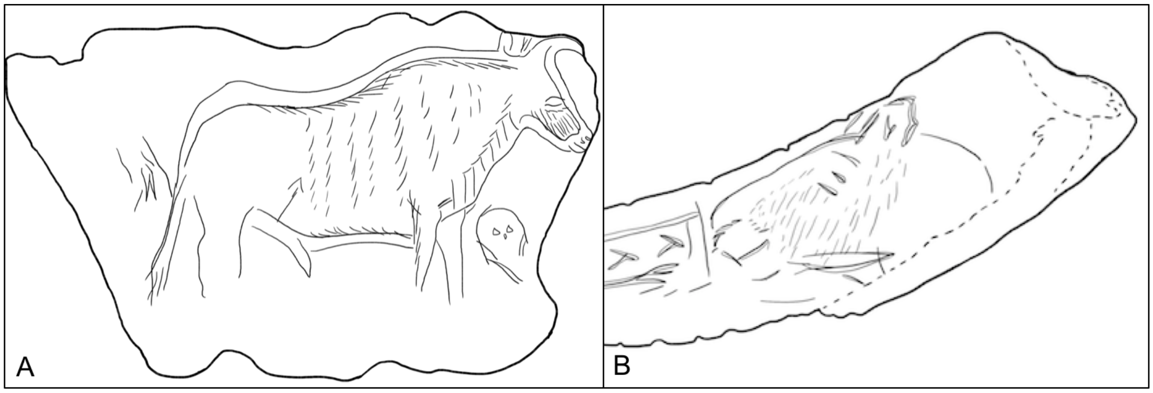


Figure 2.9. Tracing of Middle Magdalenian engraved bone and tooth from La Garma (tracing by the author).

In all regions, the use of schematic designs and symbols increased during the Upper Magdalenian (Barandiarán, 1994; Dachary, 2002; Sacchi, 1988; Rivero, 2010) – e.g., the frontal representations of ibex, identified as *fossil directeur* of that period (Montes and Utrilla, 2008). The range of different styles increased, as some artists still produced complex naturalistic representations, whereas others preferred using simpler and more schematic designs (Fig. 2.10).

These changes coincide with the major northern expansion of populations, which may have led to the creation of isolated regional styles.

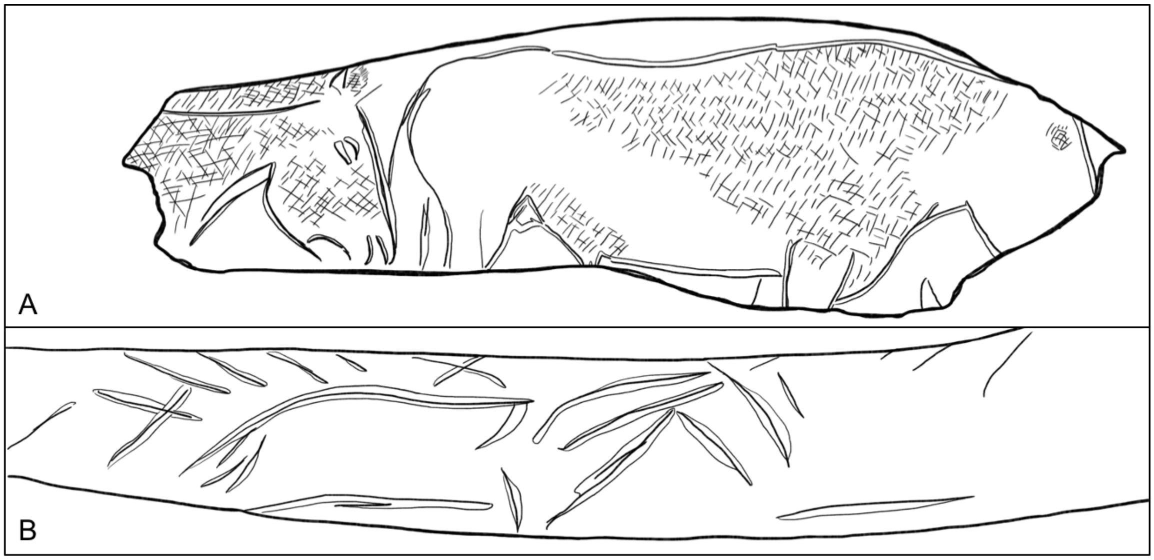


Figure 2.10. Tracing of Upper Magdalenian engraved bones from El Pendo (tracing by the author).

Symbolic Activities in Cantabria. Parietal art, portable art, and ornaments have been found in high number in Cantabrian sites. Parietal art was present throughout the Magdalenian (Alcalde del Rio et al., 1912; Arias Cabal and Pérez Suarez, 1989); however, its density increased during the Middle Magdalenian, as it may have been used as territorial marker to deal with the high population density brought by the Oldest Dryas arid climate (Straus, 1991). Almost half of Cantabrian sites have ornaments. A few of those are pierced red deer canines (Arias et al., 2011), but the majority are made from shell that could have been gathered from the nearby Atlantic Ocean (Álvarez-Fernández, 2006; Arias et al., 2011; Schwendler, 2012). The presence of a few Mediterranean shells, however, suggests the presence of long-distance movement or trade networks (Álvarez Alonso et al., 2016; Schwendler, 2012).

As in other regions, the Cantabrian portable art styles changed over time. The Lower Magdalenian portable art was mainly comprised of scapula engraved with hatched designs of red deer and bison (Almagro Basch, 1976; Corchón Rodríguez, 1986; Gomez

Fuentes and Becares Perez, 1979; González Morales and Straus, 2009; González Morales et al., 2007; Montes Barquin and Muñoz Fernandez, 2001; Montes Bernardez, 1978). In these representations, artists used hatching to represent the face and neck muscles in an attempt to capture the complexity of their subject (Sauvet et al., 2008a). The high similarity of those designs – found in multiple sites – hint at the presence of very strict artistic conventions shared throughout (Álvarez Alonso et al., 2016; Utrilla et al., 2004; Corchón Rodríguez, 2005).

A few unusual stone structures and object accumulations at El Juyo and La Garma – deemed 'ritualistic' due to their peculiarities and association with important quantities of ochre – appeared at the temporal junction of the Lower and Middle Magdalenian (Arias, 2009; Freeman and González-Echegaray, 1981; González-Echegaray and Freeman, 1982; Ontañón and Arias, 2012). Around the same time, the artistic conventions changed towards naturalist representations made on different supports, including stone slabs that usually came from the cave/rockshelter in which they were discarded (Arias et al., 2011), suggesting that they were not curated. This period also saw the introduction of external conventions, with the adoption of the Pyrenean *contours découpés* and decorated disks (Buisson et al., 1996; Dachary, 2002; Sauvet et al., 2008a, 2008b). This suggests a broadening of mobility and social contacts to include long-distance populations. As this coincided with the advent of Heinrich 1 and the cold and arid Oldest Dryas, it suggests the possible need to create networks to gather information on resource availability in different environments (as per Whallon, 2006). As in other regions, Upper Magdalenian art went from complex to schematic representations relying on the use of symbols (Barandiarán, 1994; Dachary, 2002; Rivero, 2010; Rivero and Sauvet, 2014), including the Pyrenean ‘caprid in frontal view’, which shows that the link with the Pyrenees remained important during this period (Rivero and Sauvet, 2014). Artistic representations were abundant at the beginning of the Upper Magdalenian, but decreased significantly over time (Dachary, 2002).

Symbolic Activities in the Dordogne. While Lower Magdalenian parietal representations and ornaments were abundant in the Dordogne, portable art dated to this period was almost non-existent (Barton et al., 1994; Sauvet et al., 2008a, 2008b; Taborin, 1993), and none of those objects bore animal representations. The introduction of such representations occurred slowly during the Middle Magdalenian, when, similarly to Cantabria, the Pyrenean bone disks and *contours découpés* appeared in the region (Buisson et al., 1996; deSonneville-Bordes, 1960; Reverdit, 1878; Sieveking, 1971), likely due to the creation of long-distance social networks with the Pyrenees (Fritz et al., 2007; Sauvet et al., 2008a, 2008b). While they were only found in a few sites, Middle Magdalenian portable art representations were mostly naturalistic (see Breuil, 1934; Delporte, 1990; Paillet, 1999), sometimes a bit rounded – e.g., horses from La Madeleine (Bouvier, 1990; Capitan and Peyrony, 1928).

The majority of portable art found in the Dordogne dates to the Upper Magdalenian. At the beginning of this period, the art was complex; artists used infilling to add realism to their animal representations (Crémades, 1994; Pigeaud, 1999). Plaquettes were popular supports (Alaux, 1972), especially at Limeuil (Capitan and Bouyssonie, 1924; Tosello, 1992). Discrepancies between Cantabrian and Dordogne artistic styles increased during this period. For example, Dordogne artists often engraved lines of horses with enlarged heads, as well as horses with double mane, which were not found elsewhere (Apellaniz, 1990; deSonneville-Bordes, 1960; Pigeaud, 2007; Rivero and Sauvet, 2014). In fact, the artistic conventions of this period became more regionally heterogeneous, suggesting that the networks created between the Dordogne, the Pyrenees, and Cantabria during previous periods weakened during the Upper Magdalenian (Rivero and Sauvet, 2014). This could explain why symbolic representations such as the frontal ibex depictions were found widely in Cantabria and the Pyrenees, but remained rare in the Dordogne (Rivero and Sauvet, 2014).

Magdalenian Social Networks

The presence and structure of prehistoric social networks has been assessed through sourcing of lithic raw material and shell ornaments (Álvarez-Fernández, 2006, 2009; Bahn, 1982; Dachary, 2002; Langlais et al., 2015, 2016), and through art stylistic similarities (see Buisson et al., 1996; Fritz et al., 2007; Rivero and Sauvet, 2014; Sauvet et al., 2008a, 2008b). From these research, we have gained a relatively good picture of the extent of Magdalenian networks. Examples are: the high quantities of exotic Atlantic shells and art conventions seen in Middle Magdalenian sites of the Pyrenees that show connections with the French Southwest and Cantabria (Fritz et al., 2007; Montes and Utrilla, 2008; Rivero and Sauvet, 2014; Sacchi, 1988; Sauvet et al., 2008a, 2008b), the distribution of similarly decorated spear-throwers in Western and Central Europe that suggests extensive North-South networks (Straus, 1991), and the presence of Mediterranean shells and exotic raw material in German sites, which shows the use of radial movements to and from this region (Bahn, 1982; Rensink, 1995; Schwendler, 2012). Exotic lithic raw materials are commonly found in Belgium, Germany, Switzerland and the Southwest (Bahn, 1982), sometimes found over 600 km from their source (Álvarez-Fernández, 2009; Bahn, 1982; Langley and Street, 2013; Rozoy, 1988; Taborin, 1993). It is still unclear if all these instances are the result of high mobility, long-distance exchange, or both.

The structure and extent of networks changed during the different phases of the Magdalenian. Population mobility was relatively constrained during the Lower Magdalenian, it broadened and intensified considerably during the Middle Magdalenian (Bahn, 1982; Fritz et al., 2007; Langlais et al., 2016; Rivero and Sauvet, 2014; Sauvet et al., 2008a; Schwendler, 2004; 2012), and while the number of networks decreased with time, (Schwendler, 2012), their spatial extent expanded further during the Upper Magdalenian (Rivero and Sauvet, 2014; Sauvet et al., 2008a, 2008b).

Social Networks of the European Southwest. In general, similarities in tool technology, lithic and shell sourcing, as well as artistic similarities have been used to suggest the presence of networks connecting Cantabria, the Dordogne, Catalonia, and the northern Pyrenees (Álvarez-Fernández, 2002, 2006; Bahn, 1982; Fritz et al., 2007; Fullola et al., 2012; Montes and Utrilla, 2008; Sauvet et al., 2008a, 2008b; Schwendler, 2004, 2012).

In Cantabria, the artistic record, ornament and lithic raw material sourcing show that mobility remained mostly local during the Lower Magdalenian (Álvarez-Fernández, 2002; Gravel-Miguel, 2011; Rissetto, 2009; Straus et al., 2012). This can be explained by the easy access to a wide range of local resources, including non-flint raw material of medium-high quality (Schwendler, 2012; Straus, 2005). Only a few Mediterranean shell beads found in Altamira, El Castillo, El Miron, and Tito Bustillo suggest the presence of rare long-distance networks (Álvarez-Fernández, 2002; Schwendler, 2012). In the Dordogne, lithic raw material sourcing suggests the presence of social contacts with the Western Pyrenees and the Paris Basin (Langlais et al., 2016).

Networks expanded significantly during the Middle Magdalenian, when art styles shared between Catalonia, Cantabria, the Pyrenees, and the Dordogne started to appear (Bahn, 1982; Dachary, 2002; Fullola et al., 2012; Montes and Utrilla, 2008; Schwendler, 2004; Straus et al., 2012). In particular, similar art and tools found in the Western Pyrenees and the Dordogne suggest that these two regions were more strongly connected with one another than with any other region (Dachary, 2002; Langlais et al., 2012; Rivero, 2010). During this period and the following Upper Magdalenian, sourcing of shell ornaments shows the presence of different networks in the Pyrenees; western sites were connected to Atlantic regions – i.e., Cantabria and the Dordogne – whereas eastern sites were linked to *both* Atlantic and Mediterranean regions (Bahn, 1982; Rozoy, 1988). The marked bias for Atlantic shells in the Pyrenees might have resulted from river flow direction, facilitating movement towards the Atlantic (Bahn, 1982). Studies of lithic raw material, art styles, and ornaments suggest a general decrease in the use of long-distance networks during the Upper Magdalenian (Fritz et al., 2007; Straus, 2005), especially between the Dordogne and the Pyrenees (Rivero and Sauvet, 2014).

A debate stands on how materials and objects moved over such large distances, as it could be the result of casual collection made during subsistence activities (following Binford in Bahn, 1982; see also Brantingham, 2003), the result of single long-distance trade or exchanges, or of multiple exchanges over shorter distances. The artistic similarities found on decorated tools in Switzerland and the French Southwest suggest that some of those networks may have been related to hunting practices (Schwendler, 2004). Another interpretation is that some regions with similar technology – Pyrenees and the Ariège – were seasonally occupied by the same hunter-gatherer groups (Fontana, 1999), which could have led to the extensive distribution of small groups, creating the illusion of a larger inter-connected population (Demars, 1998). Finally, the exchange of raw material and ornaments between the Dordogne and Cantabria may have been facilitated through aggregation at certain Pyrenean sites. For example, Enlène, Isturitz, and Mas d'Azil have been interpreted as aggregation sites due to their size, the presence of 100s of Atlantic and Mediterranean shell ornaments, and the portable art found within (Bahn, 1982; Fritz et al., 2007; Schwendler, 2012). Moreover, an exhaustive analysis of the *contours découpés* that originated in the Pyrenees and were found throughout the European Southwest shows that their style could have been passed on by successive contacts, probably favored by the aggregation of people from different regions in those Pyrenees mega-sites (Buisson et al., 1996). Due to their geographical position, aggregation sites located in the Western Pyrenees could have facilitated the creation of links between populations of Cantabria and the Dordogne *without* the need to travel extremely long distances.

In the next chapter, I present detailed reconstructions of the environmental context in which social networks were created in Southwest Europe (Chapter 3), which are then used in an Agent-based model to evaluate the impact of biome distribution and climate change on the extent and structure of social networks (Chapter 4).

CHAPTER 3. ENVIRONMENTAL RECONSTRUCTION

Introduction

Anthropological and ethnographic research has shown the influence of climate and resource distribution on the lifestyle of hunter-gatherers (e.g., Dyson-Hudson and Smith, 1978; Binford, 1980; Kelly, 1995, 2013). As a result, an increasing number of archaeologists have attempted to reconstruct past environments to understand behavior in its context (e.g., Corchón et al., 2008; Djindjian, 2009; Marean, 2010; van Andel, 2002). As this research follows a similar goal, it is necessary to look at the characteristics of Magdalenian geographical and temporal environmental variations. To this end, I divided this chapter in two sections. The first presents the characteristics of the Magdalenian climate in Western Europe, while the second shows how I used this climate data to reconstruct the distribution of Magdalenian biomes in the Dordogne and Cantabria.

Environmental Background

Late Glacial Environment in Western Europe. The Magdalenian techno-complex took place during the Late Glacial, the period that followed the Last Glacial Maximum ~ 22 cal. kya, when sea levels were lower than today by ~ 120m (Murray-Wallace and Woodroffe, 2014; Peltier and Fairbanks, 2006), and temperatures were ~ 5-15°C colder than they are today (Kageyama et al., 2006; Ramstein et al., 2007; Strandberg et al., 2010).

Ice core records show that the period immediately following the Last Glacial Maximum saw the onset of warmer temperature (Fig. 3.1), which led to the retreat of major ice sheets, including the glaciers found in the Pyrenees (Fullola et al., 2012) and the Cantabrian Mountain range (Straus et al., 2002). However, ice cores also show that Late Glacial temperature fluctuated often and at high amplitude (Ahn, 2012).

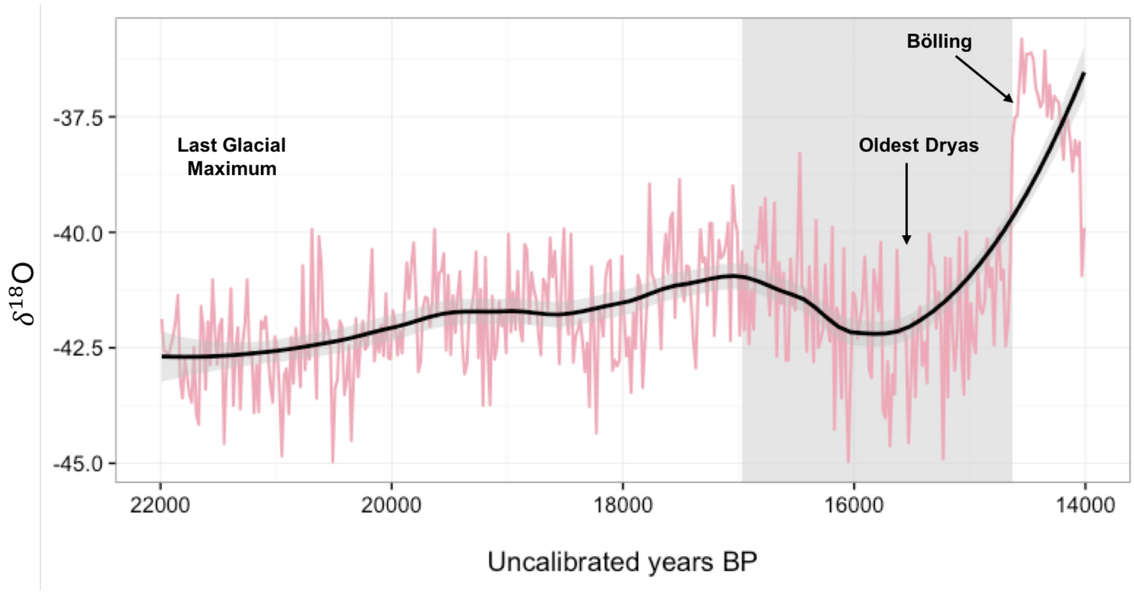


Figure 3.1. Changes in $\delta^{18}O$ *over the last 22,000* C^{14} *years (from NGRIP, 2008), which reflects temperature changes. The grey box shows the rough extent of Heinrich event 1.*

The Western European pollen record indicates the dominance of steppe-tundra vegetation during the first part of the Late Glacial, possibly due to a combination of low temperature and low atmospheric CO_2 (Ramstein et al., 2007). Around 18 cal. kya, the weakening of the meridional oceanic circulation led to iceberg discharge in the Atlantic Ocean, which interrupted the North Atlantic Deep Water production, leading to the Heinrich event 1 (Álvarez-Solas et al., 2011; Weldeab et al., 2016). This coincides with the Oldest Dryas, characterized by cold and arid climate – some of which may have been worse than during the LGM (Fullola et al., 2012) – as well as the re-advance of ice sheets (McCabe et al., 1998). This colder period was followed by a general temperature increase, gradual at first (ca. 17-15 cal. kya), and becoming abrupt during the Bölling (ca. 15-14.5 cal. kya), when temperature increased by ~ 4-6°C in under 500 years (Miller, 2012; Millet et al., 2012; TraCE-21 project).

Regional Climate. Due to the influence of water bodies and mountain ranges on local climate, the global climate changes described above would have been felt differently throughout Europe, demonstrated by the differences in temperature and precipitation of the neighboring Dordogne and Cantabria regions (Fig. 3.2).

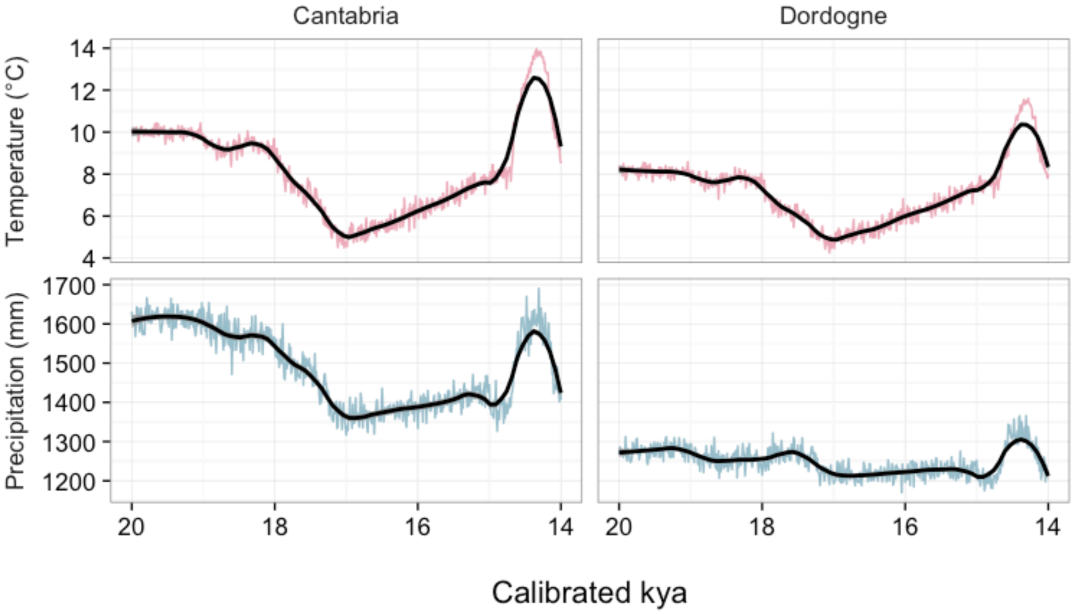


Figure 3.2. Temperature and precipitation values at decadal intervals for Cantabria and the Dordogne. Data obtained from TraCE-21ka project.

The data used for Figure 3.2 comes from the TraCE-21ka project, which used a Global Circulation Model with timed climate forcings to reproduce the climate fluctuations of the last 21,000 years at monthly and decadal resolutions. It is the only publically-available global model with projections of the Late Glacial climate; all other available models project the climate of the Last Glacial Maximum and the mid-late Holocene only. The archaeological record confirms the validity of the TraCE-21ka data; pollen, sedimentary, and faunal records from sites of both regions show that the climate in the early Lower Magdalenian was somewhat warm and humid, became gradually colder and drier during the Oldest Dryas, and regained its warmth and humidity abruptly during the Bölling (Altuna, 1992; Arias et al., 2011; Corchón Rodríguez et al., 2012; Delpech, 1990; Langlais et al., 2012; Muñoz-Sobrino et al., 2007). According to the TraCE-21ka data, temperature and precipitation were generally lower in the Dordogne than in Cantabria. The variance calculated for each Magdalenian period shows that the climate of the Dordogne fluctuated less over time (Table 3.1); however, χ^2 tests done on those values show that these differences are not statistically significant ($p = 0.22$ for temperature, and $p = 0.20$ for precipitation).

Table 3.1. Variance of the TraCE-21ka decadal data per region and period. As discussed in Chapter 2, the 3 periods are not exactly contemporaneous in the two regions.

		Lower Magdalenian	**Middle Magdalenian**	**Upper Magdalenian**
Cantabria	**Temperature**	0.08	0.10	0.13
	Precipitation	809.59	504.45	992.72
Dordogne	**Temperature**	0.06	0.09	0.09
	Precipitation	380.56	352.08	474.15

In both regions, temperature and precipitation remained relatively stable during the first half of the Lower Magdalenian, after which they decreased considerably. This coincided with the Middle Magdalenian, which was the coldest and driest subperiod in both regions. After a few cold and arid centuries, temperature started to increase relatively steadily in both regions, whereas precipitation increased in Cantabria, but remained low in the Dordogne. This marked the beginning of the Upper Magdalenian. In general, despite their climatic fluctuations, these two regions remained relatively temperate during and after the Last Glacial Maximum, which made them good refugia for northern populations (Clark et al., 1996; Jochim, 1987; Straus et al., 2000).

Climatic Subdivisions of the Magdalenian. The high variance of the Lower and Upper Magdalenian climatic values – especially in Cantabria – likely affected the temporal change in biome distribution. In other words, the biomes of the first part of the Upper Magdalenian probably differed significantly from the biomes of the second part, due to the abrupt increase in temperature characterizing the latter. Therefore, if social networks were affected by the environment – as the hypotheses of this research state – we should expect to find significant differences between the structure and extent of networks created in the two halves of that period.

As mentioned in Chapter 2, the temporal resolution of archaeological sites does not allow separating Magdalenian portable art in more than the 3 periods mentioned up to now. However, using a higher temporal resolution in the agent-based model would allow capturing the variability in network structure that should best represent the past. Therefore, in this chapter, I model the biome distribution of 5 rather than 3 Magdalenian subdivisions. The separations of these 5 periods are based on Miller's (2012) and Straus' (2013) subdivisions of the Magdalenian climate.

Table 3.2. Temporal boundaries of the 5 Magdalenian subdivisions, informed by climate change. As they relate to climate rather than culture, they are similar in both regions.

	Lower A	**Lower B**	**Middle**	**Upper A**	**Upper B**
Date range (cal. kya)	20-19	19-17.5	17.5-16.5	16.5-14.75	14.75-14

With this division, the warm and relatively stable climate is restricted to the Lower Magdalenian A, whereas Lower B catches the temperature decrease that coincides with the start of H1. The onset of warmer temperature following the Middle Magdalenian is found in the Upper Magdalenian A, but Upper B captures the abrupt temperature and precipitation increase brought by the Bölling.

Species Distribution Models

The traditional method used to reconstruct past environments entails analyzing proxies for environmental data – e.g., pollen, fauna, speleothems (Bar-Matthews et al., 2010; Laine et al., 2010; Marín, 2004; Sommer and Nadachowski, 2006). However, that method is inherently spatially restricted by its focus on individual sites; therefore, its ability to reconstruct past regional environments is limited. The recent introduction of predictive models provides an alternative to produce more comprehensive paleoenvironmental reconstructions (Verhagen and Whitley, 2012).

In the past few decades, Species Distribution Modeling – also called Ecological or Niche Modeling – has gained in popularity in ecological disciplines, following the increase in computing power that allowed for increasingly accurate predictions (Franklin et al., 2015). For the most part, species distribution models use *presence* or *presence-absence* observations of a given species as the dependent variable, and its environmental context as the independent variable to predict the probabilities of finding that species in places where it was not observed (Elith et al., 2006; Elith and Leathwick, 2009; Franklin, 1995; Guisan and Thuiller, 2005). Species distribution models are increasingly used in archaeology as valuable tools to reconstruct spatial probability distributions of prehistoric species, as seen in the recent projections of modern species-climate associations onto past climatic conditions (e.g. Banks et al., 2008a, 2008b, 2009, 2013; Hufford et al., 2012; Moriondo et al., 2013; Politis et al., 2011). However, despite their potential, species distribution models have not yet been used to contextualize prehistoric social networks. This research is the first to use such model to reconstruct Magdalenian biomes to better understand how the environmental context affected the social networks created within.

MaxEnt. I chose to use the species distribution model MaxEnt (Phillips et al., 2006) based on Elith et al. (2006)'s comparative study, which ranked MaxEnt best among available models. For a given species, MaxEnt evaluates the geographical distribution of its documented presence in terms of its climatic context (climate maps), and produces a distribution map of that species' occurrence probability, which represents the spatial extent of the environment suitability based on the species' requirements (Politis et al., 2011). MaxEnt is a *presence-only* model; it only takes into account instances where a species was directly observed, but does not consider its known absence data. This type of model works well because most species do not have robust absence data. In the past decade, MaxEnt has been used successfully to reconstruct past – and project future – distributions of insects (Beck et al., 2014) and plants (Alba-Sánchez et al., 2010; Carnaval and Moritz, 2008; Moreno-Amat et al., 2015).

Selecting Appropriate Data. For this research, faunal and floral data were available to reconstruct past biomes. I first attempted to model biomes using faunal data, as faunal remains are reported in site reports and journal articles more often than pollen, providing abundant data against which I could test the reconstructions. However, I found that, as the medium- and large-bodied mammals found in prehistoric faunal assemblages have broad environmental tolerance (Cantalapiedra et al., 2011; Hernández Fernández and Vrba, 2005), prehistoric biomes modeled using those mammals' distribution could not capture the local high-resolution diversity that was necessary for this research.

Therefore, I decided to use vegetation data to model prehistoric biomes. This decision was supported by prior research that has demonstrated the high accuracy of projecting modern vegetation-climate relationships onto past climatic conditions (Alba-Sánchez et al., 2010; Carnaval and Moritz, 2008).

Modern Vegetation Data (Collecting and Formatting). I used the Biomization method (Prentice et al., 1996) to reconstruct prehistoric biomes from plant taxa. This method relies on the assumption that the best way to reconstruct biomes is to estimate the geographical extent of the taxa most representative of each biome (Connor et al., 2004). It uses known correspondences between plant taxa and Plant Functional Types (PFTs), and between those PFTs and biomes. I used the work of Davis et al. (2015), Tarasov et al. (2000), Peyron et al. (1998), and Prentice et al. (1996) to identify a set of 17 plant taxa representative of 13 PFTs, which could then be grouped into 11 biomes (Table 3.3). Each PFT's attribution to a biome is based on the known ecology of its plant taxa (Prentice et al., 1996; Tarasov et al., 2000).

I used the Global Biodiversity Information Facility (GBIF at http://www.gbif.org) database to obtain georeferenced human observations of these plant taxa in Western Europe – particularly the United Kingdom, France, Belgium, Germany, Switzerland, Portugal, Spain, and Italy. GBIF is the largest open source modern vegetation database (Beck et al., 2014), and provides comprehensive samples of important taxa that could be used for the model. However, due to the crowd-sourced nature of the records, biases resulting from differential sampling methods, duplicate entries, and erroneous coordinates are common. To correct those problems, I removed points with oceanic coordinates, I grouped the 17 taxa by PFTs, and I used stratified sampling to reduce the number of input points to 1 per 10,000km^2 (Fig. 3.3). Beck et al. (2014, p. 11) have shown that using a stratified sample with 100 x 100km grid cells reduces the points' spatial clustering while keeping their spatial extent, which in turn improves the accuracy of the model produced with those points. I used this method to reduce the dataset of each PFT, which were then used as input for MaxEnt (Appendix B).

Table 3.3. Plant taxa included in this research with their respective PFT attribution, followed by a list of the PFTs characteristic of each biome.

Plant Functional Type (PFT)	**PFT Code**	**Plant taxon included**
Arctic/alpine dwarf shrub	AA	*Alnus alnobetula, Betula nana*
Arctic/boreal dwarf shrub	AB	*Rubus chamaemorus*
Boreal evergreen conifer	BEC	*Picea sp.*
Boreal summergreen	BS	*Alnus glutinosa*
Cool temperate conifer	CTC	*Abies alba*
Desert forb	DF	*Ephedra major*
Eurythermic conifer	EC	*Pinus sylvestris*
Steppe forb	SF	*Artemisia sp.*
Temperate summergreen	TS	*Quercus pubescens/robur*
Cool temperate summergreen	TS1	*Carpinus sp., Corylus sp., Tilia sp., Ulmus sp.*
Warm temperate summergreen	TS2	*Juglans sp.*
Warm temperate broadleaved evergreen	WTE	*Quercus ilex*
Warm temperate sclerophyll shrub	WTE2	*Phillyrea*

Biome	**PFTs included in biome**												
	AA	**AB**	**BEC**	**BS**	**CTC**	**DF**	**EC**	**SF**	**TS**	**TS1**	**TS2**	**WTE**	**WTE2**
Cold deciduous forest		X		X	X		X						
Taiga		X	X	X			X						
Cold mixed forest				X	X		X			X			
Cool conifer forest		X	X	X	X		X			X			
Temperate deciduous forest				X	X		X		X	X	X		
Cool mixed forest			X	X	X		X		X	X			
Broadleaved evergreen							X		X	X	X	X	
Xerophytic woods/scrub							X					X	X
Desert						X							
Steppe						X		X					
Tundra	X	X											

One part of the Biomization method involves reducing the distribution of each PFT to its estimated bioclimatic limits (Prentice et al., 1996). I used the values of Peyron (1998) and Prentice et al. (1996) to reduce the modern distributions, but found that this step led to the unrealistic distribution of certain PFTs. For example, according to these estimated restrictions, *Arctic/alpine dwarf shrubs* should not occur in places where summers temperature > 5°C; however, its modern distribution encompasses regions with summer temperature ~ 15°C. Therefore, as it would have considerably reduced the dataset of PFTs distribution – sometimes even removing all occurrences – I decided to skip this step of the Biomization method.

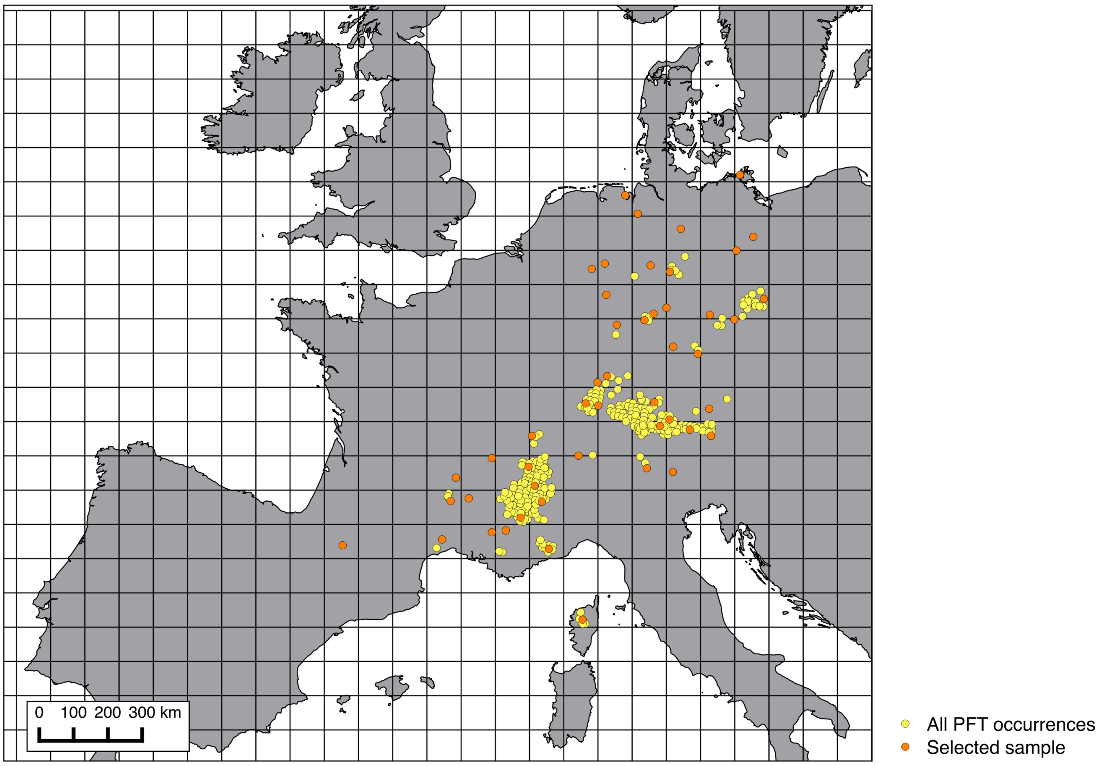


Figure 3.3. Example of the stratified sampling method used to reduce the GBIF dataset to 1 presence point per 10,000 km^2. One point (orange) per grid cell is selected randomly from the array of observations available (yellow).

Prehistoric Vegetation Data (Collecting and Formatting). I used prehistoric PFT distributions as test points to evaluate and improve the validity of the modeled distributions. I collected percentage pollen values from the European Pollen Database (http://www.europeanpollendatabase.net/index.php), focusing on the taxa mentioned in Table 3.1 found in any Western European site. As plant taxa have different pollen production densities, and as pollen size affects its transport, small quantities of certain trees' pollen can be found in areas from which those trees were absent. Therefore, to infer local presence of different taxa from pollen assemblages, one needs to use taxon-specific thresholds in pollen percentage (Douda et al., 2014). I used Connor et al. (2004), and Lisitsyna et al. (2011)'s thresholds to reduce the prehistoric pollen data to the records most likely to denote its taxon's presence within a ~ 30 km radius (Table 3.4). I could not find a threshold for *Rubus chamaemorus*, but as it is a poor pollen producer (Ehrich et al., 2008), I set the threshold arbitrarily at 0.1%. I then grouped the taxa occurrences by their respective PFTs and chronological subdivisions. Duplicates were removed when found. The resulting dataset can be found in Appendix C.

Table 3.4. Thresholds used to reduce prehistoric pollen percentages to the ones indicating local presence.

Taxa	**Threshold**	**Reference**
Alnus alnobetula	2.5%	Lisitsyna et al., 2011
Betula nana	5%	Lisitsyna et al., 2011
Rubus chamaemorus	0.1%	Based on Ehrich et al., 2008
Picea sp.	1%	Lisitsyna et al., 2011
Alnus glutinosa	2.5%	Lisitsyna et al., 2011
Abies alba	0.5%	Lisitsyna et al., 2011
Ephedra major	0.5%	Lisitsyna et al., 2011
Pinus sylvestris	10%	Lisitsyna et al., 2011
Artemisia sp.	10%	Connor et al., 2004
Quercus pubescens/robur	1.5%	Lisitsyna et al., 2011
Carpinus sp.	0.5%	Lisitsyna et al., 2011
Corylus sp.	1%	Lisitsyna et al., 2011
Tilia sp.	0.5%	Lisitsyna et al., 2011
Ulmus sp.	0.5%	Lisitsyna et al., 2011
Juglans sp.	0.5%	Lisitsyna et al., 2011
Quercus ilex	1.5%	Lisitsyna et al., 2011
Phillyrea	0.5%	Lisitsyna et al., 2011

Modern Climate Maps. Different sets of climate maps were required to reconstruct Magdalenian biomes: a modern set and five prehistoric ones – one for each climatic subdivision. Following the methods used by Alba-Sánchez et al. (2010), and due to the lack of extensive climatic data available for the Magdalenian, each set was comprised of 6 climatic maps (Table 3.5) and 2 topographical ones (elevation and slope).

Table 3.5. Bioclimate maps used to reconstruct PFTs' geographical distribution.

Climate variables included	**BIOCLIM variables (WorldClim)**
Mean annual temperature (°C)	BIO1
Maximum temperature of the warmest month (°C)	BIO5
Minimum temperature of the coldest month (°C)	BIO6
Annual precipitation (mm)	BIO12
Precipitation of the wettest quarter (mm)	BIO16
Precipitation of the driest quarter (mm)	BIO17

The modern topographical maps were made from a 30m resolution Digital Elevation Model (DEM) obtained from the USGS GMTED2010 7.5 Arc Second dataset. This data came as separate tiles, which I merged together using the *r.patch* tool in the open-source GRASS Geographical Information System (GIS). I downloaded the, 2014 bathymetry elevation map from GEBCO (30-arc second, or ~1km resolution) which I merged to the DEM so that the bathymetry map filled the null ocean grids of the DEM. I used *r.neighbors* with a circular moving 3-cell window to smooth out the boundary between the two maps. Modern climatic maps, also at a 30-arc second resolution, were obtained from the WorldClim database (www.worldclim.org) (Hijmans et al., 2005). As the WorldClim temperature data are given in °C * 10 to reduce file size, the values of the temperature maps were divided by 10 before their manipulation.

The method used to model prehistoric climate maps required performing computations on the values of modern maps. However, as the sea level changed in the last 20,000 years, the extent of the modern landmass is smaller than it was during the Magdalenian. To correct this – and to allow manipulating the values of cells that were terrestrial during the Late Glacial and are now marine – I expanded the coverage of the modern climate maps to its widest Magdalenian extent (~ -113m below modern sea-level during the Lower Magdalenian (Peltier and Fairbanks, 2006)). I created a mask of the widest land coverage and used *r.fillnulls* – spline bicubic interpolation – to extend the values of the modern climate maps to the extra strips of land (Fig. 3.4). I repeated this for all modern climate maps.

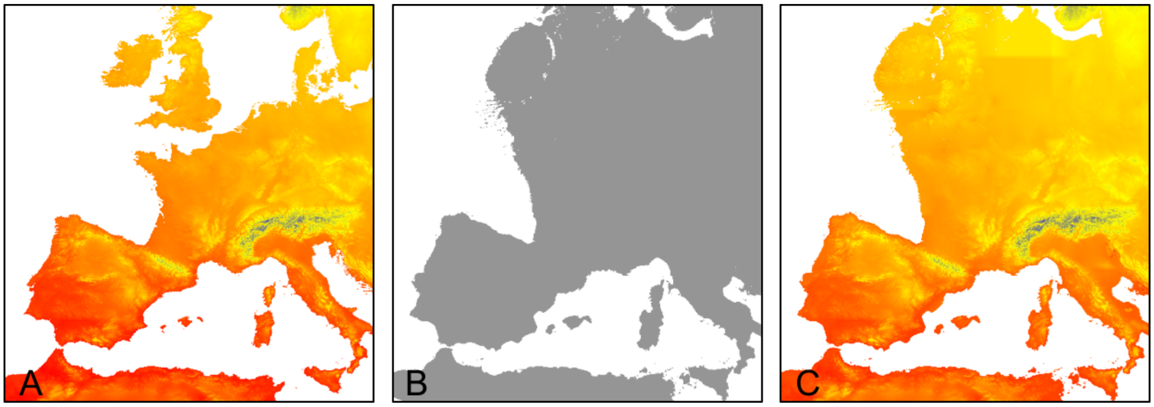


Figure 3.4. A. Modern climate map, B. Extent of the land dated to the Lower Magdalenian, C. Result obtained after filling the nulls of the modern map to cover the extent of the Lower Magdalenian.

Similarly, to create topographical maps of the different Magdalenian subdivisions, I lowered the sea level by adding the appropriately timed sea-level anomaly to the DEM-Bathymetry map (Table 3.6). Cropping the resulting maps at elevation 0 – i.e., keeping only the values above sea level – led to the creation of basemaps with extents corrected to match Pleistocene geography.

Table 3.6 Sea-level anomalies (in m) estimated from Peltier and Fairbanks (2006).

	Lower A	**Lower B**	**Middle**	**Upper A**	**Upper B**
Sea-level anomaly (m)	-113	-110	-109	-96	-78

Magdalenian Climate Maps. There are multiple sources of prehistoric climate data available; however, I chose to use the TraCE-21ka data because of its high temporal resolution, which allows for better reconstructions of the temporal vegetation changes that are important for this research. I used the central point of the TraCE-21ka raster data to reconstruct the general climatic characteristics of the 5 Magdalenian subdivisions (Fig. 3.5).

Figure 3.5. Geographical position of the TraCE-21ka grids' central points used to calculate the climate anomalies.

For each point, I used the following method: In R, I extracted modern and prehistoric TraCE-21ka data for the grid cell overlaying its geographical location. Temperature values were given as mean K/month, and precipitation as m/s. To obtain more manageable values, I transformed the temperature data of both datasets using:

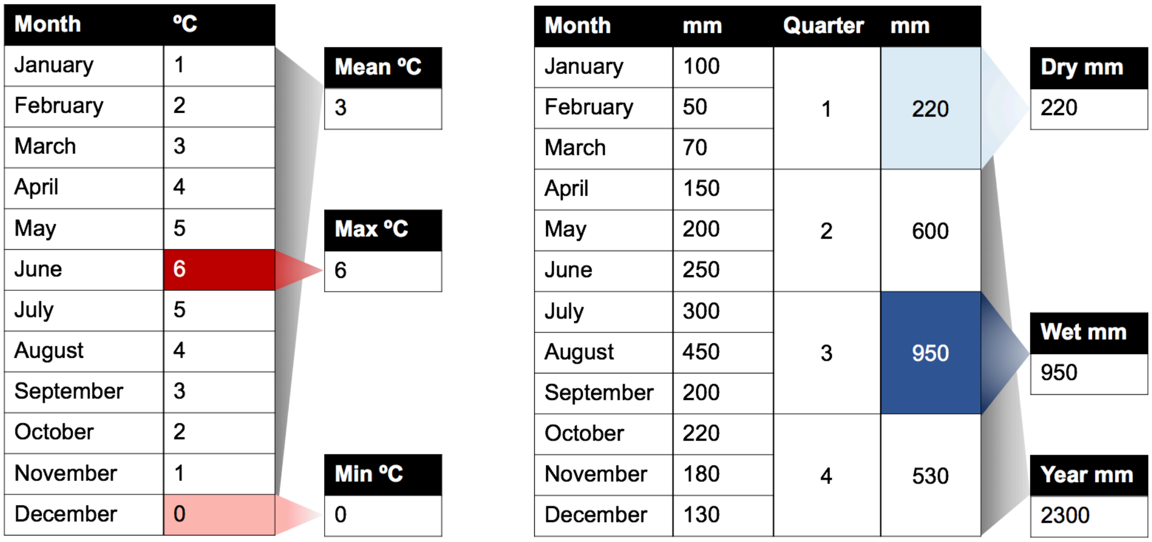
$$°C = K - 273.15$$

and the precipitation data using:

$$P_{mm/month} = P_{m/s} * 2.5922e^{9}$$

I then calculated the values of the 6 selected climate variables listed in Table 3.5. The temperatures of any year's warmest and coldest months were used for max and min temperature. The mean was an average of each year's 12 values. The annual precipitation was simply the sum of the 12-months' values. The precipitation of the wettest and driest quarters required more work. Given the extent of the region covered and the geographical climatic differences created by the Atlantic and the Mediterranean water bodies, I needed to identify the wettest and driest quarter characterizing each location. Therefore, for each point, I aggregated the modern monthly values into quarters, summed the monthly values in each quarter and identified which was the highest. That quarter was assumed to be the wettest for that location throughout the whole Magdalenian. I repeated the same technique for the driest quarter, here focusing on the quarter with the lowest value (see Fig. 3.6 for example).

To obtain modern values for these 6 variables, I selected the most recent 30 years of the modern dataset (1959-1989) and calculated the mean of each variable over those years. I also calculated the 6 averages for each Magdalenian subdivision.



Month	°C
January	1
February	2
March	3
April	4
May	5
June	6
July	5
August	4
September	3
October	2
November	1
December	0

Mean °C
3

Max °C
6

Min °C
0

Month	mm	Quarter	mm
January	100	1	220
February	50		
March	70		
April	150	2	600
May	200		
June	250		
July	300	3	950
August	450		
September	200		
October	220	4	530
November	180		
December	130		

Dry mm
220

Wet mm
950

Year mm
2300

Figure 3.6. Method used to obtain annual climate values from monthly values available. These values were created to serve as example.

Finally, to calculate the anomaly between modern and prehistoric climate at each location, I subtracted the modern mean values from the prehistoric mean values:

$$\Delta = X_p - X_M$$

where X_P is the prehistoric value and X_M is the modern value. Therefore, for each point, this created 6 anomaly values (Δ) for each of the 5 Magdalenian subdivisions. I inspected the values to identify which grid cells had outlier anomalies throughout the Magdalenian – indicating the presence of ice cover. Those ice-covered grid cells were removed from the dataset, as their prehistoric climate would not have been representative of land climate. This reduced the dataset to 59 points.

Figure 3.7 presents a summary of the 59 anomalies calculated for each Magdalenian subdivision. Several outliers are found in both datasets, resulting from the geographical extent covered by the points. Plotting the values on a map did not indicate the presence of consistent outliers, but simply confirmed the variability of climate over large areas. Only

1 point, located on the eastern coast of Ireland was characterized by minimum temperature that was significantly colder than elsewhere, but removing it would have created a new – and more extensive – set of outliers. Moreover, as the ice cover of the time would have affected the climate of the northern European regions, removing all points located near glaciers would have removed this influence from the model, and led to biased results. Therefore, I decided to keep all the points presented here.

The general pattern shown by the climate anomalies of the 5 Magdalenian subdivisions agrees with the accepted notion that climate varied extensively over time and space around the Last Glacial Maximum (Ahn, 2012; Kageyama et al., 2006). Figure 3.7 shows that the mean temperatures of the whole Magdalenian were colder than today by about 3-7 °C, which is similar to the global values obtained for the Last Glacial Maximum (Kageyama et al., 2006; Roche et al., 2007; Schneider von Deimling et al., 2006; Strandberg et al., 2011) and the postglacial (Peyron et al., 2005). The impact of the Last Glacial Maximum on anomalies varied also annually. For example, for the Lower Magdalenian, the temperature anomalies of the warmest month are significantly bigger than the anomalies of the coldest month. In other words, summers were much colder than today, whereas the winters were only a few degrees colder than they are currently. This changed during the Middle Magdalenian, when the temperature of the coldest month dropped considerably. This period corresponds to the Oldest Dryas; it has the biggest temperature anomalies of all subdivisions, and the widest range of values, which represents the impact of geography on climate – i.e., the anomalies are bigger in northern regions. The Lower Magdalenian B and the Upper Magdalenian A are the two subdivisions with the least spatial climatic variability, seen in the shortness of the

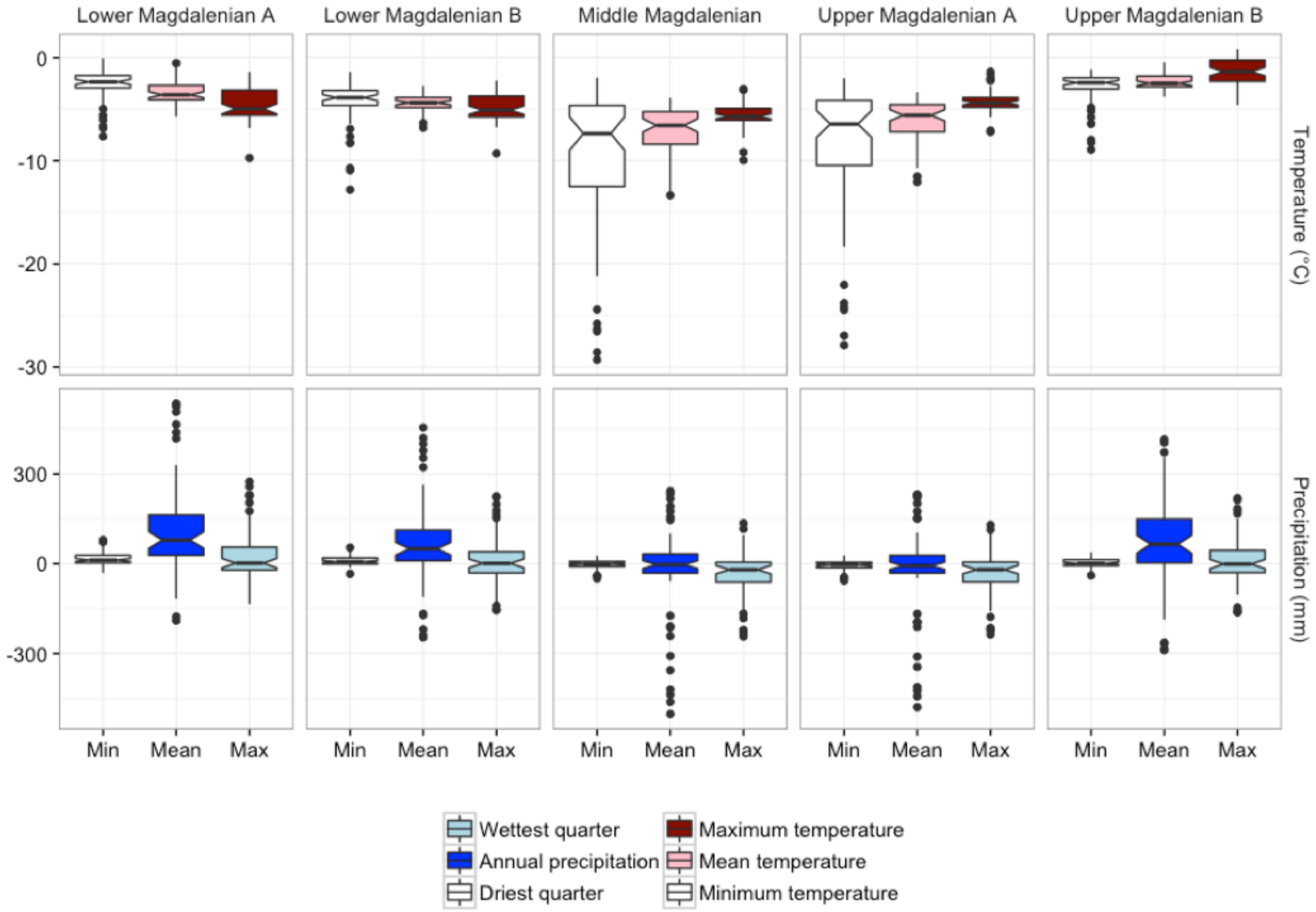


Figure 3.7. Temperature and precipitation anomalies calculated for each point.

boxplots. This suggests that the environment was probably more homogeneous then than at other times.

Surprisingly, this data suggests that, in most regions, annual precipitations were higher than today, which does not fit previous reconstructions done on Magdalenian climate (Coope and Elias, 2000; Peyron et al., 2005). Furthermore, according to this data, the precipitation of the driest quarter has remained relatively constant since the beginning of the Magdalenian, and the precipitation of the wettest quarter decreased during the Middle and Upper Magdalenian A. The annual precipitation anomalies vary the most, suggesting that the two annual quarters with average values fluctuated widely during the Late Glacial. As with temperature, the points' geographical location had an impact on their precipitation levels. For example, plotting precipitation anomalies on a map (Fig. 3.8) shows how northern glaciers reduced the ambient precipitation, whereas the Atlantic Ocean increased it.

To evaluate the range of climate fluctuations at each geographical location, I calculated the range of mean temperature and annual precipitation anomalies of the whole Magdalenian at each point (Fig. 3.9).

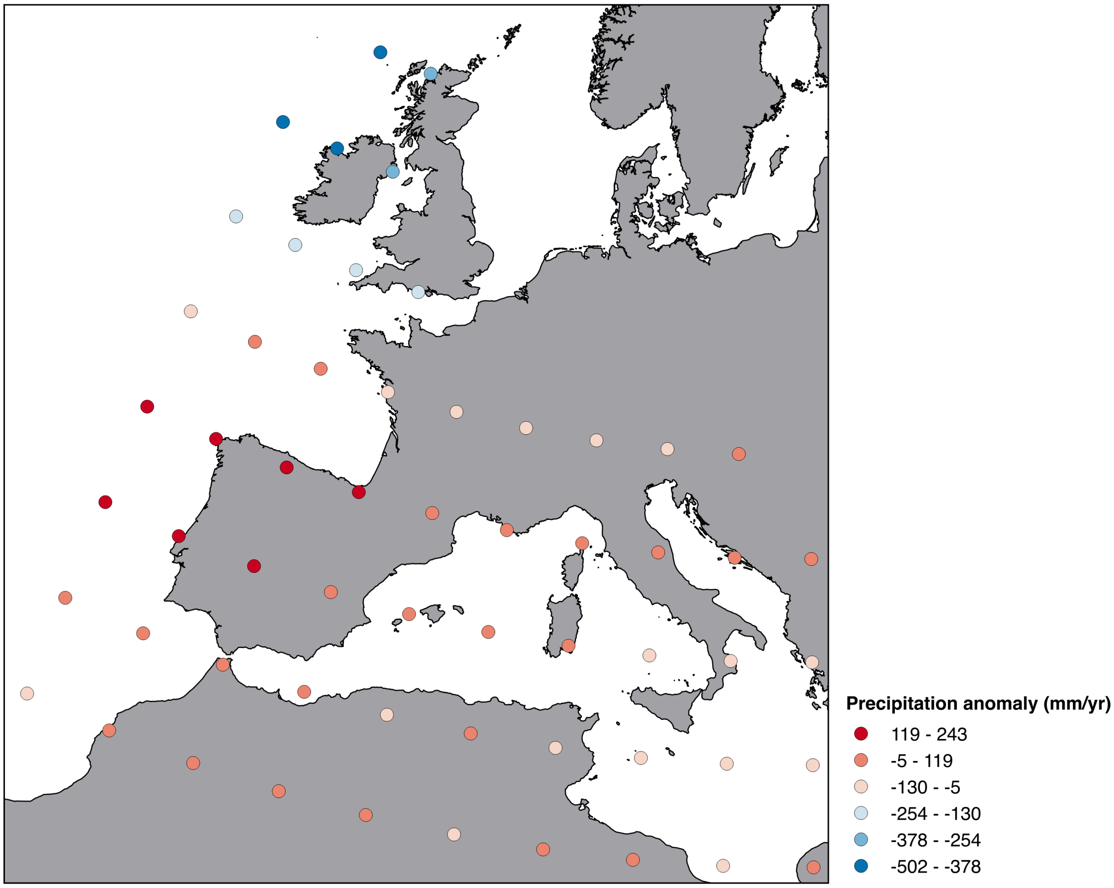


Figure 3.8. Geographical position of precipitation anomaly values (Middle Magdalenian).

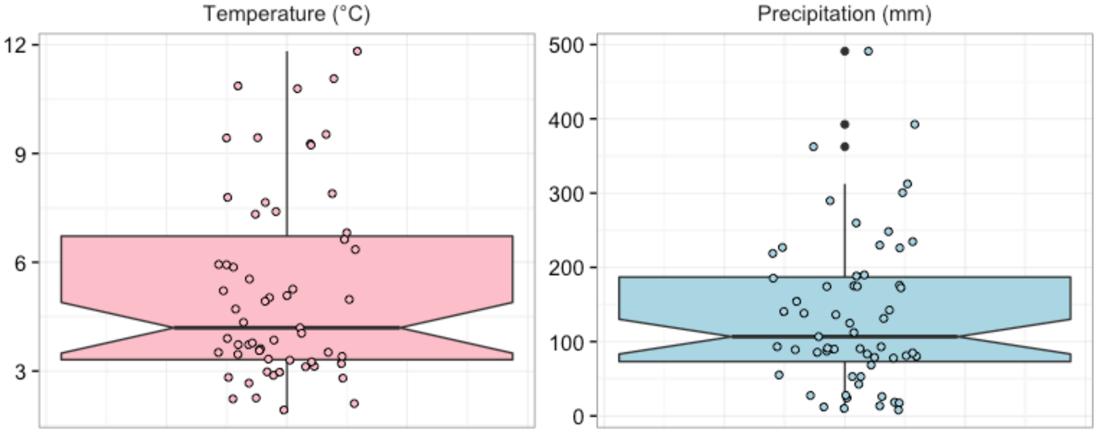


Figure 3.9. Range of mean temperature and annual precipitation anomaly at each TraCE-21ka central point.

This figure shows that the Magdalenian temperature of most regions fluctuated by ~ 3-7 °C and the annual precipitation varied by ~ 70-180mm. It also shows the presence of a few stable regions, with temperature changes lower than 3 °C and/or precipitation changes around 20mm, as well as a few points with high climatic fluctuations, which were probably influenced by the ice sheet. Despite those points, the range of some temporal fluctuations is still smaller than estimated in previous studies; for example, it does not match the 600mm difference in annual precipitation between the Middle and Upper Magdalenian in the Jura Mountains reconstructed from pollen data by Peyron and colleagues (2005) – here, the closest point to this region shows a range of 117mm, a discrepancy that probably results from the use of a linear relationship between modern and prehistoric values at a low spatial resolution. Therefore, this dataset presents some problems, but as it is still better than most others, I used it to reconstruct past environments.

The steps enumerated above provided a set of points with Magdalenian climatic values. Unfortunately, that dataset was at a poor spatial resolution (3.75 degrees), which does not represent the fine-scaled geographical climate variations necessary to reconstruct Late Glacial biome distributions. To improve the maps' resolution, I imported the georeferenced anomaly values of the 6 climatic variables for each 5 Magdalenian subdivisions into a GRASS Azimuthal projection at 1km resolution, and used bicubic *v.surf.bspline* to create interpolated anomaly surfaces. Before each interpolation, I used the 'leave-one-out' calibration test to identify the best Tykhonov regularizing parameter (λ). I also used the calculated distance and point density as the length of spline steps

(3.754e^{+05}). I added the values of the interpolated anomaly maps to their respective modern map (Fig. 3.10) to create Magdalenian climate mapsets at 1km resolution. I exported all the created maps as ASCII to use in MaxEnt.

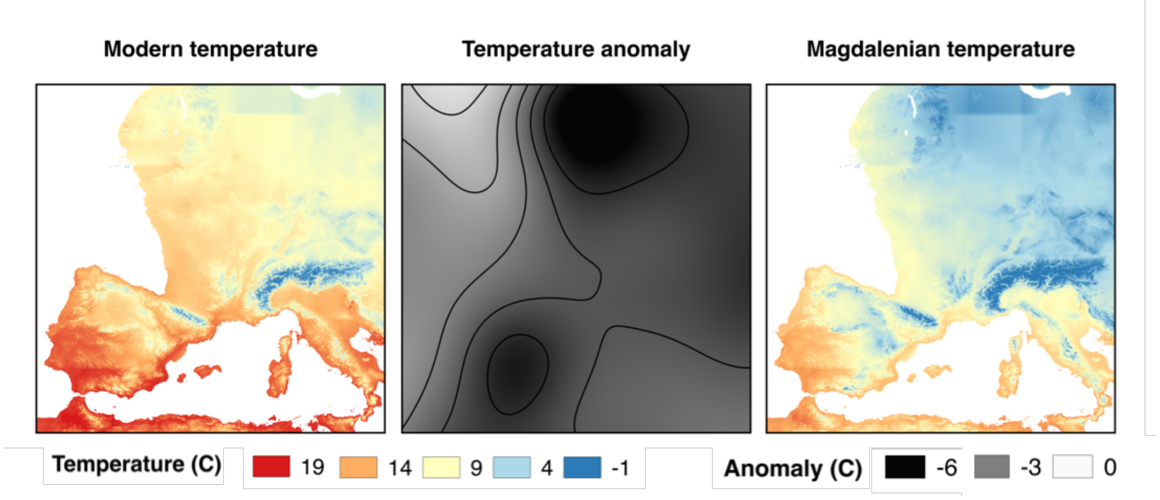


Figure 3.10. Steps followed to obtain a Magdalenian climatic map (right): Add the interpolated anomaly (middle) to the modern values (left).

Using MaxEnt to Reconstruct Past Vegetation Distributions.

Calibrating the Model. MaxEnt is a user-friendly and powerful tool. Its default settings often provide satisfactory results (Phillips, 2006); however, research has shown that changing the complexity of the model – number of variables used and types of settings chosen – impacts its results significantly (Merow et al., 2013). For example, models using several climatic variables are better at predicting modern distributions than at projecting prehistoric ones (Moreno-Amat et al., 2015). Moreover, research done on MaxEnt's reconstructions of plant distributions has demonstrated that, due to plants' environmental requirements, a single set of parameter values will predict sets of taxa with different accuracy. Therefore, it is necessary to identify which climatic variables explain best the distribution of each plant taxon (Moreno-Amat et al., 2015), and use only those variables when projecting onto prehistoric climate. Following these recommended protocols, I ran a MaxEnt test for each of the 13 PFTs mentioned in Table 3.3 to evaluate the impact of each bioclimatic variable on their predicted modern distribution. For that run, I used the default settings with all climatic and topographical maps, and I performed a jackknife test, which runs the algorithm multiple times, excluding each variable in turn to evaluate the effect of its exclusion on the prediction, and then using each variable individually to calculate the effect of its sole inclusion on the predicted distribution. To test the predictions against empirical data, the software randomly chooses 15% of the PFTs presence points to use as test points. I relied on the results of this test to calibrate the settings for further implementations.

I used the results of the jackknife tests to identify the climatic/topographic variables that best predicted each PFT's modern distribution, and to identify variables that decreased the prediction's accuracy. The accuracy of a model was evaluated using the Area Under Curve (AUC) – a measure of the model's ability to discriminate between sites where the species is present and sites where it is absent (Hanley and McNeil, 1982). I ran multiple iterations of variable combinations for each PFT until I reached the highest AUC for both training and test data. Table 3.7 shows the variables that best predict the modern distribution of each PFT.

Table 3.7. List of bioclimatic maps used to recreate the most accurate PFT distributions.

			Precipitation			Temperature		
PFT	**DEM**	**Slope**	**Wet quarter**	**Annual**	**Dry quarter**	**Max**	**Mean**	**Min**
AA	X	X	X	X	X	X	X	X
AB	X	X	X	X	X	X	X	X
BEC	X		X	X		X	X	X
BS		X	X	X	X		X	X
CTC			X	X	X	X	X	X
DF	X	X	X	X	X	X	X	
EC	X	X	X	X	X	X	X	X
SF	X	X	X	X	X	X	X	X
TS	X	X	X	X			X	X
TS1	X		X	X	X	X	X	X
TS2	X	X	X	X	X	X	X	X
WTE		X	X	X		X	X	X
WTE2	X	X	X	X	X	X	X	X

Projecting onto Magdalenian Climate. After selecting the best settings for each PFT, I projected the modern plant-climate relationship onto the climatic context of the 5 Magdalenian subdivisions. In MaxEnt, this simply required providing the link to the folder containing all the relevant prehistoric climate maps. The software then selected the relevant maps automatically. When available, I used prehistoric PFTs' presence data to test the outcomes of these projections using independent data (see discussion by Franklin et al., 2015). However, due to the low number of Magdalenian pollen records, some of the PFTs were not represented for all temporal periods. No test points were used in those cases.

I used the AUC values for training and test points to evaluate the accuracy of the projected past distributions (Table 3.8). The results were satisfactory for most PFTs

(AUC > 0.75). However, the AUCs for *Boreal summergreen (BS)*, *Steppe forb* (*SF)*, and *Cool temperate summergreen* (*TS1)* were not; their projection did not correspond well to past PFTs distribution. As these 3 PFTs are conspicuous throughout modern Europe, they do not have strong climatic signatures, which led MaxEnt to over-represent their Magdalenian distribution. I dismissed the *BS* and *TS1* projections, as better-predicted PFTs were available to identify the biomes to which they belonged; however, I kept *SF* because it was the only taxa that could be used to identify the presence of steppe – and 2/5 of its prehistoric projections were satisfactory. Using the method described below, I combined the Magdalenian projections of all satisfactory PFTs to create a single map of biomes' spatial distribution for each Magdalenian subdivision.

*Table 3.8. AUC values of the projections tested against 15% of the sample points (training), and against prehistoric pollen samples for the 5 subdivisions (test). *Satisfactory.*

PFT	Training	LMA-test	LMB-test	MM-test	UMA-test	UMB-test
AA	0.866*					
AB	0.871*					
BEC	0.927*					
BS	0.709					
CTC	0.830*				0.733	0.725
DF	0.910*	0.783*		0.775*	0.787*	0.779*
EC	0.798*					
SF	0.731	0.824*	0.772*	0.691	0.657	0.607
TS	0.833*					
TS1	0.690			0.362	0.481	0.450
TS2	0.756*					
WTE	0.867*					
WTE2	0.884*					

Creating Magdalenian Biomes. The last part of the Biomization method was to assign PFT distributions to specific biomes. I used Prentice and colleagues (1996)'s 'fuzzy attribution' technique, which requires calculating biome correspondence indices that take into consideration the presence and absence of given PFTs at a location (see Table 3.3). For example, tundra requires the presence of *Arctic/alpine dwarf shrub* (AA) and *Arctic/boreal dwarf shrub* (AB), and the absence of all other PFTs. Therefore, the tundra index of a pollen sample containing all PFTs is 2, as the required PFT absences are not respected. On the other hand, the tundra index of a pollen sample including only AA and AB is 13, as the presence and absence of all 13 PFTs are respected. Normally, this technique is used on pollen samples taken at individual sites (Peyron et al., 1998; Prentice et al., 1996; Tarasov et al., 2000); however, I used it on all grid cells of the European landscape, as I assumed that the set of PFT distribution maps could be used as a proxy 'pollen sample' at any geographical location. This is similar to the work of Huntley and colleagues (2003), but performed at a higher resolution.

To calculate the biome indices for the Magdalenian European Southwest, I created presence and absence maps of all PFTs' distributions for each Magdalenian subdivision. As the distribution maps produced by MaxEnt are continuous probability values [0-1], I had to define a threshold separating absence from presence. I decided to use the logistical thresholds provided in the MaxEnt outputs; however, as there is a current debate on which threshold produces the most accurate results (Distler et al., 2015; Liu et al., 2005; Nenzén and Araújo, 2011), I used 3 different ones – 10th percentile training presence, equal training sensitivity and specificity, and maximum training sensitivity plus specificity – and combined their results. Using GRASS, I produced a presence map (below threshold = 1, above threshold = 0) and its inverse absence map (above threshold = 0, below threshold = 1) for each taxon. I then used *r.series* to calculate the biome indices for all grid cells in Southwest Europe. For example, to calculate the tundra index, I summed the values of the *AA* and *AB* presence maps, and the other PFTs' absence maps. For each biome, this created an index map, which indicated how many of the presence/absence requirements were met anywhere on the land. I then used *r.series* with those biome index maps to select the biome with the highest index score for each grid cell. The order of the biome index maps was based on Peyron and colleagues (1998); when ties were found between the high scores of two or more biomes, the higher on the list was selected. I followed this method with the 3 different thresholds, and using *r.series*, I combined the 3 biome maps using their mode average. In places where all three maps differed, the algorithm used the lowest value, which corresponded to the highest biome on the list. I reproduced this method for each of the 5 Magdalenian subdivisions.

Testing the Reconstructed Biomes. I used dated archaeological faunal and pollen assemblages (Appendices A and B) to test the accuracy of the biome reconstructions. The pollen assemblages were obtained from the European Pollen Database (EPD), and were transformed into biomes using the biomization method as described above. The faunal data came from a literature research on archaeological assemblages, and included only assemblages that were radiocarbon dated. I relied on the 95% confidence interval of the calibrated dates associated with the pollen and faunal data to separate them into the 5 temporal subdivisions. I plotted both data types against the reconstructed biomes to test their validity.

Most of the reconstructed biomes conform to what we would expect if climate were the only factor in their distribution. In that respect, the diachronic vegetation changes reflect well the climatic changes that occurred during the Late Glacial, and support the assumption that hunter-gatherers living in Western Europe during that period had to face subsistence changes. However, when tested against the pollen and faunal empirical data, the modeled biomes differ from the empirical proxy data. In particular, forests are often found in modeled biomes where the proxy record indicates the presence of steppes.

The recent work of Kaplan and colleagues (2016) shows that this discrepancy has been noted in other recent studies of Late Glacial and postglacial European environments, and can potentially be explained by the impact hunter-gatherers had on their landscape. According to that recent research, hunter-gatherers would have altered their environment much earlier than previously thought, simply using fire that prevented the growth of trees and favored the growth of grass. Their model shows that the cold climate and low CO_2 level would have increased the impact of small fires in the region. In this light, I decided to add human impacts to my model with the aim of improving correspondence between modeled biomes and those reconstructed from the proxy record.

Human Impacts on the Environment

I estimated the Magdalenian population distribution using MaxEnt and dated sites. I relied on the Radiocarbon Palaeolithic Europe database v.20 (2016) and my own literature review to compile a list of Western European sites dated to each Magdalenian subdivision. Given the problems with the database – it is crowd-sourced and thus filled with errors, duplicates and unreliable dates – I cleaned the dataset using the following steps: 1) I removed dates with a margin of error > 250, as well as dates with incomplete information (no reference, no margin of error, no lab code). 2) I corrected typos in lab codes based on my knowledge of the most common codes (e.g., Ly instead of Lv). 3) I removed dates with lab code duplicates. I kept one of the duplicated dates when they were linked to identical information, but removed both when the information differed. 4) I removed dates associated with techno-complexes that were not contemporaneous with the Magdalenian (e.g., Gravettian, Aurignacian, and Mousterian), as well as those that were undetermined. 5) I updated the geographical coordinates for the sites that were already part of my database, as the coordinates in my database had already been checked against the literature. 6) I used the R *BChron* package to calibrate all remaining dates using the IntCal13 curve, and I filtered the dates, using their mean calibrated date, to separate them into the 5 subdivisions. 7) Finally, I removed the site duplicates found in each subdivision. The resulting dataset can be found in Appendix D.

For each subdivision, I used MaxEnt to calculate the relationships between the dated sites' distributions and their climatic context, and to produce the probabilistic distribution of human occupation. I used the default settings, and chose a random 15% of the sites to test the accuracy of the distributions. Table 3.9 presents the AUC values obtained.

Table 3.9. Training and testing AUC values for the distributions of human occupation.

Subperiod	**Lower A**	**Lower B**	**Middle**	**Upper A**	**Upper B**
AUC training	0.929	0.910	0.919	0.906	0.893
AUC test	0.856	0.889	0.926	0.832	0.837

In GRASS, I used these human distribution maps to change the coverage of tree and grass PFTs before re-applying the Biomization method on the PFTs distributions. Based on Kaplan and colleagues (2016), the presence of human population would have reduced the tree coverage and increased the growth of grasses. Therefore, I decided to add part of the human probabilistic distribution to grass PFTs (DF and SF) distributions, and remove the same portion of the human probabilistic distribution from the distribution of all tree PFTs (BEC, CTC, EC, TS, TS2, WTE, and WTE2). I evaluated the impact of several values on the biomes using pollen data as testing point. Using $^1/_3$ of the human probabilistic distribution value gave the most accurate results. Therefore, for a probabilistic human distribution value of 0.6, I added 0.2 to the probabilistic distribution of grasses, and removed 0.2 from the distribution of trees. I then transformed the PFTs distributions into binary presence/absence using the same thresholds as in Table 3.4, and followed the Biomization method as presented above. A flowchart summarizing the methods detailed above can be found in Appendix E. The results are presented below.

Results

For most temporal subdivisions, the biomes reconstructed with human impact on the vegetation offer more accurate results than the biomes reconstructed with climate-only. In the human-climate reconstructions, the extent of steppes is increased substantially, leaving small pockets of forests along streams and mountainsides. Here, I compare the two sets of maps to show the improved results. The separate maps are available in a bigger format in Appendix F.

Lower Magdalenian A (20,000-19,000 cal. BP). The Lower Magdalenian A climate-only biomes (Fig. 3.11 and 3.12) show that, based on bioclimatic values, France should have been covered by cold-cool mixed forest, cold conifer forest in the southwest, and tundra and taiga in the north. The Cantabrian region should have strips of different biomes – taiga, cold deciduous and cool mixed forest – compressed on the flanks of the mountains, which falls in line with common knowledge that the topography of the Cantabrian mountains led to the creation of different ecological zones (Straus, 1986). However, while all pollen records dated to this period suggest the presence of steppe and cold desert, only one of those records fall within a region where those are the dominant reconstructed biomes.

In this regard, the human-climate biomes fit the pollen record better. In this reconstruction, the extent of the steppe and tundra biomes increase substantially, while the extent of cold and cool forests decrease. Not all cold desert-steppe pollen records fall within or near a cold desert or steppe environment, but the majority do (5/7), which suggests that these biomes represent well the reality of the Lower Magdalenian A.

The faunal assemblages dated to the Lower Magdalenian A confirm the best fit of the human-climate reconstructed biomes. The fauna found in the Dordogne is dominated by steppe-tundra species – reindeer, bison, saïga – which could not have lived in the forests of the climate-only scenario, but would have thrived in the steppe-tundra found in the human-climate scenario. Red deer (*Cervus elaphus*) and mountain goat (*Capra sp.*) dominate the faunal assemblages of Cantabrian sites. Red deer are usually found in forests, and could have been found in the cold deciduous forests modeled in both reconstructions. Mountain goats prefer bare mountain slopes, which are represented here as taiga- or steppe-tundra covered mountain flanks. Both climate-only and human-climate biome reconstructions comply with the Cantabrian assemblage; however, the Dordogne assemblage shows that the human-climate reconstruction is the most accurate.

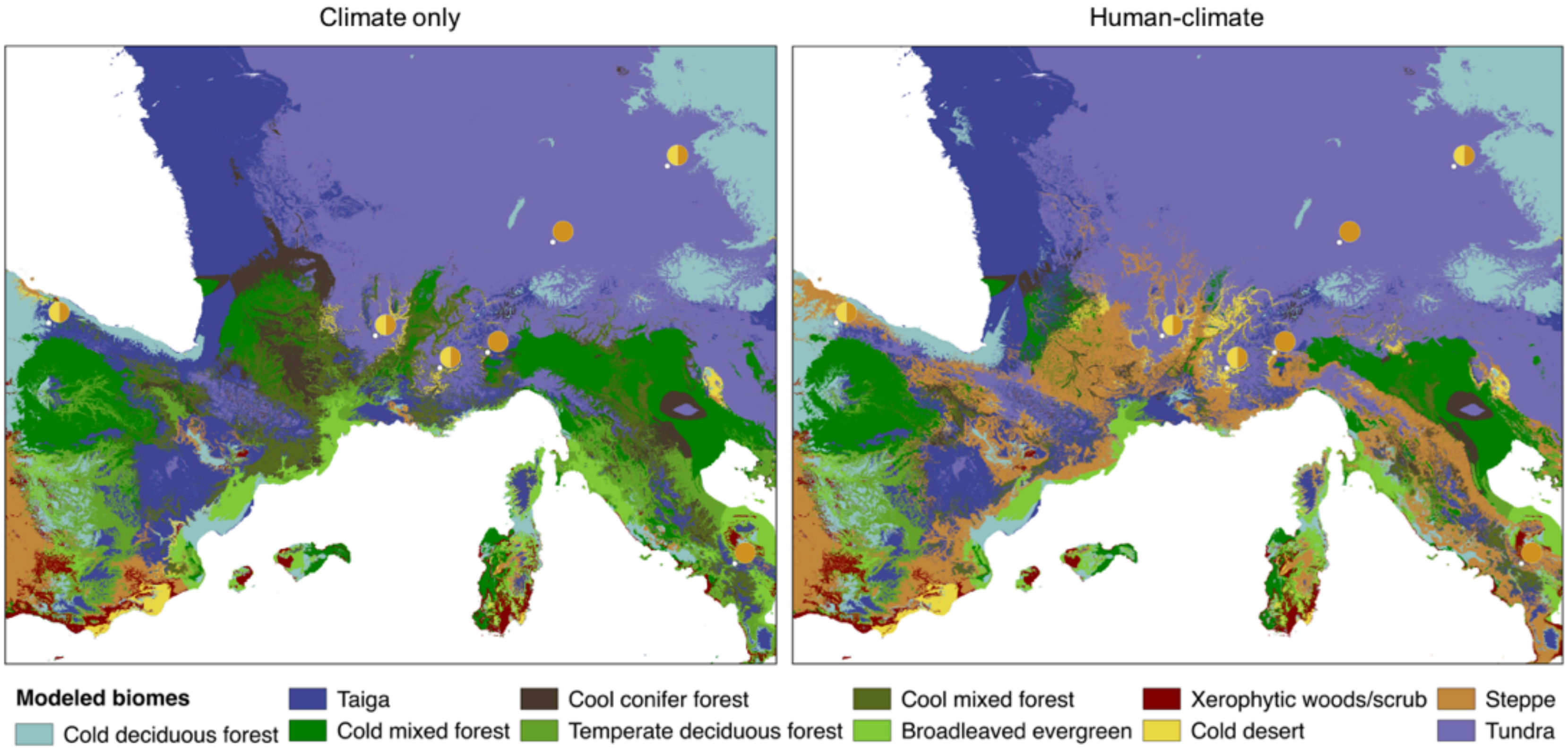


Figure 3.11. Distribution of the biomes – without and with human impact – associated with individual pollen records dated to the Lower Magdalenian A.

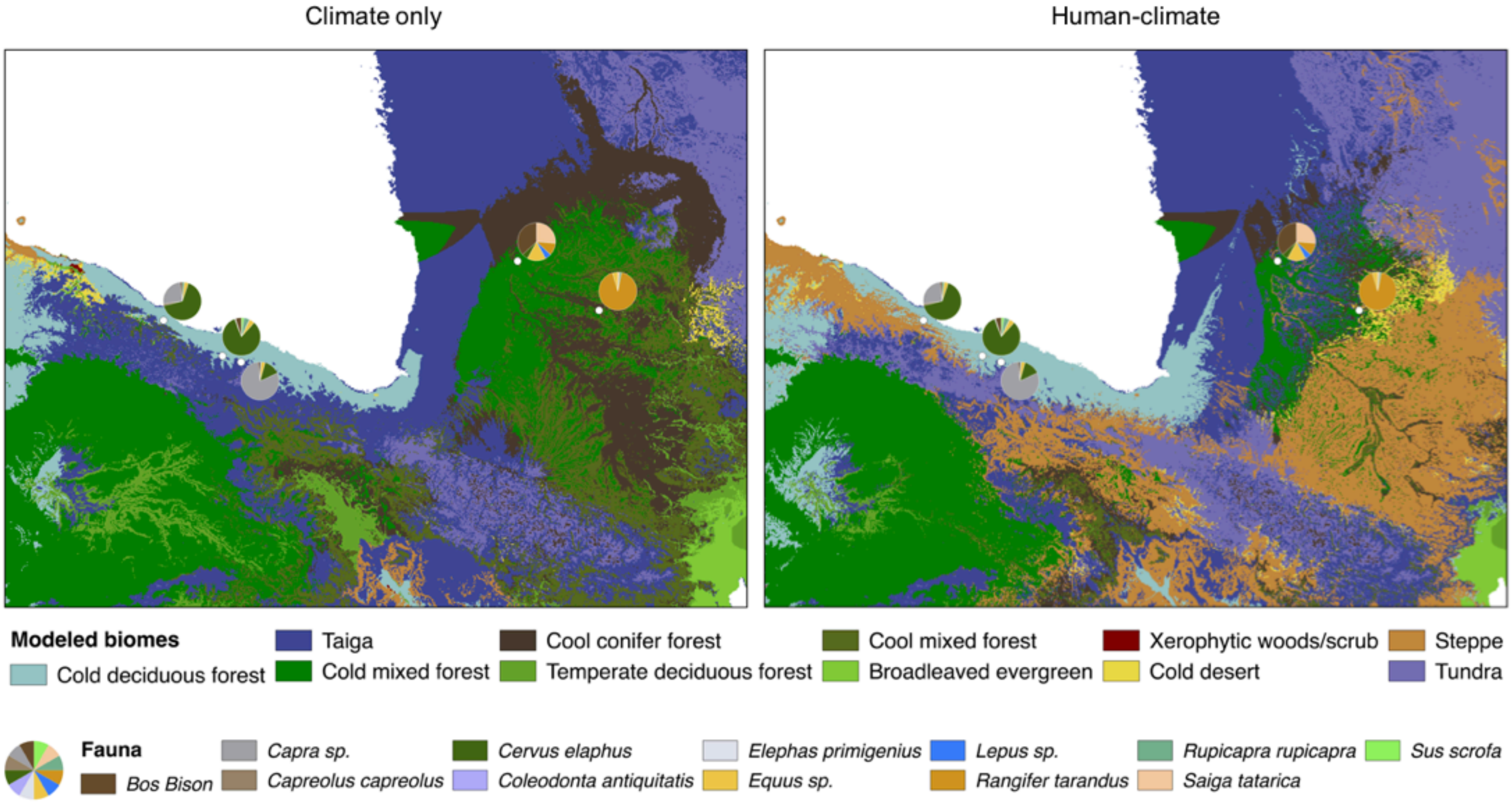


Figure 3.12. Distribution of the biomes – without and with human impact – associated with faunal assemblages dated to the Lower Magdalenian A.

Lower Magdalenian B (19,000-17,500 cal. BP). The colder temperatures of the Lower Magdalenian B should have reduced the cover of warm and cool forests, and expanded the cover of cold vegetation (steppe-tundra, taiga, and cold forests). While this is captured by both reconstruction scenarios, its extent is more accurate in the human-climate one (Fig. 3.13 and 3.14).

As before, most pollen records suggest the presence of steppe and cold desert in Southeast France, Central and Northern Italy, and Western Cantabria. The landscape of the climate-only scenario is over-forested, while the human-climate reconstruction fits the pollen data almost perfectly. A few northern steppe-dominated pollen records do not fit the reconstructed biome, but as the remaining records (8/11) do, I deem those results satisfactory.

Similarly to the record of the Lower Magdalenian A, steppe-tundra species dominate the faunal assemblages of the Dordogne, whereas a mix of forest and non-forested species form the assemblages of Cantabria. While the Cantabrian faunal record fits well with both reconstructions, the faunal record of the Dordogne could not have been found in the forest of the climate-only scenario.

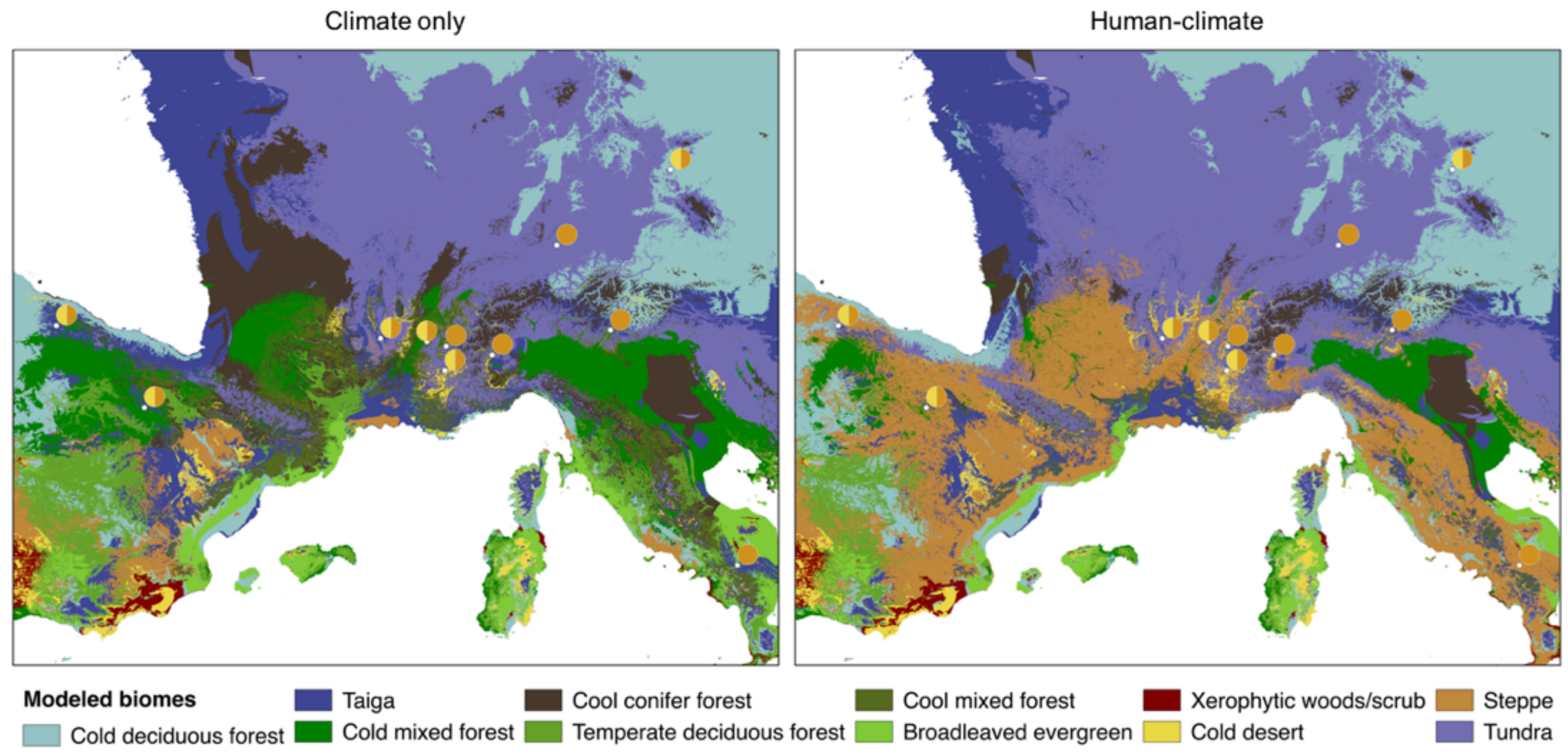


Figure 3.13. Distribution of the biomes – without and with human impact – associated with individual pollen records dated to the Lower Magdalenian B.

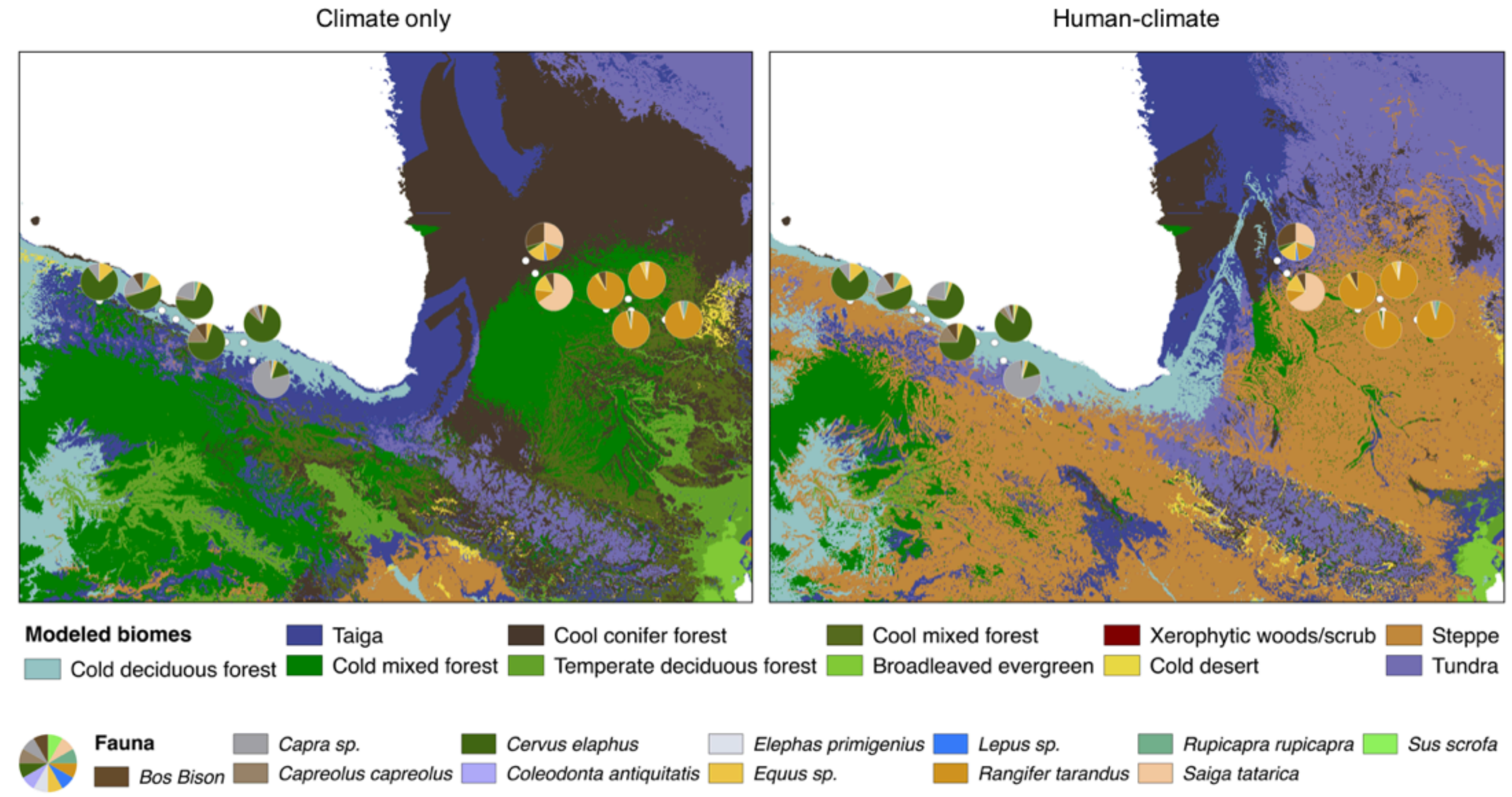


Figure 3.14. Distribution of the biomes – without and with human impact – associated with faunal assemblages dated to the Lower Magdalenian B.

Middle Magdalenian (17,500-16,500 cal. BP). The climate of the Middle Magdalenian corresponds to the cold and arid Oldest Dryas, which explains the further increase in the steppe-tundra and taiga cover in both reconstructions. Here again, the human-climate biome reconstruction proves to be more accurate than the one made with climate-only (Fig. 3.15 and 3.16), despite not being as accurate as it was for the Lower Magdalenian.

The pollen records dated to the Middle Magdalenian show a small change in the region's vegetation, with the appearance of broadleaved evergreen and xerophytic woods/scrubs in southeastern Spain and on the island of Menorca. The remaining records, however, demonstrate the constant presence of cold desert and steppes. The climate-only reconstruction is again too forested to fit the proxy pollen record of the Middle Magdalenian; the modeled biomes match with only 4/15 of the pollen records. The climate-human reconstruction fares slightly better with 7/15 correct biome attributions. However, as for the other Magdalenian subdivisions, the vegetation of the northern regions remains incorrect. The fact that none of the two Middle Magdalenian reconstructions is a strong fit with the pollen record suggests that factors other than temperature, precipitation, and human impact played a role in the biome distribution of that cold period.

The faunal assemblages dated to the Middle Magdalenian follow the same pattern. The climate-only reconstruction fits the Cantabrian faunal records better while the human-climate reconstruction fits the Pyrenean and Dordogne records better. The French faunal records are dominated by reindeer, saïga, horse, and bison, which would have

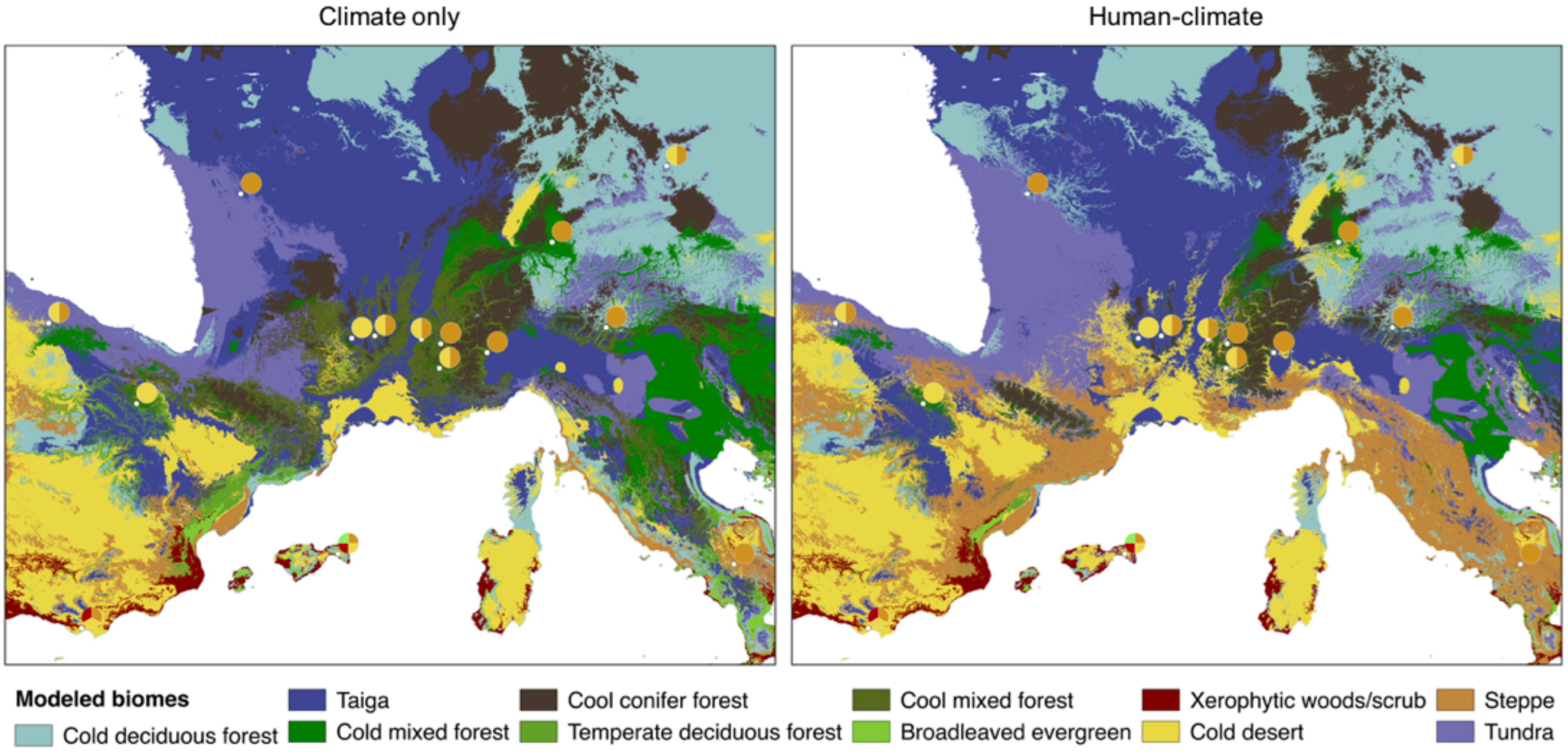


Figure 3.15. Distribution of the biomes – without and with human impact – associated with faunal assemblages dated to the Middle Magdalenian.

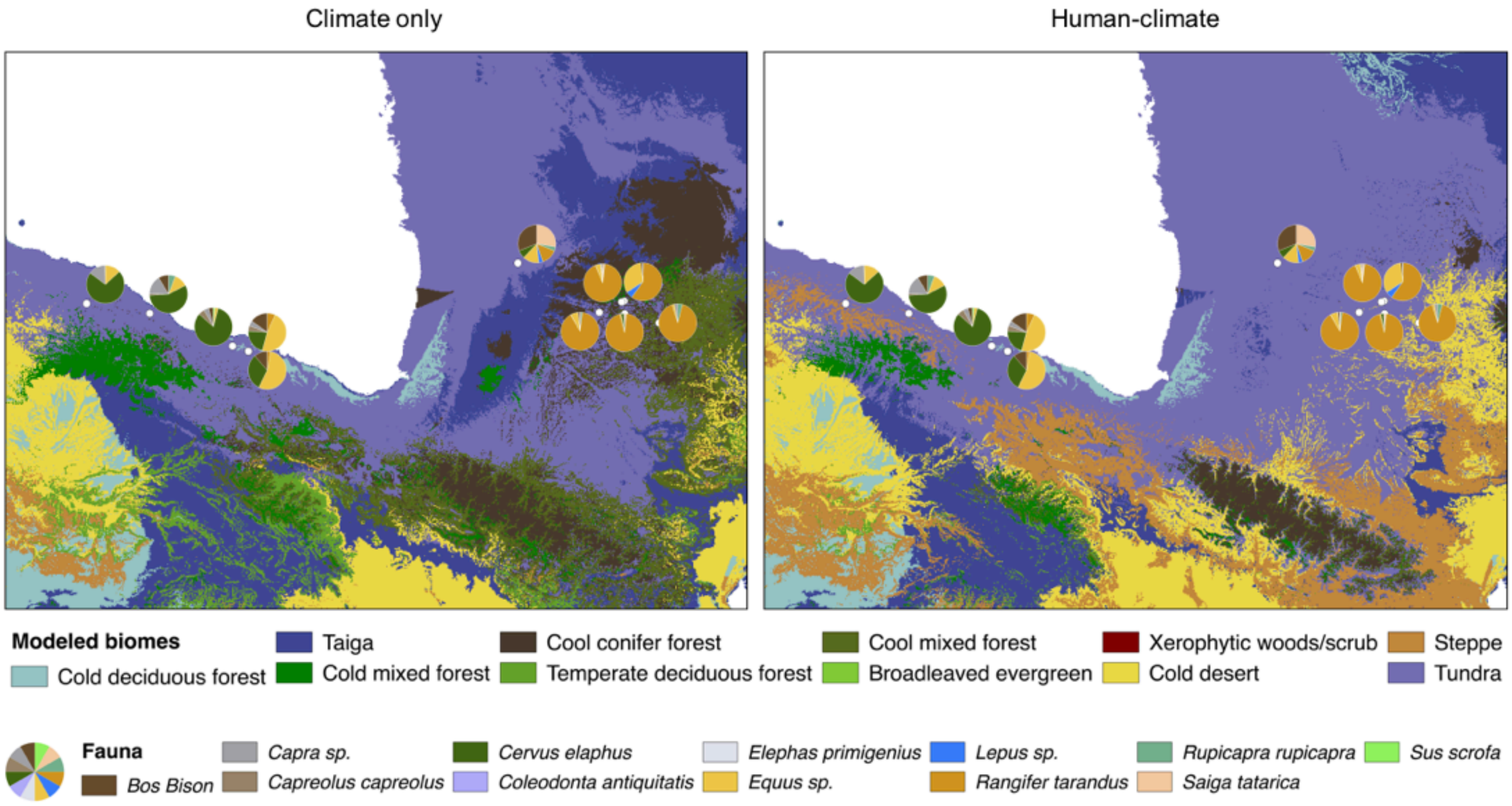


Figure 3.16. Distribution of the biomes – without and with human impact – associated with faunal assemblages dated to the Middle Magdalenian.

lived better in the tundra of the human-climate reconstruction than the taiga-cool mixed forests of the climate-only reconstruction.

The eastern Cantabrian sites show an increased reliance on horses and a steady reliance on mountain goats, which fits the tundra expansion seen in both reconstructions. However, the red deer-dominated fauna of some sites does not fit with either reconstruction. Therefore, both faunal and pollen records suggest that the reconstructed Middle Magdalenian biomes are somewhat problematic, especially in the Cantabrian region.

Upper Magdalenian A (16,500-14,750 cal. BP). The climate of the Upper Magdalenian A saw a steady increase in both temperature and precipitation, which should have favored a renewed expansion of forests throughout Europe. However, the pollen and faunal records dated to the Upper Magdalenian A contradicts this expectation (Fig. 3.17 and 3.18), showing instead that cold desert and steppe biomes still dominated the landscape, with some patches of xerophytic woods on Menorca and a mix of cold mixed forest, cool conifer forest, and tundra at the Massif Central and the Alps. As for other periods, the human-climate reconstruction better fits the empirical evidence than the climate-only one (12/22 vs. 7/22, respectively) despite its over-representation of cold desert biome.

The French faunal record confirms the good fit of the human-climate reconstruction (Fig. 3.18). The dominance of reindeer, horse, and bison suggests the presence of wide steppe/tundra regions, which are not found in the climate-only reconstruction, but are present in the human-climate one. The small increase in the proportion of forested species

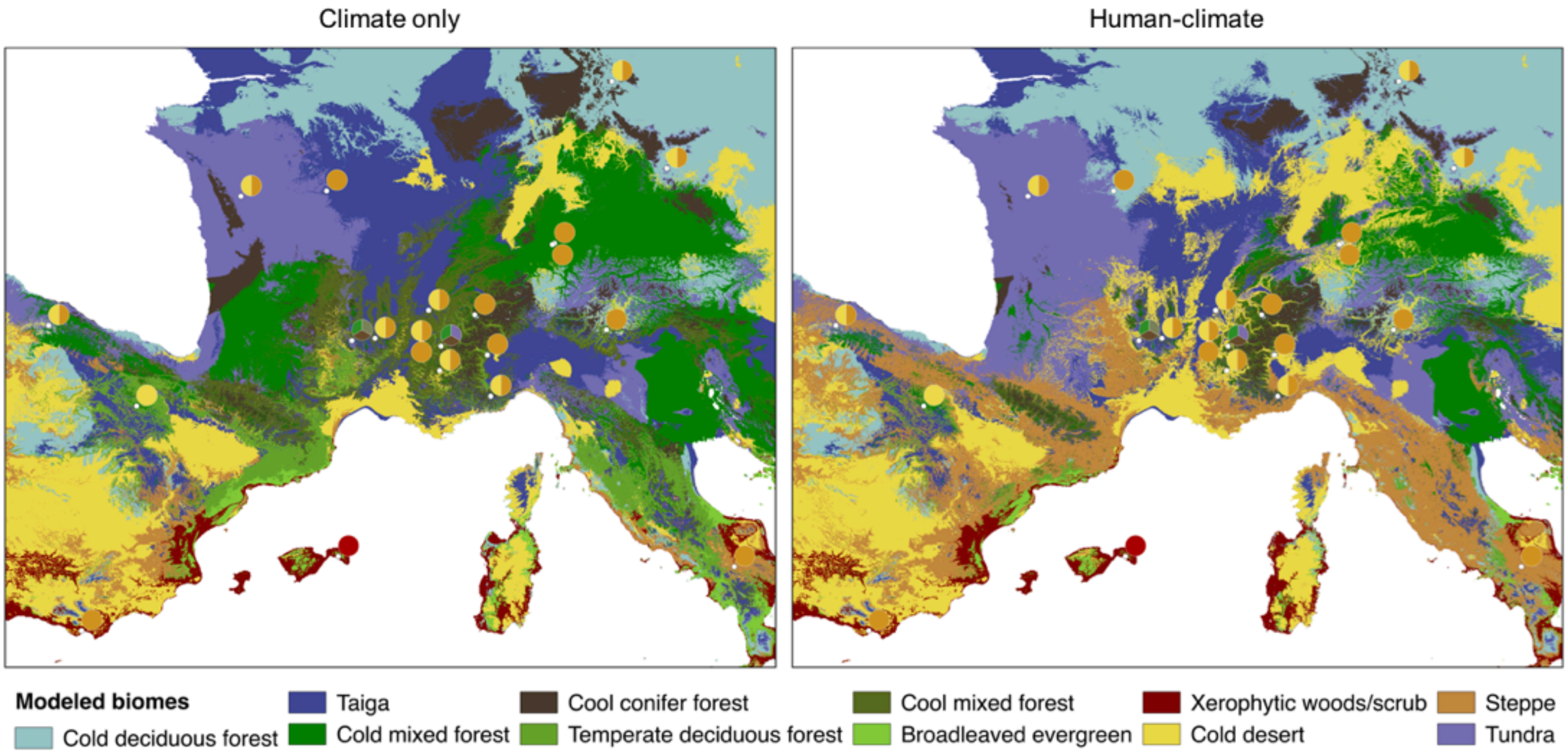


Figure 3.17. Distribution of the biomes – without and with human impact – associated with faunal assemblages dated to the Upper Magdalenian A.

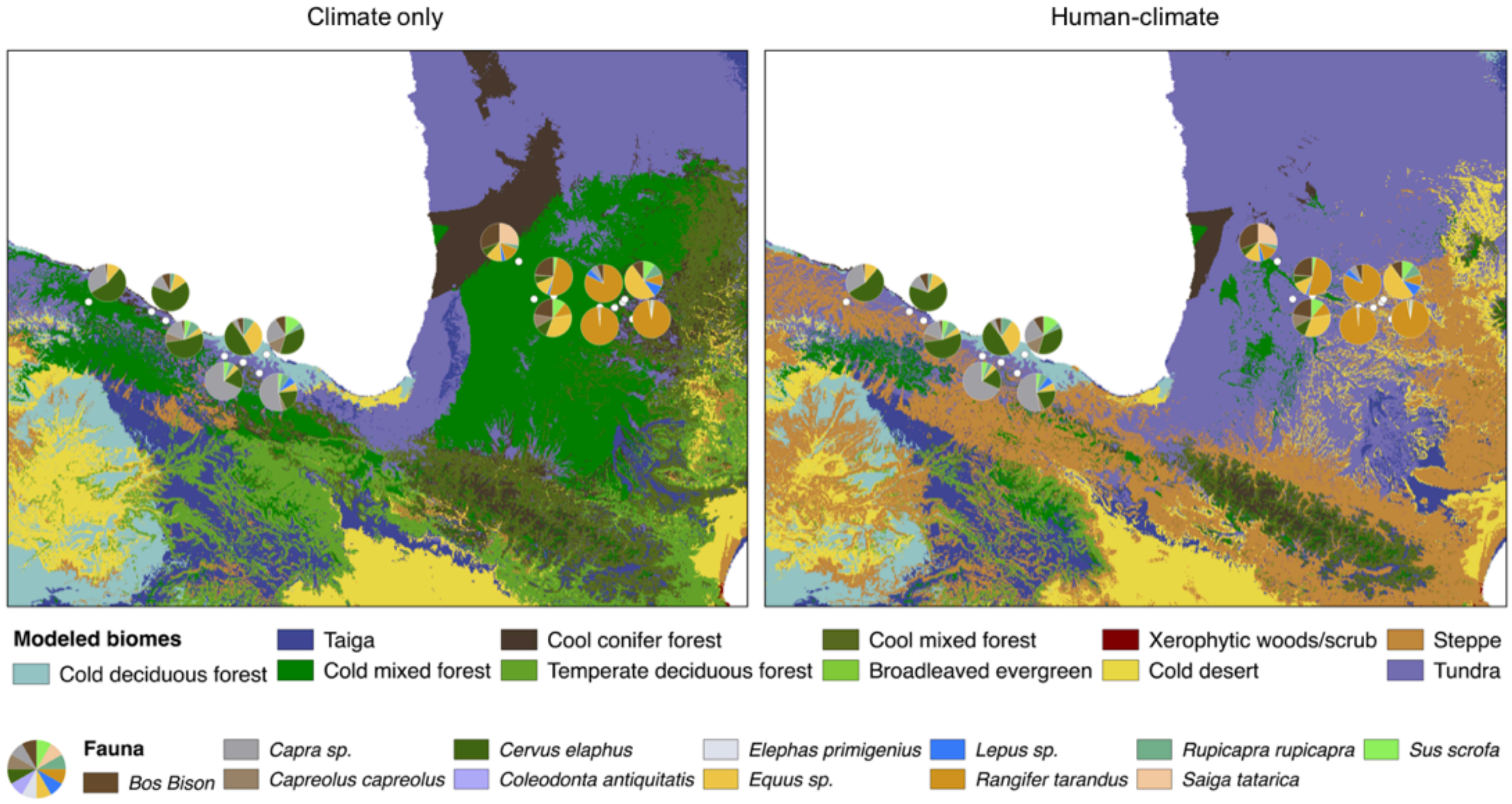


Figure 3.18. Distribution of the biomes – without and with human impact – associated with faunal assemblages dated to the Upper Magdalenian A.

such as boars (*Sus scrofa*), red deer, and rabbits (*Lepus sp.*) coincides with the appearance of small patches of forest located in river valleys. However, the concordance differs in Cantabria; there, the mosaic of forested and non-forested environments of the climate-only reconstructions provides a better fit to the faunal record, focused on forest species (red deer) and open landscape ones (mountain goat). In turn, the steppe-dominated landscape of the human-climate reconstruction does not provide enough forested environments to account for the large proportion of red deer in archaeological assemblages. This discordance between the best fit in the two regions suggests that the incentives of changing one's environment may have been stronger in the Dordogne than in Cantabria.

Upper Magdalenian B (14,750-14,000 cal. BP). The climate of the Upper Magdalenian B corresponds to the Bölling, characterized by an abrupt increase in temperature and precipitation, which should have led to an even wider expansion of the tree coverage in Europe and a decrease in tundra-steppe and taiga biomes. The climate-only biome reconstruction conforms to these expectations (Fig. 3.19 and 3.20).

The pollen records dated to the Upper Magdalenian B show the continued dominance of steppes, which are not represented in the climate-only biome reconstruction. Xerophytic woods and broadleaved evergreen are correctly identified in southern Spain and northern Italy respectively, but most of the remaining records are problematic. Following the trend of the other subdivisions, the human-climate reconstruction conforms well to the pollen record (15/20), with some discrepancies in the Iberian plateau and around the Alps. This suggests that humans still altered their environment significantly.

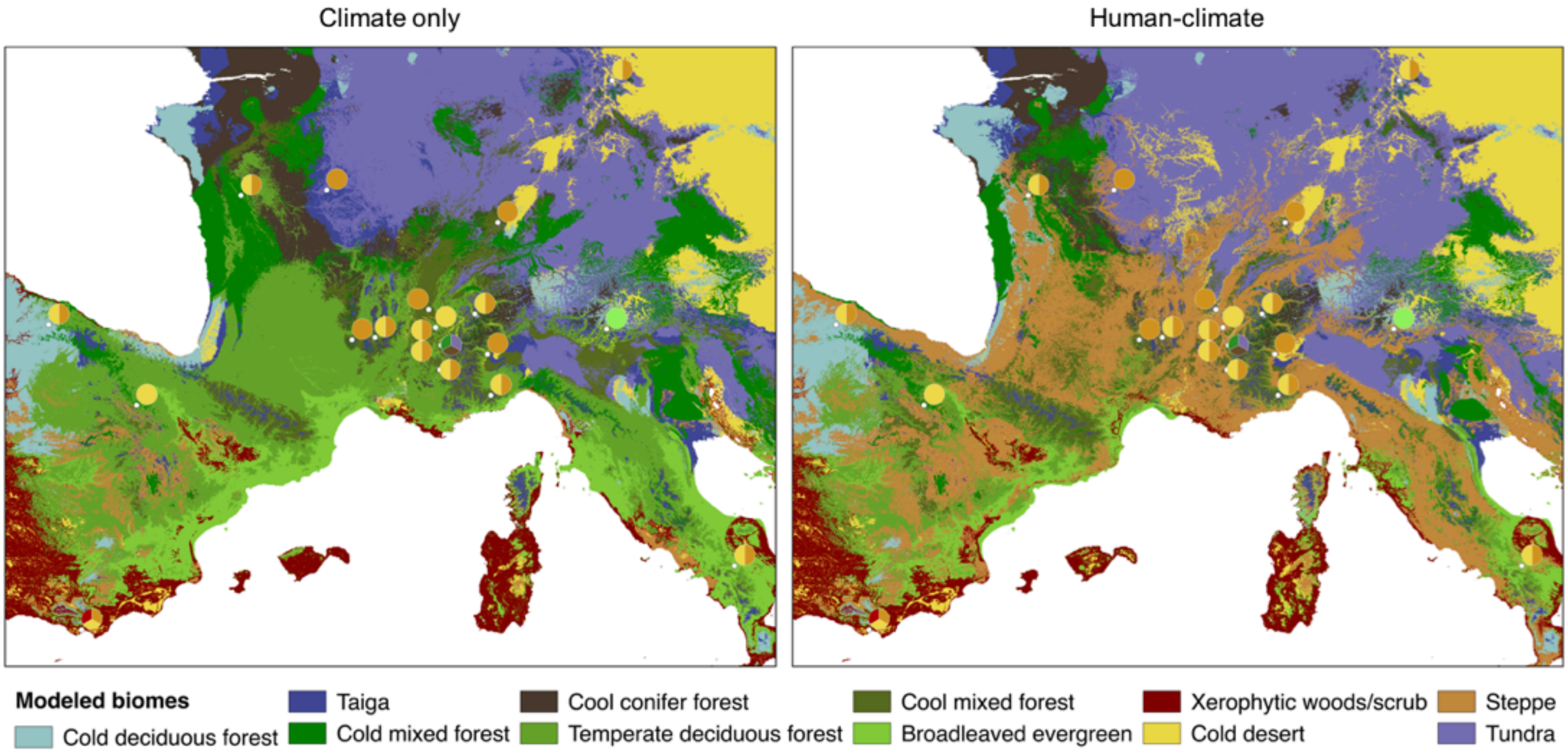


Figure 3.19. Distribution of the biomes – without and with human impact – associated with faunal assemblages dated to the Upper Magdalenian B.

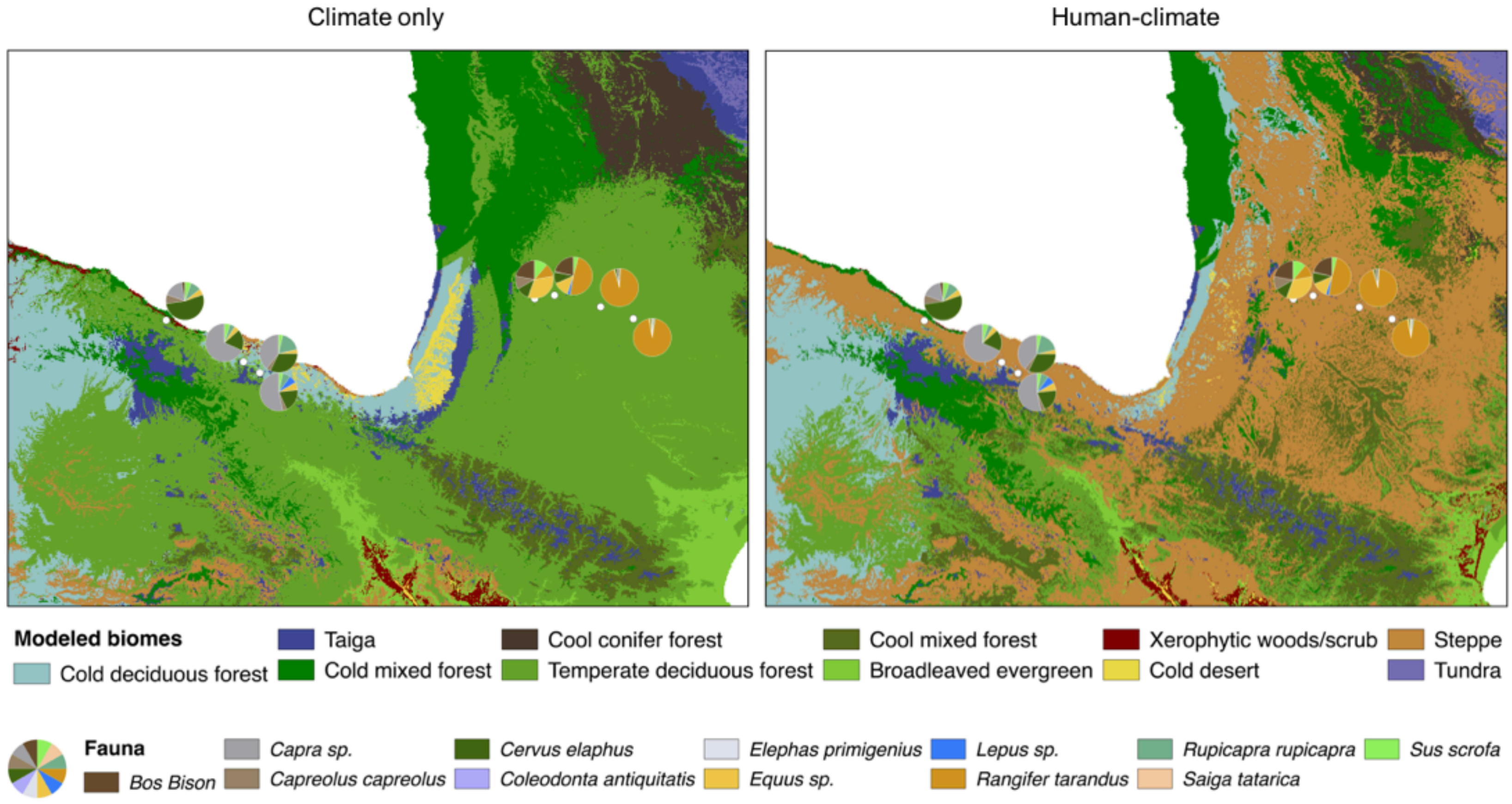


Figure 3.20. Distribution of the biomes – without and with human impact – associated with faunal assemblages dated to the Upper Magdalenian B.

Similarly to the pattern documented for the Upper Magdalenian A reconstructions, the Upper Magdalenian B faunal assemblages show that the human-climate reconstruction fits better the faunal record of the Dordogne (Fig. 3.20). The proportion of steppe-tundra species in the Dordogne still dominates the assemblage, with the small addition of a few red and doe deer, which prefer forests. However, this pattern differs from the Upper Magdalenian A in that the human-climate reconstruction is now a better fit to Cantabrian fauna as well, as the bare mountain flanks of the human-climate reconstruction comply best with the faunal assemblages dominated by mountain goats.

Biome Metrics

As mentioned above, the correspondences between proxy records and reconstructed biomes are not perfect in either scenario, which likely results from the use of modeled climatic data, biased human distribution reconstructions, hunting biases, and/or differential pollen preservation (see Tweddle and Edwards, 2010; Xu et al., 2016). However, the fit of the human-climate reconstructions to the test points is sufficient to allow using them for this research.

To evaluate how resources changed over time and space, I used GRASS to calculate the biome diversity (Table 3.10) and biome fragmentation (Table 3.11) of the human-climate reconstructions for each region and Magdalenian subdivision. The metrics were calculated only for grid cells below 1000m above sea level (asl) to represent the hunting range around Magdalenian camps, which are only found below 600m asl. I added the arbitrary 400m to capture the biome of mountain kill-sites, prevalent in Cantabria. I used the *r.li.simpson* tool to calculate biome diversity for each map.

Table 3.10. Simpson biome diversity, calculated only for the grid cells at altitude below 1000m asl.

	LMA	**LMB**	**MM**	**UMA**	**UMB**
Cantabria	0.77	0.74	0.67	0.71	0.72
Dordogne	0.81	0.72	0.27	0.50	0.49

To calculate biome fragmentation, I used the *r.neighbors* circular moving window – with the interspersion function – with a radius of 30km to represents a minimal band territory. For each grid cell, this tool calculates the percentage of cells in the given radius that have a different value from the cell at the center. I calculated the mean of all cells' values to obtain the general biome fragmentation for each period and region.

Table 3.11. Biome fragmentation calculated for grid cells below 1000m asl.

	LMA	**LMB**	**MM**	**UMA**	**UMB**
Cantabria	19.16	19.73	19.68	28.27	25.61
Dordogne	24.13	19.77	11.60	18.21	21.04

Combined, these two metrics show that biomes were more diverse and more fragmented in the Dordogne than in Cantabria during the first part of the Magdalenian, and that Cantabrian biomes became more diverse and more fragmented over time. In both regions, biomes were the least diverse during the cold Middle Magdalenian. The biome fragmentation of the Dordogne was also at its lowest point during that cold period. In Cantabria, however, the lowest fragmentation occurred during the Lower Magdalenian A, but remained somewhat constant until the Upper Magdalenian. When combined to the diversity of faunal assemblages discussed in Chapter 2, these biome fragmentation values correlate strongly with the mean diversity of the hunted fauna (Pearson's $r = 0.75$), while biome diversity does not ($r = 0.26$).

Discussion

Both pollen and faunal data show that, for most Magdalenian subdivisions, taking human impact into consideration is necessary to model accurately the Late Glacial environments of Western Europe. This inclusion also provides interesting insights on the social behavior of different populations, as it suggests that hunter-gatherers living in the Dordogne altered their environment substantially while the groups living in Cantabria did not. I do not discuss this pattern further here, as it is tangential to the research; however, it is a pattern that should be investigated further in future studies.

The biome maps presented in this chapter are the first plausible extensive reconstructions of Magdalenian biome, and they provide a good baseline against which I could evaluate the extent and structure of the social networks created during the Magdalenian subdivisions. Analyzed alongside the ethnographic and archaeological data summarized in chapters 1 and 2, the characteristics of the reconstructed biomes modified slightly the expectations linked to hypotheses 1 and 3 of this research.

Hypothesis 1. Magdalenian social networks in the Dordogne were, in general, spatially more extensive than the networks created in Cantabria.

Where social networks are created between groups living in different environments, high biome fragmentation should increase the likelihood that close neighbors live in different biomes, and thus, should produce geographically constrained networks. Therefore, if Magdalenian networks were created to serve as safety net against resource fluctuations, I expect the Cantabrian networks to be larger than the ones created in the Dordogne during the Lower Magdalenian, but smaller the rest of the time (refer to Table 3.11).

Hypothesis 3. The intensity of use of the social networks in the Dordogne varied more over time than in Cantabria.

Climate changed at a higher amplitude in Cantabria than in the Dordogne; however, biome diversity and fragmentation varied more in the Dordogne than in Cantabria. Therefore, testing this hypothesis will demonstrate which factor – climatic or environmental – has the strongest impact on the creation of social networks. If it is the former, we should expect to find more temporal variation in the networks of Cantabria than those created in the Dordogne. The situation should be inversed if biome diversity has a stronger impact on social networks than climate change.

The reconstructed biome maps are used in the next two chapters. In Chapter 4, they are integrated to an agent-based model that simulates hunter-gatherer social behavior and mobility in diverse environments. In Chapter 5, I analyze empirical data from Magdalenian sites to reconstruct networks representing the transmission of cultural constructs. I then use the reconstructed biome maps to evaluate the environmental differences of the linked territories to test the hypothesis that alliances were created between sites set in different environments.

CHAPTER 4. SIMULATING ENVIRONMENT-SOCIAL NETWORKS INTERACTIONS

Introduction

I used an agent-based model as a heuristic tool to estimate the characteristics of prehistoric social networks to test the validity of the hypotheses presented in Chapter 1. In this chapter, I present the general features of the model, I discuss briefly the sensitivity analyses done to calibrate it and reduce the number of parameter values used in my official runs, and I present and discuss the results of the runs performed. I separate the results section in two parts. The first shows how I used the model to test the assumption that a social network reconstructed through archaeological assemblages reflects well the underlying social interactions that created those assemblages. The second part focuses on the results evaluating the impact of topography and environmental resources on the extent and structure of social networks. Finally, I discuss how the model can be used to interpret the networks reconstructed through the archaeological record.

Model Summary

Computational models should be simple enough to reduce the complexity of real-world situations, while being complex enough to allow the formation of interesting patterns (Lake, 2010; Wobst, 1974). Following these general guidelines, I built a model that focuses on the interaction of three processes: the environment, the daily mobility of hunter-gatherers, and their transmission of cultural traits. I modeled these processes in the two studied regions and the 5 Magdalenian temporal subdivisions discussed in Chapter 3 to evaluate the impact of the environmental setting on those processes. My model includes most of Doran's requirements (1970) for a good archaeological simulation; it places agents in a landscape where they interact with their environment and with one another, and where they produce objects that form a simulated archaeological record. By doing so, my model creates a bridge between different scales, as it shows how the traces of short-term behavior add up to form long-term assemblages.

The simulation was done in NetLogo, and was set in a world representing the topography and resources of each region. The topography came from a DEM of the region, reduced to a resolution of 1km per grid cell – also called *patch* – producing a world of 324 x 222 grid cells (Fig. 4.1). Sea level change was taken into consideration; therefore, simulations taking placing during different Magdalenian periods used different DEMs. I used these DEMs to create maps of the slope and slope aspect in GRASS GIS, which were then exported to NetLogo. This set of maps gave each patch an elevation value in meters, a slope in degree, and a slope direction in degree between 1-360 (with 360° representing North). GRASS calculates direction clockwise with North at 90°; however, NetLogo requires North to be 360°. Therefore, I used the following GRASS *r.mapcalc* statement to convert the values for each grid cell:

$$\text{if}(x = 0, 0, \text{if}(x < 90, 90 - x, 360 + 90 - x))$$

where x represents the direction of the original map.

To reflect the importance of waterways in Magdalenian mobility (Álvarez-Fernández, 2002; Lenoir, 1992; Rensink, 1995), I then manually set the slope of river patches to 2, and their elevation to 5m lower than their neighboring patches, making these the easiest patches to travel on. As discussed further below, traveling downward on a gentle or moderate slope (0-12°) is faster than traveling on a flat or an ascending surface. Therefore, by making the river patches lower than their neighbors and giving them a gentle slope, I artificially made these patches more attractive to traveling agents.

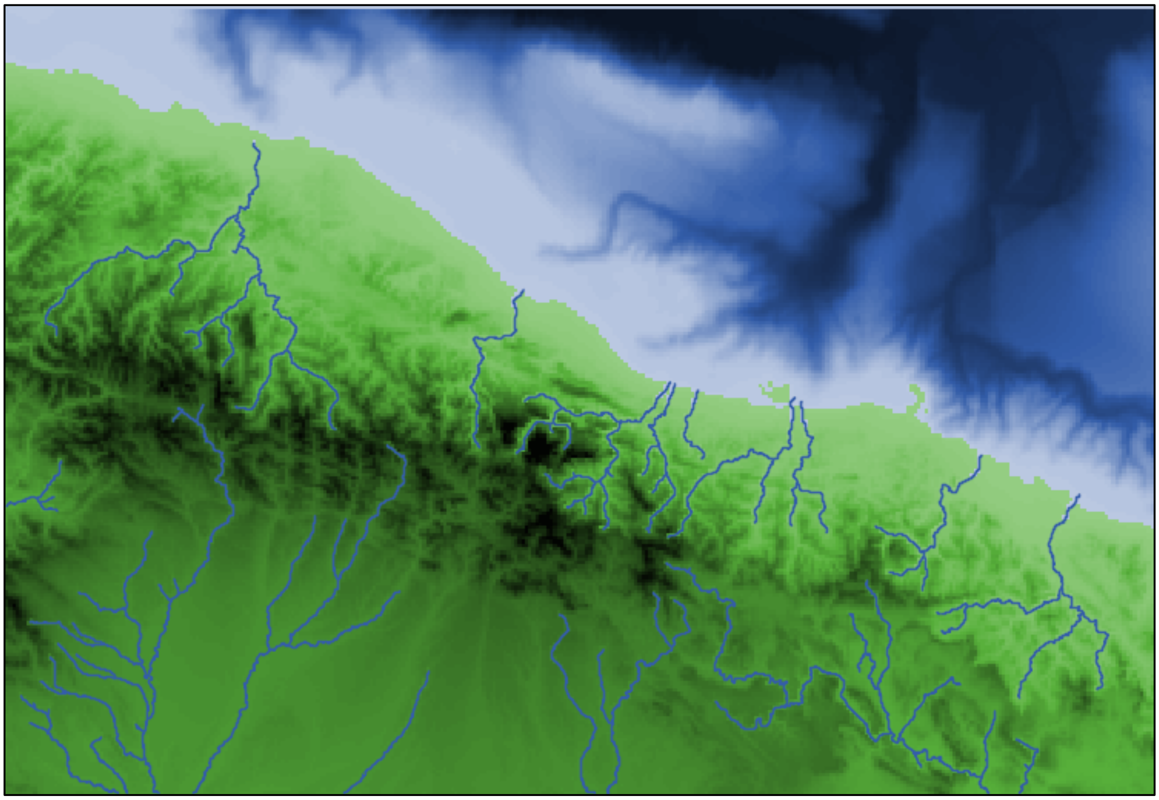


Figure 4.1. Example of the DEM represented in the model (Lower Magdalenian Cantabria).

I recreated the resource level of each patch from its precipitation and temperature values for each Magdalenian period. While resource level is usually derived from a region's primary productivity (see Kelly, 2013), this metric requires using evapotranspiration data, which was not available for the Magdalenian. Therefore, following Kelly's (2013, p. 440) statement that primary productivity is "a product of effective precipitation and solar radiation," I estimated that value by combining data on annual precipitation and data on effective temperature (*ET*) – a good indicator of solar radiation (Kelly, 2013). I calculated *ET* using the following formula (from Binford, 1980):

$$ET = \frac{18W - 10C}{(W - C) + 8}$$

where *W* stands for the mean temperature of the warmest month, and *C* for the mean temperature of the coldest month. I obtained the climatic values from the TraCE-21ka dataset mentioned in Chapter 3, averaged for each of the Magdalenian period. The results showed that effective temperature were lower but more variable in Cantabria than in the Dordogne (Table 4.1 and Fig. 4.2). As *ET* is set on a scale from 8 (poles) to 26 (equator) (Kelly, 2013), these seemingly small changes would still have had important environmental consequences.

Table 4.1 Effective temperature averages for each region and Magdalenian subdivision.

	Lower A	**Lower B**	**Middle**	**Upper A**	**Upper B**
Cantabria	12.77	12.58	11.95	12.33	13.34
Dordogne	12.78	12.67	12.08	12.50	13.42

As explained above, I approximated primary productivity by multiplying annual precipitation with *ET*. I then standardized the resulting values by rescaling them to a range of 0-1 to retain the model's simplicity and allow easy calibration. For all periods, the coastal and riverine patches were given a resource value of 1 to represent the abundance and importance of their resources (Álvarez Alonso et al., 2016; Álvarez-Fernández, 2002; Dachary, 2002; Erlandson, 2001; Kelly, 2013; Marean, 2010, 2016). The biomes reconstructed in Chapter 3 were added to the model as a code attributed to each patch – e.g., 'tund' and 'clmx' for tundra and cold mixed forest, respectively. In both regions, each of the 5 Magdalenian subdivisions was modeled using its specific biome and resource maps.

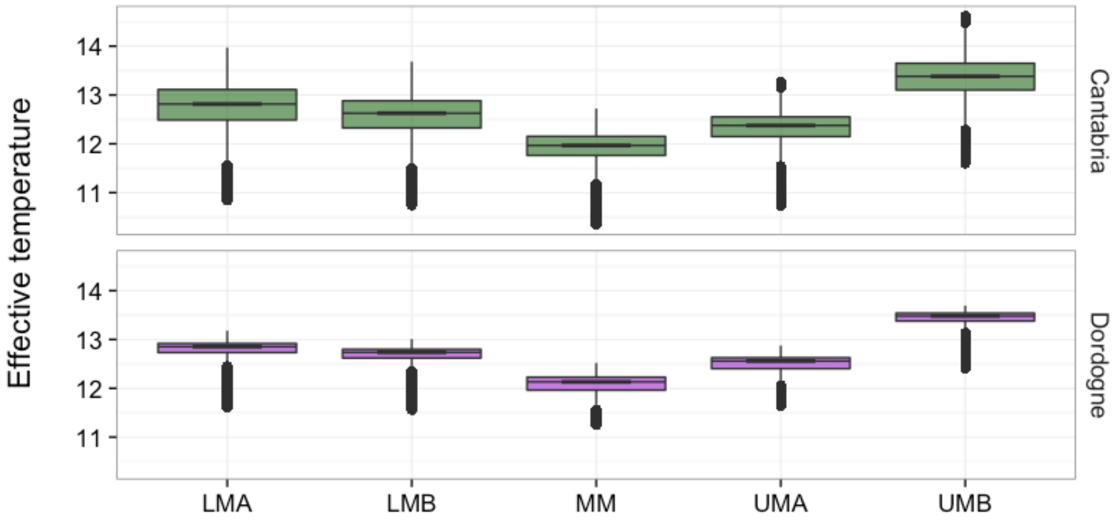


Figure 4.2. Effective temperature per region and period. The central line represents the median. All differences are statistically significant (Student t-test p < 0.001).

The created agent-based model focuses on alliances between minimal bands, identified as a permanent social unit in hunter-gatherer societies (Kelly, 1995, 2013; Wobst, 1974). Therefore, at the setup of each simulation, 10 minimal band camps are set at random on the landscape (Fig. 4.3). Two rules govern their placement: camps cannot be placed on water patches or at altitude higher than 600m above sea level (asl), as a quick survey of Magdalenian sites' position showed that none were located higher than 600m asl. Each camp is assigned a few agents and campers, as well as a 'territory', represented by the patches within a 30km radius.

Modeled agents travel between camps to create alliances, whereas campers transmit cultural information to one another. Each camper is linked to one of the agents, whom it follows in circumstances detailed below. Each tick of the model represents 10 minutes of travel time by agents. This high temporal resolution is necessary to model mobility on a realistic landscape. Each agent travels for a maximum of 6 hours per day. Weeks have 7 days, and months are set at 4 weeks.

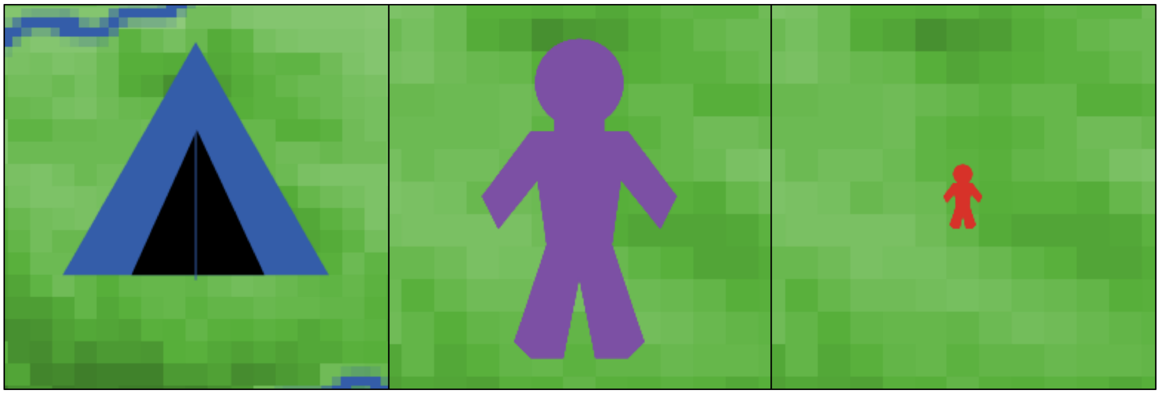


Figure 4.3. Camp, agent, and camper represented in the model.

To model an average and realistic hunter-gatherer population, each camp contains 24 occupants (c.f., Birdsell, 1968; Lee and DeVore, 1968; Wobst, 1974). However, as this model does not focus on demography, or kinship, not all of these 24 occupants have a purpose; this number is important only to calculate the amount of resources necessary to keep the population alive. Therefore, to reduce the model complexity and speed up computation, the model explicitly simulates the activities of only half of these occupants (6 *agents* and 6 *campers*). To model the resource needs of 24 occupants through 12 simulated ones, each camper requires 3x the amount of food that each agent require. Therefore, every day, each camp calculates the amount of resources needed by its occupants using:

$$R = r(A + 3C)$$

where A *and* C stand respectively for the count of agents and campers located at the camp, and r represents the amount of resource required by each occupant (value set at the beginning of the simulation). Each camp then gathers *R* resources from patches located within its foraging radius (10km around the camp for foragers and 30km for collectors) to feed its occupants. While this action does not change the state of the camp or its occupants, it depletes the resources of nearby patches. The number of patches to deplete is based on the territory's remaining resource level, using:

$$x = R \Big/ \frac{1}{n} \sum_{i=1}^{n} P_i$$

where *P* stands for the patches with available resources and *x* for the number of those patches required to satisfy *R*. This simply divides *R* by the average resource level of all pristine patches within the foraging radius. When it is calculated, *x* number of patches, selected randomly within the foraging radius, change their resource value to 0.

If most patches are already depleted and the remaining resources are not enough to feed all occupants, one camper dies. If all campers are dead and the resources are still insufficient, one agent dies. The camp dies when all its occupants are dead, and the simulation stops when no camp is left. This model does not focus on demography; therefore, for the sake of simplicity, agents and campers do not reproduce and their number can only decrease over time.

To reproduce the resilience of natural environments, every day, a certain percentage of depleted patches are chosen at random to replenish their resources. This percentage is set at the beginning of the simulation, and remains constant during.

Main Parameters. The model simplifies complex social behavior to focus on the creation of alliances between prehistoric groups. Multiple parameters can be changed to run the simulation with different settings, or to change how it operates (Table 4.2). A few of these parameter values were selected for this research, and are discussed below. For more details on the model's modules, see the flowcharts and ODD protocol in Appendices G and H.

Table 4.2 Parameter settings

Variables	Possible values
Region	Cantabria, Dordogne, No GIS
Period	Lower Magdalenian A, Lower Magdalenian B, Middle Magdalenian, Upper Magdalenian A, Upper Magdalenian B
Hours per day	4-12
Alliance choice	Resource-driven, Socially-driven
Settlement pattern	Collector, Forager
Food requirement	0-1
Replenish rate	0-100%
Switchback	0-0.5
Cultural transmission	Autodidact, Conformism, Prestige
Rate of transmission	0-100%

Region [Cantabria, Dordogne, No GIS]. The first two regions use the topographical and environmental maps mentioned above to reproduce a simplified version of the world in which Magdalenian hunter-gatherers interacted. The No GIS setting produces a flat surface separated into four quadrants representing 4 different biomes, and with resource values chosen at random between 0 and 0.6. This flat surface is used as a null model against which I could compare the networks produced in the other two settings to evaluate the effect of topography on social networks.

Biome [Lower Magdalenian A, Lower Magdalenian B, Middle Magdalenian, Upper Magdalenian A, Upper Magdalenian B]. This does not affect the No GIS landscape; however, it determines which biome and resource maps are used to reproduce the relevant prehistoric environment.

Alliance Choice [Resource-Driven, Socially-Driven]. This impacts how camps form alliances. When alliances are resource-driven, every week, camps evaluate if they have enough resources available to feed their occupants for the next two weeks – used to represent hunter-gatherers' adaptation to fluctuating resources. The camps with depleted territories ask their allies for help. If they already have allies, an agent and its camper are sent to live in the closest allied camp. Therefore, to relieve the pressure on the camp, a few individuals move in and out as needed, but the camp remains where it is. This is inspired by Wiessner's (1982) account on !Kung families who cope with low resources by visiting the relatives with whom they have *hxaro*. Camps without allies send agents to create alliances. The modeled agents move through the landscape and visit camps until they find a suitable ally. Every time they find a camp, they evaluate if it has enough resources to feed an additional family of 4 (the agent and its very-hungry camper). The alliances can only be formed between two camps located in different biomes, as ethnography shows that alliances formed to safeguard against resource fluctuations are usually made between groups living in different environments (Kelly, 1995, 2013; Whallon, 2006; Wiessner, 1982). When an ally is found, the agent moves its camper to that camp. All visitors remain in an allied camp until its resources become too low to sustain its occupants and visitors. If an evaluated camp is not suitable (same biome or not enough food), the agent removes that camp from its list of possibilities and moves to another one. The agent continues walking until all camps have been visited. It then returns to its origins, and the search cycle starts over.

When alliances are socially driven, the resource level does not affect mobility. Camps send agents out at least once a year, but not as often as every week – modeled as a 3/10,000 chance to send an agent out at each tick. When an agent is sent out, it moves to its goal and creates an automatic alliance between the goal and its original camp as soon as the agent reaches it. The agent is then joined by its camper. The length of the visit is also set at random, with 3/10,000 probability of return at every tick – value set for the same reasons as explained above. This random movement is set to represent the alliances created between groups of hunter-gatherers for reasons unrelated to the environment – e.g., social aggregation, mate exchange, or simple social calls (Conkey, 1980; Gamble, 1998). To differentiate between the characteristics of social networks created as safety nets and those created for social reasons, no setting allows both types of alliances to be created within a singular simulation.

In both settings, the model records the spatial length of each alliance and the number of times each is used.

Settlement Pattern [Collector, Forager]. This parameter controls the camps' annual movement within their territory, and is based on ethnographic research on hunter-gatherer settlement topologies (Kelly, 1995, 2013; Binford, 1980). Collectors move their camp seasonally and use logistical forays to take advantage of the resources available in their entire territory, whereas foragers move camps regularly to patches of abundant resources. While a computer model has shown that settlement patterns can impact the cultural transmission of single traits (Perreault and Brantingham, 2011), their impact on larger networks is still unclear. I modeled simplified extremes of the forager-collector spectrum to shed light on this question.

Camps of both settlement patterns have a circular territory with a 30km radius, based on estimates of minimal band territory size (from Whallon, 2006). While the size of the whole territory is the same for both settlement patterns, their resources gathering strategies differ, as explained below (Fig. 4.4).

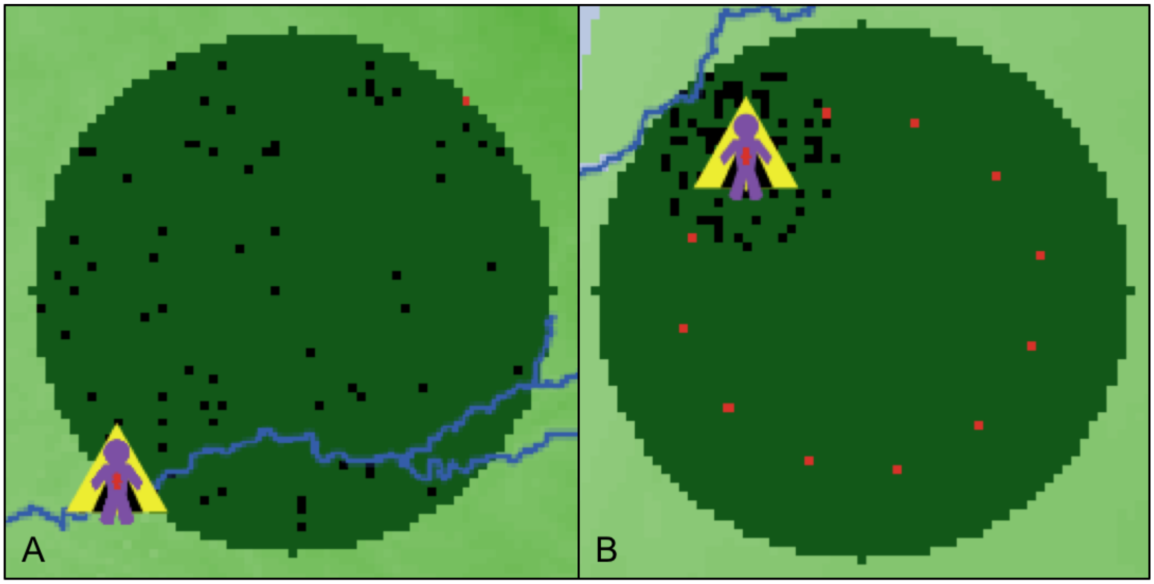


Figure 4.4. Territory and movement of camps for both settlement patterns. A. Collector (logistical mobility), B. Forager (residential mobility). The black patches represent where the resources are gathered while the red patches show where the camp will move to during the year.

Collectors move their camps only twice a year, once to the highest point of their territory, and once to the lowest point. This represents the Magdalenian inferred seasonal preference for higher altitude in the summer and lower altitude in the winter (Marín Arroyo, 2009; Straus, 1981, 1986, 1992). Every day, however, collector camps gather resources from the whole territory, which represents the usage of small logistical forays far from the camp (Binford, 1980; Conkey, 1980; Rensink, 1995; Straus, 1986).

Forager camps start the simulations 10km from the edge of their territory, and move clockwise every month. The movement represents a shift of 30° angle from the center of the territory, which allows the camp to cover the whole territory over a year. Every day, forager camps collect resources only from the patches located within a 10km radius.

For both settlement patterns, the camps consider only the immediate 10km radius territory when evaluating the level of resources available to feed its occupants for the next 2 weeks. This modeling choice allows camps of both types to suffer resource shortages. While collectors gather resources from their whole territory, asking them to evaluate the resource level of their immediate surrounding is a simple way to model the seasonal resource shortages that deplete entire parts of real collectors' territory.

Due to the relatively low effective temperature (~ 12) and the highly variable climate of both regions, I assumed that the economic defendability of those territories was too low to lead to territoriality and defense of resources (as per Dyson-Hudson and Smith, 1978, see also Marean, 2016), which is supported by the lack of signs of violence in the Magdalenian (Lahr et al., 2016). Therefore, modeled camps can have overlapping territories, and they do not defend their resources.

Learning Method [Autodidact, Conformism, Prestige]. This models the transmission of cultural information between campers. All campers start the simulation with a list of 5 values, representing style variants, taken from a random-normal distribution with their camp number as the mean, and a standard deviation of 5. Negative values are always set to 0. Using the camp number as the mean of a normal curve creates natural clusters at each camp, which represent cultural 'styles' that are primarily transmitted within minimal bands before being exposed to external influences (Axelrod, 1997; Buisson et al., 1996; Wiessner, 1983; Wobst, 1974). The three distinctive learning methods – based on the work of Eerkens and Lipo (2005, 2008) affect how the list is updated every day.

Autodidact implies that cultural traits are not passed on between individuals. Instead, all campers learn for themselves by copying their own traits every day. Autodidact is modeled as a control against which I could compare the other two methods. When the transmission method is set on *Conformism*, campers copy the average of all other campers found at the camp. Each trait in the list is replaced by the mean of the campers' similar trait. In other words, the first trait of a camper is replaced by the mean of the other campers' first traits. *Prestige* transmission requires attributing 'prestige' to a certain number of campers – here set arbitrarily as 20% of the campers. Campers copy the list of a prestigious individual only when they are in the same camp. In all transmissions, 3% reproduction error is added to the new values to account for human error (Eerkens and Lipo, 2005, 2008). This is represented by Eerkens and Lipo (2005)'s equation:

$$Y(t+1) = Y(t) + Y(t) * c * N(0,1)$$

where *Y(t)* is the value copied, *c* is the error rate (3% divided by 2), and *N*(0,1) is a random variable chosen from a normal curve with mean 0 and standard deviation 1.

The percentage of campers transmitting cultural information via prestige and conformism methods is set by a parameter value. If the value is set at 10%, roughly 10% of the campers learn from others every day; the other 90% use the autodidact method. To evaluate the effect of differential levels of transmission on the visibility of networks through transmitted traits, I ran simulations with varied levels of transmission. As using 0% transmission would be identical to using the autodidact method, I chose to model two extremes with low transmission at 25% and high transmission at 100%. Eerkens and Lipo (2005) show that, while transmission as low as 5% creates more stylistic variations than 0%, the difference between 5 and 25% is not as big. Therefore, 25% seemed like a reasonable choice to represent low transmission.

Least-Cost Path Module. Simulating realistic mobility across topography is one of the features that distinguish this study from other models that aimed to simulate prehistoric cultural transmission (Axelrod, 1997; Eerkens and Lipo, 2008; Mesoudi and O'Brien, 2008; Perreault and Brantigham, 2011; White, 2012). This part of the code is used to represent realistic walking patterns in a modeled landscape. Its general characteristics are based on GIS least-cost path scripts, which use the elevation, slope, and direction of raster cells to calculate an easy-to-travel path between two points. While GIS least-cost path tools efficiently find the easiest way to move between two points, I could not use those for my agent-based simulation for two reasons:

1. With a GIS tool, all grid cells in the computational region are used in the calculation, which is time consuming. In my model, a total of 60 agents can travel at the same time, which requires the creation of 60 simultaneous but independent least-cost paths. Using the GIS tool to create those paths would considerably slow down the runs.
2. A GIS tool takes the whole landscape into consideration to identify the best path between two points. This is not how human move on the landscape, where they have a limited knowledge of their surroundings. Humans make walking decisions with the information available to them wherever they are, which means that they

can choose a route that seems easy at first, but that might lead to a cul-de-sac or a very steep slope in the end.

To represent realistic human movement between sites, I wrote an agent-informed version of the GRASS least-cost path tool for this model. In this script, the path is defined through decisions made by the agent based on information provided by the surrounding patches. An agent always has a general goal towards which it is walking as well as a temporary target that helps monitor its progress. When it leaves its camp to find allies, the agent's general goal is one of the other 9 camps, set at random. At the beginning of each tick, the agent evaluates if it has reached its temporary target. Only if the agent has reached it can it look for a new one.

To select its temporary target, the agent evaluates its neighboring patches and chooses the one that allows fastest travel towards the goal. The speed of travel on rugged surface comes from the *r.walk* tool in GRASS GIS based on Naismith's rule (Aitken, 1977) and Langmuir (1984). It suggests that an agent can walk 5km/h on flat terrain and up to 6km/h on a gentle downward slope (between 5-12°), but that the speed decreases to 2km/h when going up or down on a steep slope (> 12°). While these speed values are probably lower than what is found in modern and prehistoric hunter-gatherer populations, documented reduced mobility during the Last Glacial Maximum (Holt, 2008) suggests that the speed of movement could have been close to these estimates.

The model has a *switchback* value that allows agents to temporarily move away from their general goal to go around mountains using switchbacks rather than escalate them.

Agents record the length of their trip between camps by summing up the number of patches they travel on. Along the way, they may encounter a camp other than their goal. If they have already evaluated the potential of that camp on this search cycle, they ignore it. However, if this is a new unevaluated camp, it becomes their new general goal. Whenever an agent reaches another camp, the distance it traveled – which represents the least-cost path distance between the agent's origin and the visited camp – is recorded as part of an invisible link between the two camps. Other agents can update that value only they have found a quicker path. This insures that the quickest least-cost path between two sites will be the one used for analysis.

Sensitivity Analyses and Parameter Calibrations

Before running the experiments for this study, I performed local sensitivity analyses to evaluate the impact of each parameter on the model and calibrate their values (see discussions by Costopoulos, 2010; Lake, 2010; Railsback and Grimm, 2011). I evaluated the effect of tested parameter values (Table 4.3) on the level of available resources, the number of camps, agents, and campers at the end of a run, and on the number and structure of networks created and used. I used BehaviorSpace to run different configurations of the model and create outputs of the metrics at every tick.

Table 4.3. Parameter values tested.

Variables	Values tested
Food requirement	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1
Replenish rate	2, 4, 6, 8, 10, 30, 50, 70, 90
Switchback	0.1, 0.2, 0.3, 0.4, 0.5

The first analysis was done to find the equilibrium between the food requirements of occupants and the speed of resource replenishment. As the goal of the model was to reproduce the structure of networks created to cope with resource insecurities, it was important to keep the resources depleted enough to force camps to seek allies, but abundant enough to avoid killing all their occupants. I tested the impact of *Food requirement* and *Replenish rate* values on the resources available to collector and forager camps set in the Upper Magdalenian Dordogne, and collated the results (Fig. 4.5).

The results showed that the optimal food requirement was 0.3, as this value guaranteed that some of the sites located in less productive environments would need to find allies, and that other sites would have enough resources to help. Moreover, this value led to the highest number of networks and the least death – not shown here.

The results also showed that varying replenishment rates between 0 and 10 had a big impact on food availability, on the survival of the agents/campers, and on the number of networks created. However, beyond this value, the differences decreased substantially. To model times of abundant resources as well as times of food shortage, I chose to keep two extreme values (8 and 50) to use for the simulations.

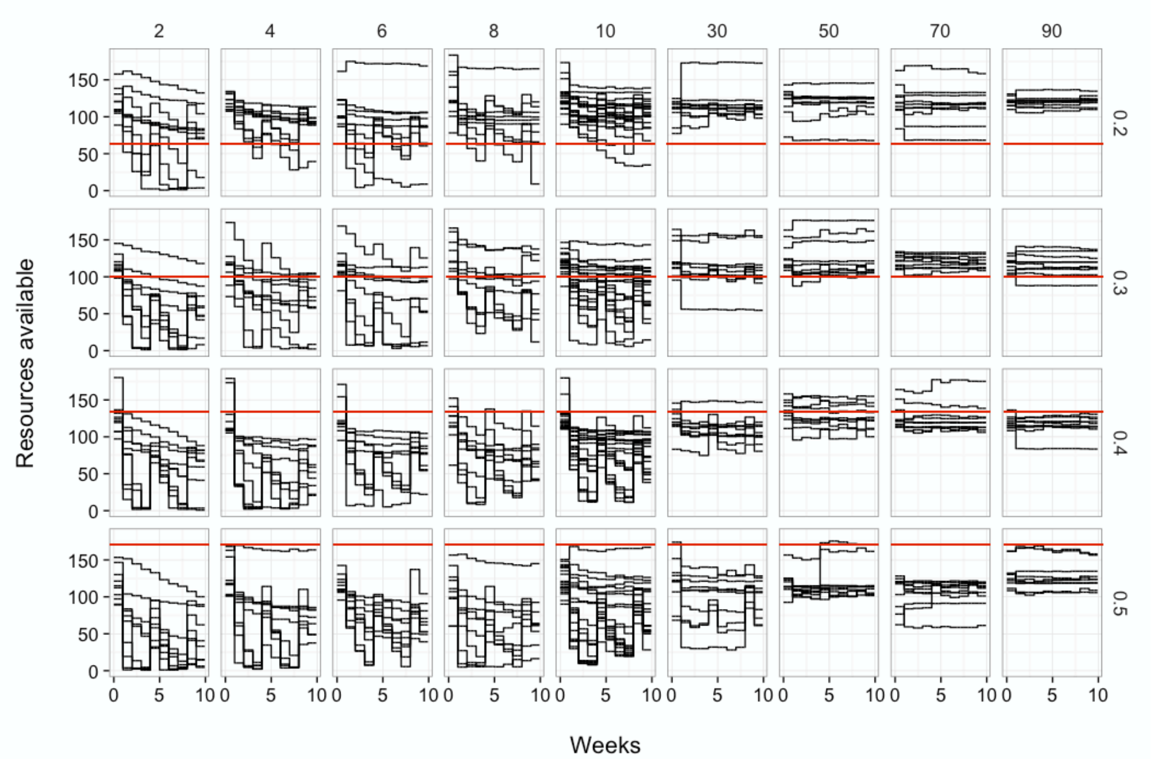


Figure 4.5. Available resources based on combinations of food requirements (y axis) and replenishment rate (x axis). The red lines represent the threshold under which a camp will not have enough resources to feed its occupants.

I used another sensitivity analysis to calibrate the length of switchbacks allowed for least-cost path mobility. This value helps an agent choose the easiest patch to walk on, even if it means getting temporarily farther from its goal. A value too low restricts movement and leads the agent to face steep slopes, whereas a value too high allows the agent to move further away from the goal, which increases the time spent traveling, and sometimes leads to getting lost and dying. To calibrate this value, I ran 30 repetitions of the model with different switchback values. I tested the impact of each value on the number of agents remaining at the end of a simulation, and on their mean travel speed (Fig. 4.6). I found that 0.2 led to the best compromise between speed and number of dead agents.

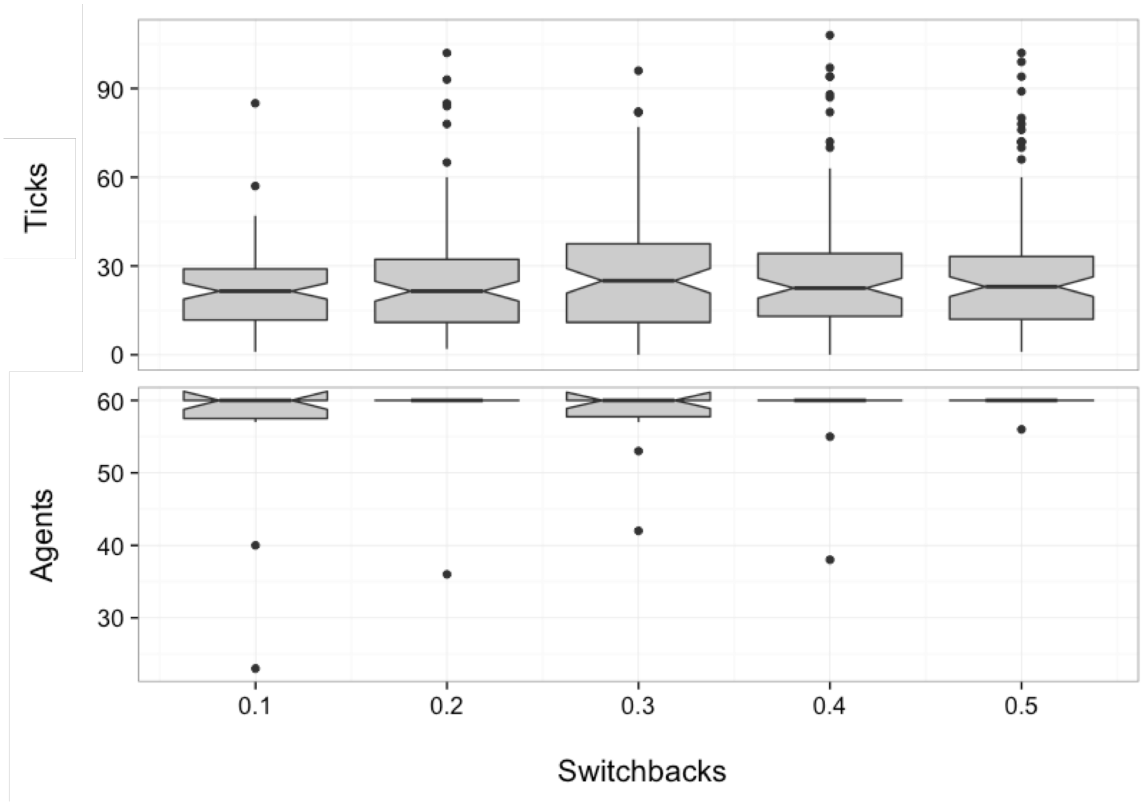


Figure 4.6. Impact of switchback values on travel speed and number of remaining agents.

To identify the optimal length of simulations, I ran 200 long simulations, for which I recorded key network values at every tick – mean betweenness centrality, mean closeness centrality, and cluster coefficient. The parameter values were set to varied combinations to ensure that all the variations would be considered. The results showed a rapid change in network structure in the first 25,000 ticks, followed by a slower stabilization (Fig. 4.7). From those results, I determined that a length of 60,000 ticks would be enough to catch most of the networks' changes.

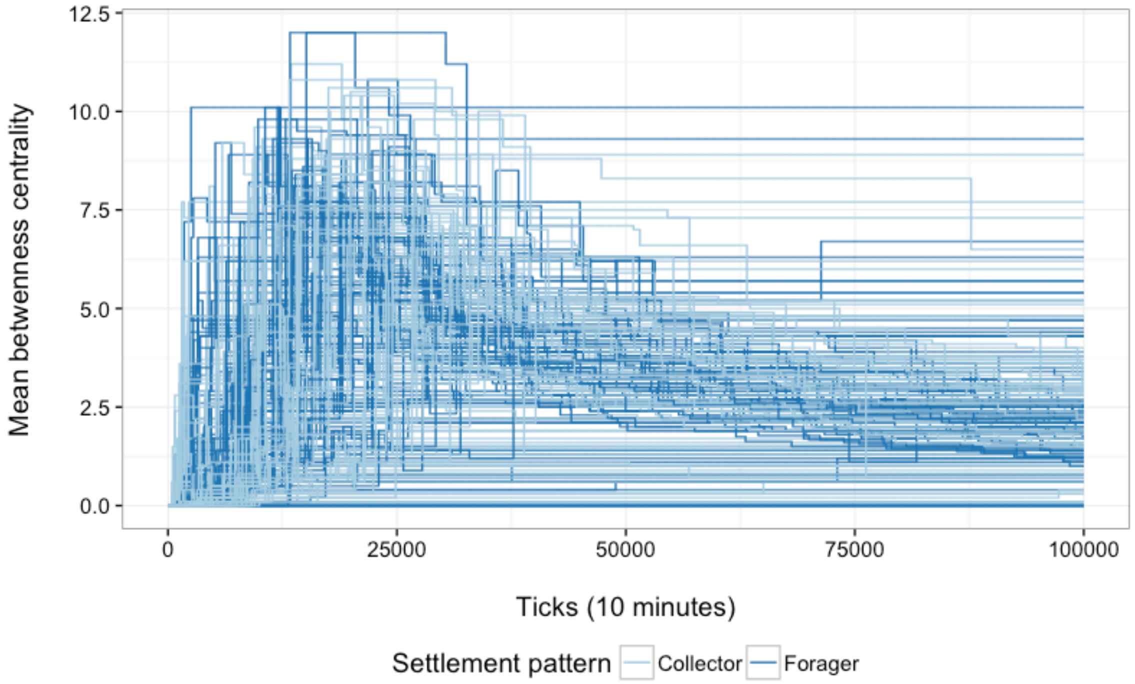


Figure 4.7. Mean betweenness centrality over time.

Finally, I determined the number of iteration that would best capture the variation produced by the model's stochasticity, while keeping the length of the simulations to a minimum. To do so, I ran 100 iterations of 2 parameter combinations for 12,500 ticks, and recorded the final number of networks created for each simulation. This created a population of 200 values, from which I then selected random samples, and used two-tailed t-tests to evaluate if the samples were representative of the whole population. I repeated this 1000 times for all possible sample sizes between 5 and 200. Figure 4.8 summarizes the results. The *x* axis represents the sample sizes selected from the population, whereas the *y* axis shows the *p*-values of the t-test ran between sample and population. The points and lines show the *p*-values means and standard deviations around the means for each 1000 random samples. The red horizontal line shows the 0.05 threshold under which a sample would be statistically different from the population. This figure shows that the results of any sample size are likely representative of the model's general outputs. I thus chose to run each simulation 15 times to capture the important variation while producing a manageable amount of data.

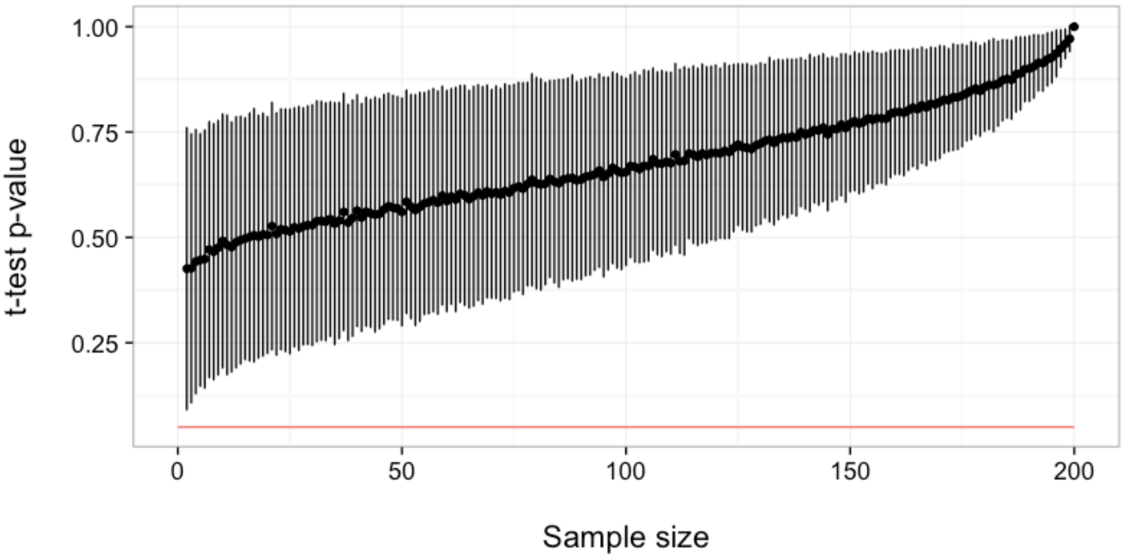


Figure 4.8. One standard deviation over the mean p-value between 1000 random samples of size x and the whole population (n = 200).

The final range of parameter combinations is presented in Table 4.4. I ran a total of 384 parameter combinations for a total of 5,760 runs. At the beginning of each run, a CSV file was created to record the list of traits of every camper every month after the first year, as well as the number and length of alliances created between pairs of sites. These files were analyzed further to evaluate the structure of networks created.

*Table 4.4. Parameter values used in this experiment. *No GIS runs had only one biome map, representing 4 quadrants with different values. Similarly, **Autodidact learning method was run with a constant learning-rate of 100%.*

Variables	Values used
Hours per day	6
Switchbacks	0.2
Region	No GIS*
	Dordogne
	Cantabria
Period	Lower Magdalenian A
	Lower Magdalenian B
	Middle Magdalenian
	Upper Magdalenian A
	Upper Magdalenian B
Turtle need	0.3
Replenish rate	8, 50
Alliance choice	Resource-driven
	Socially-driven
Settlement pattern	Collector
	Forager
Learning method	Autodidact**
	Conformism
	Prestige
Transmission rate	25, 100

Analysis of the Model's Outputs – Observed vs. Reconstructed Networks

Comparing General Structures. In addition to providing information on the impact of climate and environmental resources on social networks, this model evaluates the impact of social contact on the transmission of cultural traits, and on the visibility of that transmission in the archaeological record. In the absence of written records, studying prehistoric social networks can only be done through archaeological proxies, such as stylistic similarities in artistic representations or tools. However, this implies assuming that the characteristics of the reconstructed networks are good representations of the latent social interactions that produced them. I tested this assumption by comparing the characteristics of the reconstructed and observed (latent) networks created in the model. This test allowed me to evaluate if observed and reconstructed networks are generally similar enough to allow inferring the invisible prehistoric social behavior through networks reconstructed from artifacts (see Fig. 4.9).

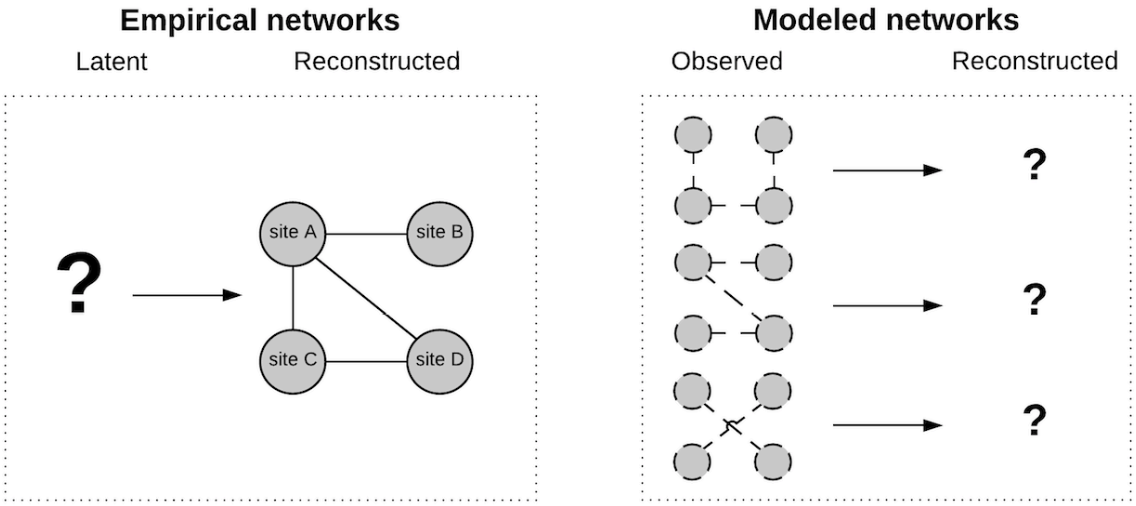


Figure 4.9. Test performed by the model: are observed and reconstructed networks similar? Can we get at latent empirical networks by analyzing the networks reconstructed from archaeological assemblages?

To reconstruct the modeled networks through their culturally transmitted data, I used the list of traits outputted from the campers as a modeled representation of an archaeological artifact assemblage. I thus refer to that list of traits as the ‘art’ produced by the campers, and I assume that similar traits shared between lists show the presence of a shared ‘artistic style’. I modeled 3 different cultural transmission methods (*Autodidact*, *Conformism*, and *Prestige*) and 2 rates of transmission (25% and 100%) to evaluate the level of transmission necessary for stylistic similarities to reproduce accurate networks of direct social contacts.

The outputs of the model recorded artistic traits every month to create palimpsests of art objects comparable to the assemblages found in the archaeological record. For each palimpsest, I calculated the Euclidean distance between every pair of art objects. I used trial and error to define the threshold (<= 1) at which two objects were similar enough to indicate shared cultural conventions. I regrouped all similar artifacts by camp, tallying how many similar pairs of objects were found for each camps pair, thus producing networks of linked camps. I then used Quadratic Assignment Procedure (QAP test) to calculate the similarity between the reconstructed and observed networks of each simulation. This method uses the Monte-Carlo approach to create a given number of random networks ($n = 1000$) and calculates the probability of creating a network more similar to the control (observed network) than the one provided (reconstructed network). For this test, the null hypothesis is that two networks are different. Therefore, a p-value < 0.05 indicates that the similarity between two networks is statistically significant.

The networks recreated with objects produced via the *Autodidact* method were used as a control against which I could compare the networks reconstructed from culturally transmitted traits. I expected *Autodidact* reconstructed networks to differ more from their underlying observed networks than networks reconstructed from assemblages created with *Conformism* and *Prestige* transmission. The QAP test confirmed my expectations (Fig. 4.10); the networks reconstructed from culturally transmitted art better reflected their underlying observed networks than networks reconstructed from the art of autodidact campers. Furthermore, I found that most reconstructed and observed networks were statistically similar even when the cultural transmission occurred only 25% of the time. This result supports the work of Eerkens and Lipo (2005), which states that even infrequent cultural transmission occurrences have important impacts on the stylistic variability of artifact assemblages. While 25% conformism produced networks that were slightly more accurate than 25% prestige, both methods of cultural transmission led to structurally accurate networks even at those relatively low rates of transmission. The QAP *p*-values did not vary significantly between rates of transmission for *Conformism* (two-tailed t-test $p = 0.12$), but it varied significantly for *Prestige* (two-tailed t-test $p < 0.001$).

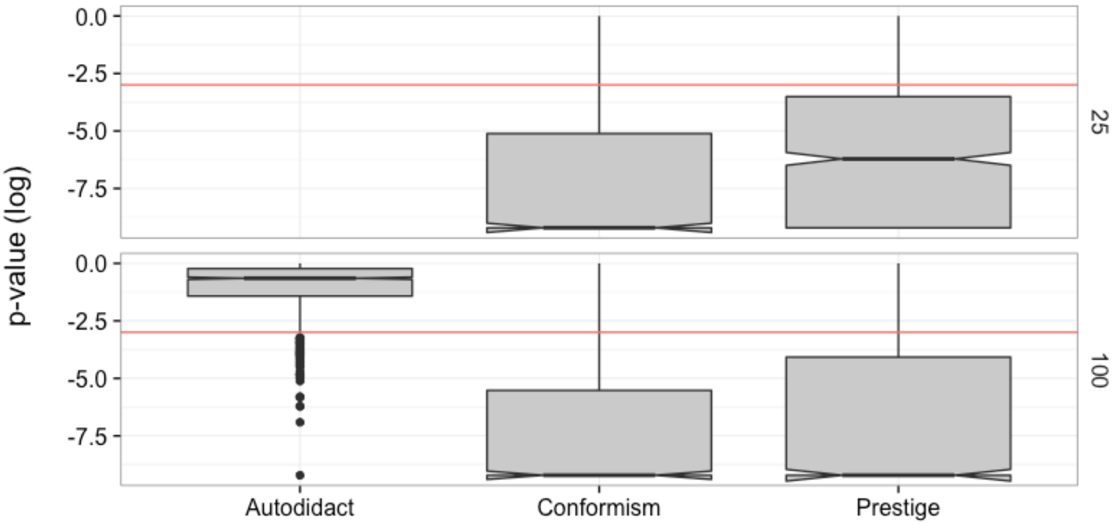


Figure 4.10. Quadratic Assignment Procedure p-values for each cultural transmission method and rate. The red line represents the log of the 0.05 threshold for significance.

Comparing Network Metrics.

Metrics Studied. While the QAP test shows the presence of structural similarities between the reconstructed and observed networks of simulations using *Conformism* and *Prestige* cultural transmission, a detailed analysis of those networks' metrics show that there are also important differences between them. The compared metrics relate to the networks' structure and geographical extent.

Structure is assessed from the number of used alliances, graph density, and shortest path. In the case of reconstructed networks, the number of used alliances represents the number of similar art objects between camps, whereas for observed network, it represents the number of visits between them.

Graph density is the number of links created between camps divided by the total number of possible links. For example, a network formed of 10 camps can have 90 links if all camps are inter-connected. If there are only 20 links, then the graph density is 20/90=0.22. Therefore, the higher the graph density, the more connected the network.

Shortest path is calculated for connected camps only. Each camp calculates how many other camps it needs to go through to reach all linked camps. For example, in Figure 4.11, A needs to go through B to reach C or D, therefore the shortest path of A is 2. The shortest path of B is 1, because it is directly connected to all other nodes. E is not connected to any of the other nodes; therefore, it has a shortest path of 0. For this research, I used the average shortest path of whole networks – which would be (2+1+2+2)/4 = 1.75 for the network in Figure 4.11, as it only includes connected nodes. The lower the value, the more direct are the links between connected camps.

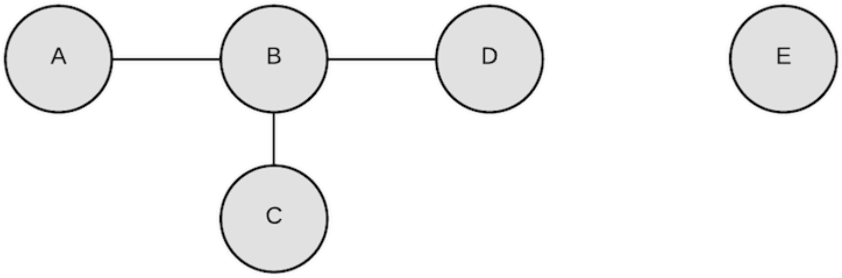


Figure 4.11. Example of a network. The shortest path values of A, C, and D are 2, the value of B is 1, and the value of E is 0.

To evaluate network extent, I recorded the length of the longest inter-camp link, the distance between the camps sharing the strongest connection, and the Pearson correlation *r* between the length and strength of alliances. A strong negative *r* represents a network where close neighbors are relied upon more often than long-distance allies. For observed networks, the distance between camps represented the least-cost path identified by visiting agents. However, for reconstructed networks, that value was calculated as a direct as-the-crow-flies distance, because least-cost path distances did not exist for all pairs of camp (all camps were not always visited by all agents).

Results of the Metrics Comparisons. To obtain results applicable to archaeology, I calculated the network metrics mentioned above for simulations set in Cantabria and the Dordogne, where alliances were resource-driven, and where cultural information was shared through conformism and prestige. The results of those comparisons are presented in Figure 4.12. To determine if these metrics correlated linearly, I calculated the Pearson correlation *r* between the observed and reconstructed network metrics of every simulation (Table 4.5).

Table 4.5. Pearson r between observed and reconstructed networks.

Metrics	**Pearson *r***
Used alliances	0.32
Graph density	0.68
Shortest path	-0.15
Longest alliance	0.26
Strongest alliance	0.24
Correlation length~strength	0.06

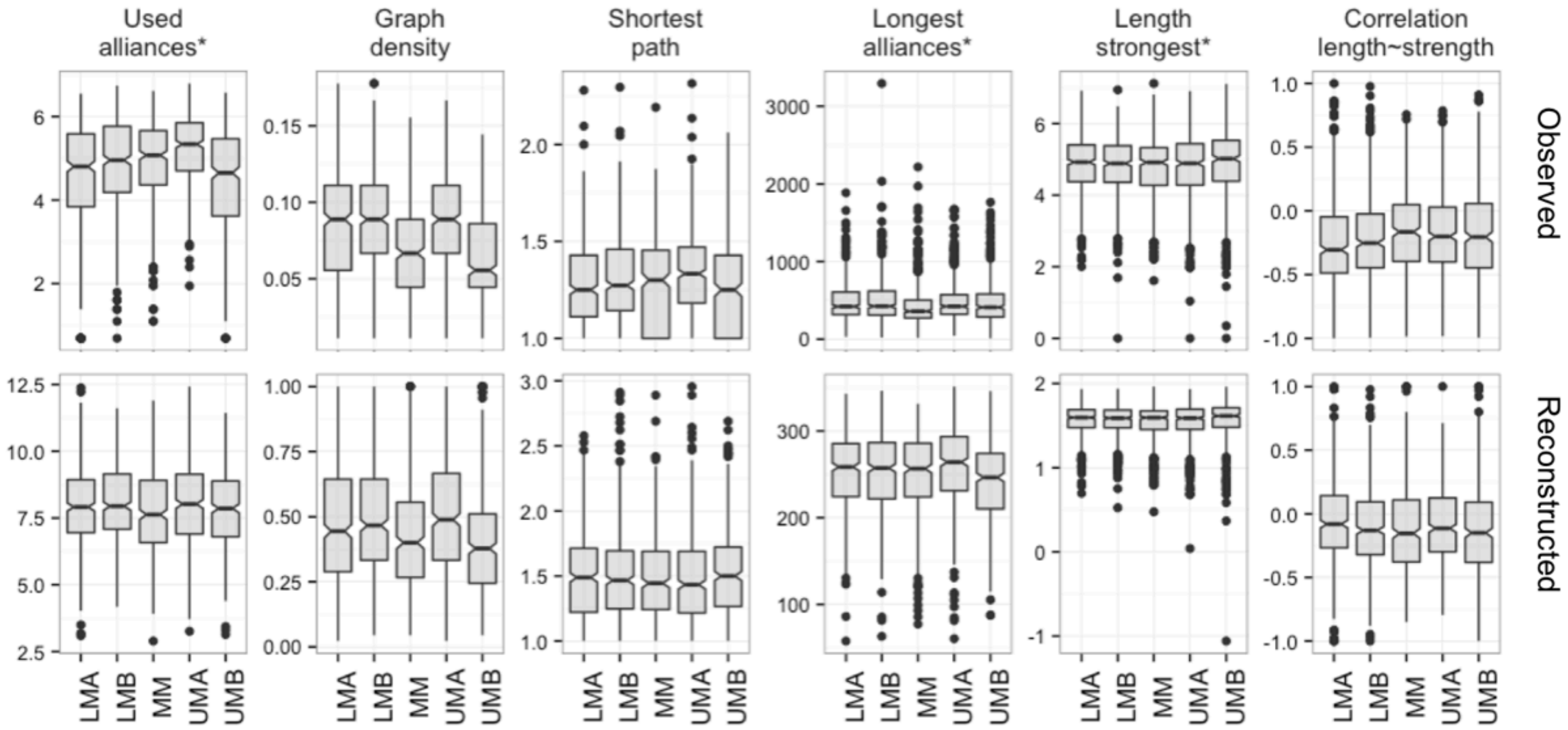


*Figure 4.12. Comparison of the temporal changes of observed vs. reconstructed modeled networks. *Logged values.*

Figure 4.12 and Table 4.4 show that the graph density of the two types of networks co-vary strongly, while the other metrics do not. This can be explained by the influence of indirect transmission on reconstructed networks. Because campers visiting a camp transmit their traits to campers who might visit other camps later, the indirect transmission of cultural traits leads to reconstructed networks that are generally more connected than the observed ones (Fig. 4.13). This has a particularly strong impact on shortest path and longest link, as camps that were indirectly linked in the observed network are often directly linked in the reconstructed network. For example, in Figure 4.13, the shortest path of camp 3 changes from 4 in the observed network to 1 in the reconstructed network. Similarly, the longest link of the observed network is located between camps 0 and 4, but a longer link is created between camps 0 and 3 in the reconstructed network. This shows that important metrics of reconstructed networks cannot be trusted to represent real latent interactions. To improve the accuracy of the modeled reconstructed networks, I tried removing their weakest links, but could not find a threshold that removed the indirect links without removing some of the weak direct ones.

Therefore, as it is difficult to distinguish between the stylistic traces of direct vs. indirect transmission, a few important general characteristics of a real social network cannot be assessed from the archaeological assemblages it produces. This is a very important, because it shows that archaeologists need to proceed with caution when analyzing reconstructed networks to infer changes in social organization (e.g., Mills et al., 2013). For the present research, this result meant that I could not use the networks reconstructed through Magdalenian art similarities to test the hypotheses presented in

Chapter 1. To bypass this problem, I used the agent-based model as a tool to estimate the characteristics of the Magdalenian social interactions that created the studied art objects. I explore this method further in Chapter 6. In the next section of this chapter, I put aside the networks reconstructed through the campers' traits, and rather focus on the impact of topography and environment on the modeled observed networks only.

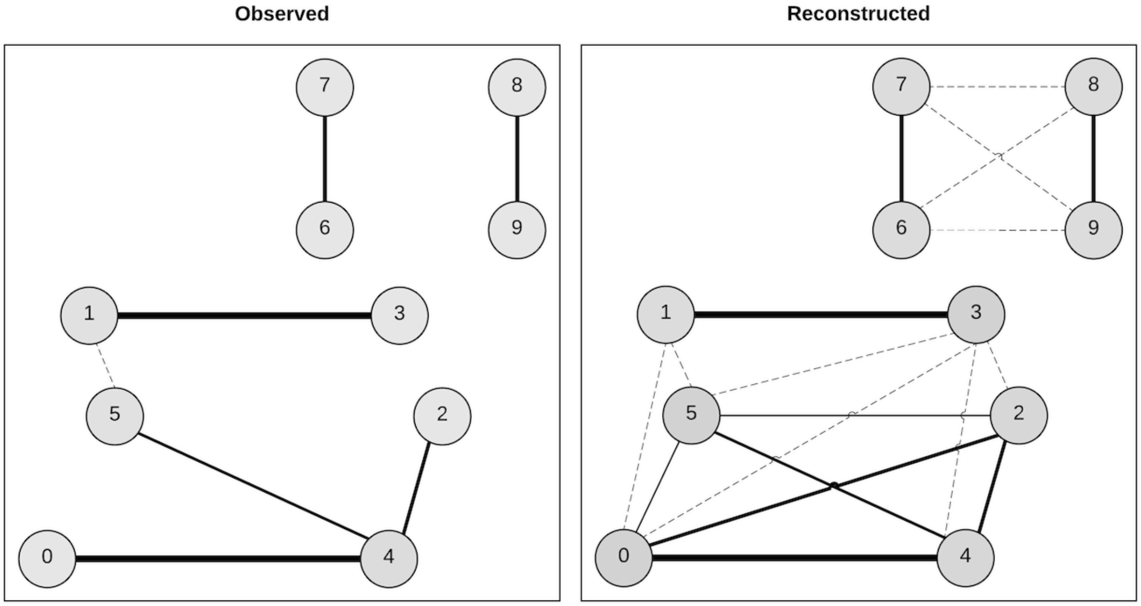


Figure 4.13. Comparing the observed network and its reconstructed network created from a simulation using 25% conformism transmission. The nodes represent camps. The width of the links reflects the strength of the alliances between camps. Dashed links are the weakest.

Analyses of the Model's Outputs – Impact of Context on Observed Networks

I first present the results of the simulations done with socially-driven alliances, as these runs allow evaluating the impact of geography on networks, independently from resources. I then present the results of the simulations done with resource-driven alliances to show the impact of biome and resource levels on the networks. The network metrics discussed are the same as the ones presented above, namely the number of used alliances, graph density, shortest path, the length of the longest alliance, the length of the strongest alliance, and the Pearson correlation coefficient between alliances' length and strength.

Socially-Driven Alliances. From these simulations, I did not expect to find any significant differences between the networks created in the different regions and time periods, given that camps decided at random when and where to send their agents. However, the results show that Cantabrian networks differ in structure and extent from the ones created in the Dordogne and in the control No GIS (Fig. 4.14). These results suggest that Cantabrian topography and site placement affect both structure and extent of the created networks.

Network Structure Metrics. Figure 4.14 shows that, despite the similar probability of agent deployment in both regions (3/10,000 at each tick), the number of used alliances is significantly lower in Cantabria than in the Dordogne. This suggests that the Cantabrian topography slowed the mobility of agents enough to increase the interval between deployments – as camps cannot send agents when all agents are already out – and thus the overall number of alliances created. The graph density is not statistically different between the three regions, which suggests that the *proportion* of connections between sites is not affected by topography. However, shortest path values are significantly lower in Cantabrian than in the other two regions, suggesting that rugged topography leads to the creation of networks that are more directly connected.

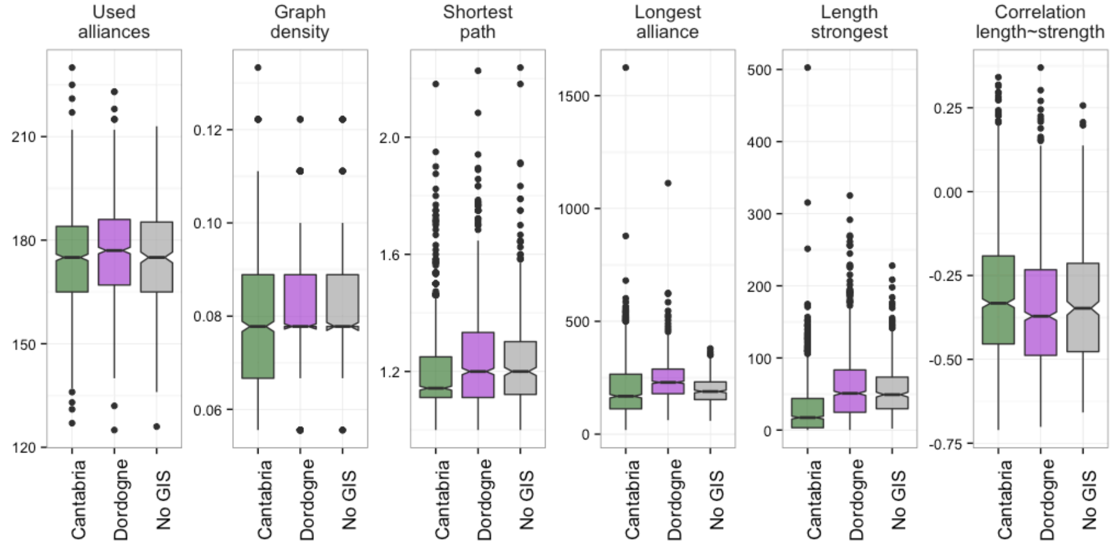


Figure 4.14. Social network metrics for socially-driven alliances.

Network Extent Metrics. The geographical extent of Cantabrian networks is also significantly lower than the extent of networks created in the Dordogne and the control, as seen in the lengths of the longest and the strongest alliances (Fig. 4.14). This may be explained by the Cantabrian site placement; as the sites are aligned on the coast, agents have more chances to stop by the neighboring camps they encounter while walking towards a farther one than in the Dordogne. As a reminder, agents change their course if their path to one site brings them close to another unvisited site. Therefore, the Cantabrian site placement is not conducive to creating alliances with far-away camps. This is less the case in the Dordogne and in the control, where the sites are spread out more uniformly on the landscape, making such accidental encounters rarer. As Cantabrian sites create more connections with the close neighbors they walk by accidentally, the chances that remote sites will be connected decreases. While this scenario should lead to a strong negative Pearson *r*, the high cost of traveling within the Cantabrian mountain range actually weakens the correlation between alliances' length and strength; as it increases the likelihood of finding a few very long and relatively strong alliances.

Figure 4.14 also shows that the topography of the Dordogne leads to the creation of longer alliances than the control, which can be explained by the fact that walking between remote sites will always be faster on a flat surface than on gentle rolling hills. This affects long-distance alliances more than local ones, as reflected in the non-significantly different length of the strongest alliances.

In summary, the results of the simulations done with socially-driven alliances show that topography affects the structure and the extent of social networks, independently of subsistence resources. The placement of sites on the landscape determines the possible type of networks that groups can build when they do not choose their allies based on resource type and abundance. The following section shows how this pattern changes when the need to find complementary resources comes into play.

Resource-Driven Alliances.

General Impacts of Resources on Networks. To evaluate the impact of resource on networks independent of topography, I first compared the characteristics of the networks made of resource-driven alliances to the characteristics of networks made of socially-driven alliances (Fig. 4.15).

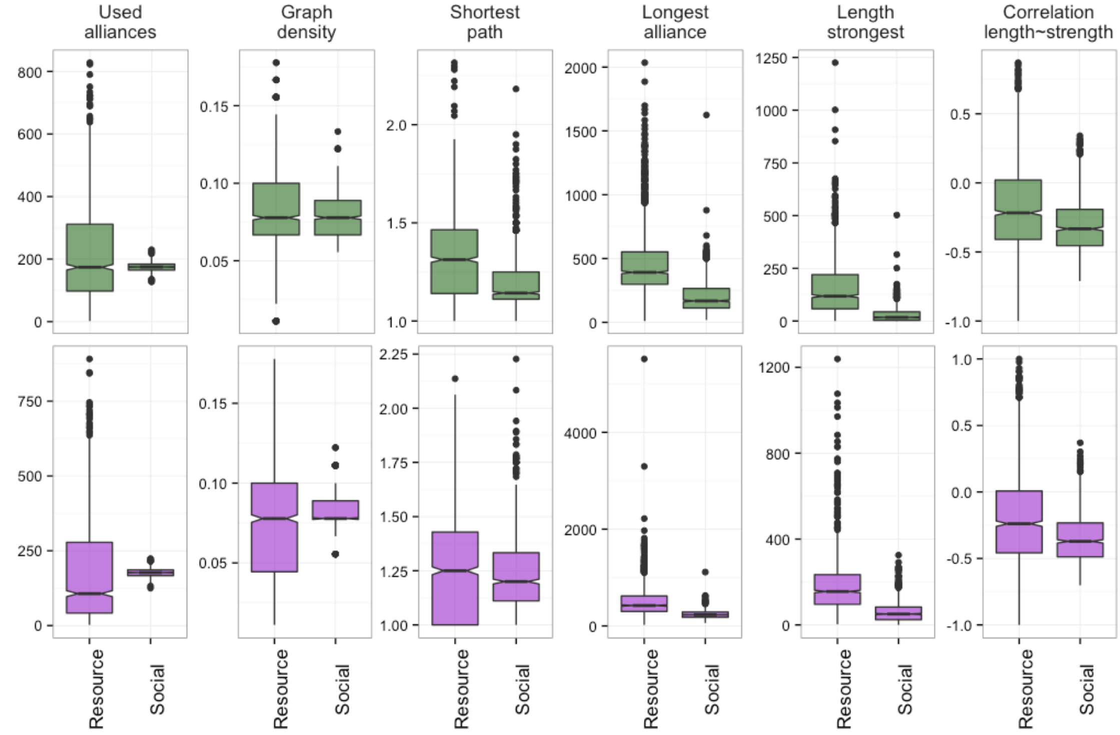


Figure 4.15. Comparison of the social network metrics of resource-driven and socially-driven alliances in Cantabria (green) and the Dordogne (purple).

The number of used alliances and the graph density of both network types do not differ statistically in Cantabria, but the number of resource-driven alliances is significantly lower than socially-driven alliances in the Dordogne. This could be the result of the higher effective temperature in the Dordogne, which provides a generally higher level of resources, and thus reduce the need to create safety net alliances. In both regions, the mean shortest path is significantly higher for networks made of resource-driven alliances than socially-driven alliances. This is not surprising, as inter-sites resource-driven alliances can only be made between sites that are located in different environments. This reduces the range of possible alliances, and thus creates less homogeneous networks than when the alliances are socially-driven.

The changes in extent metrics follow expectations. As groups look for allies living in different environment, they expand their search beyond the extent of the biome they occupy, and create alliances with remote camps more often. This explains the significantly higher longest and strongest alliances, and reduced strength of the negative correlation between length and strength of alliances.

Cantabria: Network Metrics. To evaluate the effect of environmental *change* on network characteristics, I compared the temporal network metrics to the environmental metrics calculated for each region and period. The environmental metrics considered were biome diversity and fragmentation (Tables 3.10 and 3.11 in Chapter 3), as well as mean available resource (Fig. 4.16).

Within Cantabria, environmental change impacts network structure more strongly than extent, as seen in the range of boxplot notches in Figure 4.16. While the median values of longest alliance, length of strongest alliance, and correlation between length and strength change over time, their temporal differences are not statistically significant. However, the number of used alliances and graph density vary significantly over time, especially during the Upper Magdalenian A, where both metrics are significantly higher than during other periods, suggesting the creation of a lot of inter-camp alliances that were moderately used. The graph density of the Middle Magdalenian and the Upper Magdalenian B are significantly lower than during other periods. Combined to the relatively high number of used alliances during the Middle Magdalenian, this suggests that camps modeled in that cold period were linked by only a few alliances that were intensively used. The Upper Magdalenian B, with its generally higher resource level would have reduced the need to create and rely on already created alliances, thus

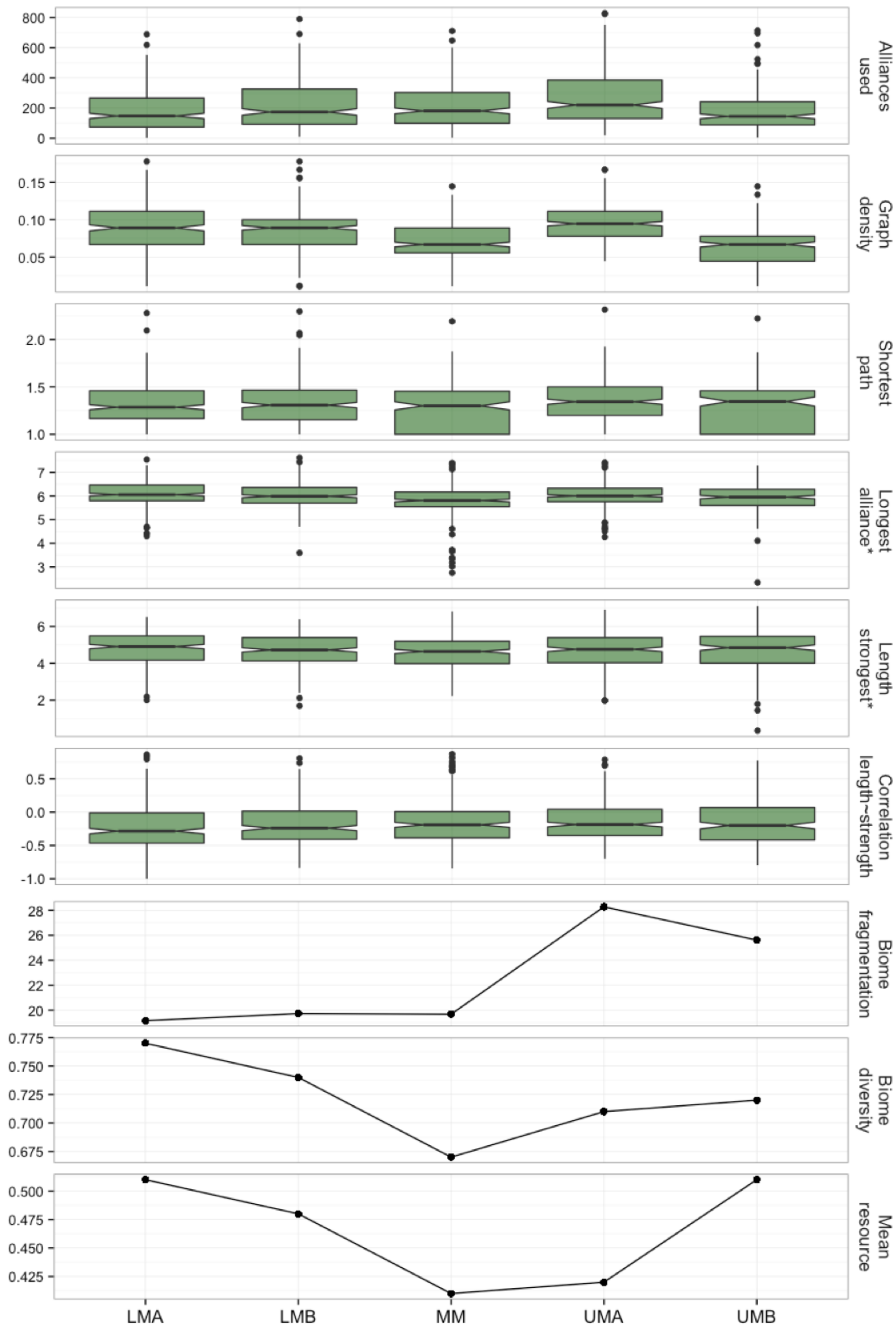


*Figure 4.16. Temporal change of the discussed socio-environmental and social network metrics in Cantabria. *Logged data*

explaining the reduced graph density and number of used alliances. Shortest path varies slightly over time, but none of those differences are statistically significant, which suggests that the general structure of the networks was efficient enough to remain constant – or that another configuration was simply impossible due to the restrictions imposed by the geography, as discussed above. None of the network metrics vary linearly with the environmental variables, which shows that not one of these are solely responsible for the changes that occurred in the networks' structure.

Dordogne: Network Metrics. Environmental variables have a stronger impact on network extent in the Dordogne than in Cantabria (Fig. 4.17), as most of the temporal variations in the length of longest alliance and the correlation between length and strength of alliances are statistically significant. It is important to note that the Pearson r between length and strength of alliances is significantly higher during the Middle Magdalenian than during the warmer Lower Magdalenian and Upper Magdalenian A, which suggests that long-distance alliances were more often relied upon during that cold period than during the warmer periods – apart from the Upper Magdalenian B.

The networks' structure varies also significantly over time. Similarly to Cantabria, the number of used alliances and site connections are significantly lower during the highly productive and diverse Upper Magdalenian B. The low shortest path of that same period suggests that most of the connections created then were direct inter-camp links. In contrast, the low graph density, and relatively high number of used alliances and shortest path of the Middle Magdalenian suggests that a few highly-connected camps with high resources might have been heavily relied upon to provide help to several camps with low resources. Here again, none of the network metrics correlate linearly with one of the

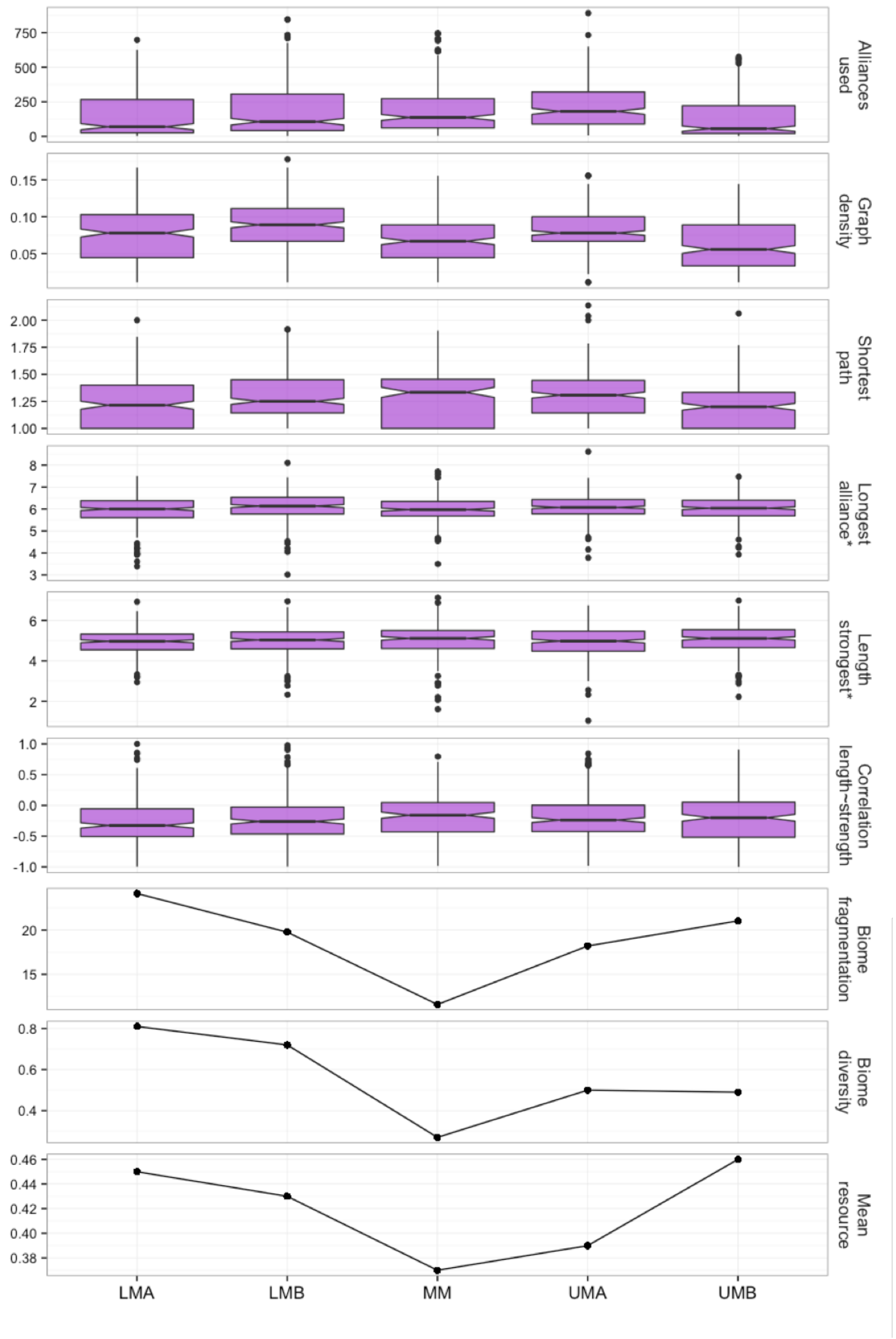


Figure 4.17. Temporal change of the discussed socio-environmental and social network variables in the Dordogne.

environmental variables, suggesting that the social changes are due to a combination of environmental factors rather than any specific one.

Discussion

This chapter demonstrates the advantages of using an agent-based model as a heuristic tool to test assumptions and simplify complex problems (see discussion in Costopoulos, 2010; Lake, 2010; White, 2012). In particular, it provides two important contributions to the archaeological discipline.

First, it demonstrates how cultural transmission muddles what archaeologists can infer about social interactions from archaeological palimpsests. The thought of the social interaction school is that the level of similarity between artifacts is a good indicator of the social distance between the artifacts' makers (Barton, 1997); however, this model shows that the reality is not as simple, as important differences are found between the characteristics of social networks reconstructed through archaeology and the characteristics of their latent networks – especially regarding the networks' density and extent. This has important ramifications for the study of archaeological social networks, as it implies that network changes documented through artifacts may not be accurate representations of the invisible behavioral changes that actually took place. Further comparisons of network metrics need to be undertaken to identify which ones can be used to estimate reality, and how.

Second, the analysis of the general model outputs provides simplified information on the relationship between topography, environment and social behavior. The results suggest that, in a simulated environment, topography impacts mobility, which in turns influences the possible alliances that camps can form. Moreover, the results show that environmental variables such as resource level and biome distribution affect some of the characteristics of social networks, but that those relationships are not linear.

As this dataset comes from modeled simulations, it does not represent the complexity of the real interactions that took place during the Magdalenian. Therefore, I cannot use the results discussed above to test the hypotheses presented in Chapter 1. Instead, in the next chapter, I reconstruct Magdalenian social networks through a statistical study of art similarities. In Chapter 6, I combine the results of these empirically-reconstructed networks to the results of the agent-based model to estimate the characteristics of the latent Magdalenian social networks, which I use to test the hypotheses.

CHAPTER 5. PORTABLE ART ANALYSIS AND SOCIAL NETWORKS

Introduction

In this chapter, I reconstruct the Magdalenian social networks visible through a stylistic analysis of portable art representations. I begin by briefly discussing the notion of style as applied in the study, and explaining why I used portable art objects to get at social networks. I then describe the methods used for the formal analysis of Magdalenian portable art representations. I close this chapter with a short description of the social networks reconstructed through this study. I do not analyze the characteristics of those networks in this chapter, as they do not represent accurately the latent social networks that created them, as discussed in Chapter 4. Instead, I carry the results over to Chapter 6, where they are combined to the results of the agent-based model, and analyzed.

The archaeological practice of reconstructing past social networks through material culture is still relatively new (Brughmans, 2010), it is therefore lacking established procedures. In fact, there is a growing consensus that formal Social Network Analysis (SNA) tools might not be applicable to all types of archaeological data (Gjesfjeld, 2015; Leidwanger et al., 2014; Mills et al., 2013), and that some of those formal tools should be adapted to the specific needs of archaeological assemblages (Brughmans, 2010). Reconstructing prehistoric hunter-gatherer social networks offers additional challenges due to the sparse nature of the data and the mobility of the agents producing it (Gjesfjeld, 2015). In the absence of defined guidelines, I combined the methods already used in Paleolithic archaeology (Bahn, 1982; Conkey, 1978, 1980; Sauvet et al., 2008a, 2008b; Pigeaud, 2007; Rivero and Sauvet, 2014; Schwendler, 2004, 2012) to the methods used to study cultural transmission through pottery similarities (Braun and Plog, 1982; Mills et al., 2013; Plog, 1978; Rautman, 1993). I thus relied on stylistic similarities to infer social contact.

Formal Definition of Style. Style has been classified as ‘adjunct’ or ‘isochrestic’ and as ‘active’ or ‘passive’ (Sackett, 1982). Depending on whose definition one follows, style can be related to choices embedded in the technology (Sackett, 1982), it can be a cognitive process (Hodder in Hegmon, 1992) or it can communicate information, be it collective or individual (Wiessner, 1983; Wobst, 1977). Style is found in the controlled variation of certain formal ‘symbols’ that refer to certain information (Conkey and Redman, 1978, p.66), which can be ‘emblemic’ or ‘assertive’ (Wiessner, 1983). Emblemic style refers to the composition and *assemblage* of formal attributes that provide information about the maker’s affiliation to a certain group, be it politic, religious, or symbolic (Thomas et al., 2009); it demonstrates the presence of distinct groups, but does not show how much interaction there is between them. On the other hand, assertive style refers to the individual’s personality, and can be embedded into emblemic style through conscious variations on a broad theme (Thomas et al., 2009). Assertive style can be influenced by social contacts (Wiessner, 1983, p.258), making it a good indicator of the level of interactions between individuals. While emblemic style is better studied by comparing large samples of objects, assertive style should be looked at primarily *within* group assemblages, as individual modifications should be seen in contrast to the group’s norm. Therefore, as the identification of assertive style requires in-depth studies of singular assemblages, which is not possible here due to the small size of most Magdalenian assemblages, I rely mostly on emblemic style for this research.

For this research, I calculate similarities in the presence of formal attributes to identify close contact between artists, and thus reconstruct broad social networks. I define style as variability in formal attributes created by the maker based on cultural conventions that transmit information about identity (Conkey and Redman, 1978; Sackett, 1977; Wiessner, 1983). In this chapter, the term 'cultural transmission' refers to the process by which information is passed from one individual to another. It does not necessitate formal teaching, but implies the presence of learning (Mesoudi, 2008).

Why Portable Art? Ethnographic research tells us that style is present in regularly made and highly visible objects with complex production sequences (Wiessner, 1983). While most archaeologists have looked at this topic through pottery styles (e.g., Braun and Plog, 1982; Friedrich, 1970; Hegmon, 1992; Plog, 1978; Rice, 1996; Van Keuren, 2001, 2006), portable art objects and ornaments also comply with these requirements. In the absence of Magdalenian pottery, one can look at style in lithics – following Wiessner's study of the San arrow points (1983) – or in symbolic objects and representations such as ornaments, and parietal or portable art. Some researchers agree that lithics are not the best medium to study cultural transmission because their utilitarian purpose influences the steps of their manufacture in ways that leave small place for individual stylistic variations. They also agree that symbolic objects are more likely to carry stylistic markers reflective of cultural affinity between social groups (Barton et al., 1994; Barton, 1997; Conkey and Redman, 1978; Newell, 1990). Finally, ethnographic research shows that symbolic objects are often exchanged to solidify alliances (Wiessner, 1982), making portable art objects a good medium to study style and reconstruct social interactions.

The link between non-utilitarian objects and hunter-gatherers' environment is inferred from different sources. Research has shown that alliance networks are an adaptive way to deal with fluctuating climate (Barton et al., 1994; Whallon, 2006; Wiessner, 1982). Rituals and other sacred behaviors involving the use of non-utilitarian objects have been shown to reduce social stress (Rappaport, 1971), and have been interpreted as ways to transmit information (Conkey and Redman, 1978). Research has shown that processes promoting group survival usually lead to the formation of emblemic style and the appearance of aggregation sites (Conkey, 1980; McDonald in Hegmon, 1992, p.523); however, it has also shown that art stylistic diversity should not be used to *identify* aggregation sites (Conkey, 1992). Studies of prehistoric portable art objects have led to the hypothesis that these objects were manufactured regularly and held important information (Almagro-Basch, 1976; Apellaniz, 1990; Arias Cabal and Ontañón Peredo, 2004; Farbstein, 2011; Mazo et al., 2008). In this light, Magdalenian portable art has been studied to get at artistic conventions (e.g., Pigeaud, 2007; Rivero Vila, 2010; Rivero and Sauvet, 2014) and general characteristics of social networks (Bahn, 1982; Schwendler, 2004, 2012). In fact, such research has shown the variations in the density and geographical distribution of Magdalenian portable art objects and ornaments, which suggest temporal and geographical variation in the communication of information. Here, I assume that studying this variation provides information on the temporal changes in cultural transmission, which can be combined to the results of the agent-based model to estimate the changes alliances formed during the climatically unstable Late Glacial.

Design Analysis

A flowchart summarizing the important steps detailed below can be found in Appendix I.

Data Collection. To analyze the style of portable art representations, I built upon previous studies and collected design information on all dated portable art objects found in Magdalenian sites, combining my own first-hand study with published images of objects. I focused on recognizable representations of bovids, caprids, cervids, and equids, to work with designs consistently found across the largest number of assemblages. Only drawn or photographed representations were included to document the presence/absence of design elements. I relied on my own tracings of the Cantabrian artifacts, and on published images of the Dordogne artifacts. For data from published sources, I used both recent available tracings of representations and photographs of the artifacts, as tracings alone have been shown to include important biases and errors (Tosello, 2003). This first sample contained 337 artifacts from assemblages recovered from 42 sites.

I noted the radiocarbon date associated with each object. In the absence of dates, I relied on the correspondence to one of the 3 major Magdalenian periods – i.e., Lower, Middle, and Upper – as interpreted by the excavator. Due to the coarseness of the classification, this assemblage was separated in 3 rather than the 5 subdivisions used in Chapters 3 and 4. I evaluated the reliability of all dates, and kept only the dates with margin of error $\leq$ 250 years. I calibrated these dates with the *BChron* package in R, using the IntCal13 calibration curve, and used the calibrated 95% confidence interval to classify each object in its corresponding subperiod. Objects with dates overlapping two periods equally were attributed to both. I confirmed the accuracy of my classification by comparing it to previous archaeologists' attributions. I then removed all objects without a clear subperiod attribution, which created the final sample of 302 artifacts. It is important to note that no portable art animalistic representations date to the Lower Magdalenian of the Dordogne (see Table 5.1), which is problematic when trying to document the temporal changes in social interactions in the region. I discuss this further below.

Table 5.1. Sample sizes per country and Magdalenian subperiod. The main number represents the number of representations (not objects) per region and period. The number in parentheses corresponds to the number of sites where those representations were found.

	Lower Magdalenian	**Middle Magdalenian**	**Upper Magdalenian**
Cantabria	50 (10)	36 (6)	41 (12)
Dordogne	0 (0)	26 (4)	247 (16)

Binary Data. For each representation, I collected presence/absence data of design elements. I based the list of considered elements on previous research (e.g., Pigeaud, 2007; Rivero and Sauvet, 2014), as well as my personal preliminary evaluation of the designs (Table 5.2). I recorded the design elements as descriptions (e.g., *Double linear mane* or *Single hatched mane*, see Fig. 5.1), also called *nominal* data. This dataset can be found in Appendix J. However, as nominal data cannot be studied with most standard statistical tests, I transformed the nominal data into binary presence/absence data. Information missing due to breakage was entered as *N/A* rather than absent, and the presence *and* absence of an element were considered separate attributes. For example, for an engraved deer without antlers, the element *Antlers Absent* had a value of 1, whereas *Antlers Simple* and *Antlers Complex* had the value 0. This data format helped distinguish between the representations that were broken and the ones where the artist intentionally failed to represent specific parts of the animal.

Table 5.2. List of design elements recorded for each representation.

Attribute	Value	Code	Taxon
Antlers	Absent	AN	Ce
	Complex	AC	Ce
	Simple	AS	Ce
Body coat	Absent	BCN	B, Ca, Ce, E
	Present	BCY	B, Ca, Ce, E
Beard	Absent	BN	B, Ca
	Present	BY	B, Ca
Body muscle	Absent	BMN	B, Ca, Ce, E
	Present	BMY	B, Ca, Ce, E
Ear	Absent	EaA	B, Ca, Ce, E
	Complex	EaC	B, Ca, Ce, E
	Simple	EaS	B, Ca, Ce, E
Eye	Absent	EN	B, Ca, Ce, E
	Almond	EA	B, Ca, Ce, E
	Dot	EDo	B, Ca, Ce, E
	Double	ED	B, Ca, Ce, E
	Round	ER	B, Ca, Ce, E
	Schematic	ES	B, Ca, Ce, E
Eye arch	Absent	EAN	B, Ca, Ce, E
	Present	EAY	B, Ca, Ce, E
Facial coat	Absent	FCN	B, Ca, Ce, E
	Present	FCY	B, Ca, Ce, E
Facial muscles	Absent	FMN	B, Ca, Ce, E
	Present	FMY	B, Ca, Ce, E
Forelock	Absent	FN	B, E
	Hatched	FH	B
	Hatched lines	FHL	B
	Present	FY	E
Horn	1	H1	B
	2	H2	B
	1-Complex	H1C	Ca
	2-Complex	H2C	Ca
	1-Simple	H1S	Ca
	2-Simple	H2S	Ca
	Absent	HoN	Ca
	Double	HD	B
	Simple	HS	B
Hump	Absent	HN	B
	Hatched	HH	B
	Lines	HHL	B
Hump limit	Absent	HLN	B
	Hatched	HLH	B
	Lines	HLL	B
Legs	Anatomical	LeA	B, Ca, Ce, E
	Pointy	LeP	B, Ca, Ce, E
	Square	LeS	B, Ca, Ce, E
	Unfinished	LeU	B, Ca, Ce, E
Lips	Absent	LN	B, Ca, Ce, E
	Complex	LC	B, Ca, Ce, E
	Simple	LS	B, Ca, Ce, E
Mane	Absent	MI	E
	Double	MD	E
	Hatching	MH	E
	Linear	ML	E
	Mixed	MM	E
	Single	MS	E
Nose	Absent	NN	B, Ca, Ce, E
	Complex	NC	B, Ca, Ce, E
	Simple	NS	B, Ca, Ce, E
Outline	Hatching	OH	B, Ca, Ce, E
	Mixed	OMx	B, Ca, Ce, E
	Multiple	OM	B, Ca, Ce, E
	Single	OS	B, Ca, Ce, E
Tail	Absent	TN	B, Ca, Ce
	Double	TD	E
	Multiple	TM	E
	Present	TY	B, Ca, Ce
	Single	TS	E
Technique	Bas relief	TBR	B, Ca, Ce, E
	Champlevé	TCL	B, Ca, Ce, E
	Contour découpé	TCD	B, Ca, Ce, E
	Engraving	TE	B, Ca, Ce, E
	Sculpting	TeS	B, Ca, Ce, E
Traits	Anatomical Complex	TAC	B, Ca, Ce, E
	Anatomical Simple	TAS	B, Ca, Ce, E
	Angular	TA	B, Ca, Ce, E
	Caricatural	TC	B, Ca, Ce, E
	Rounded	TR	B, Ca, Ce, E

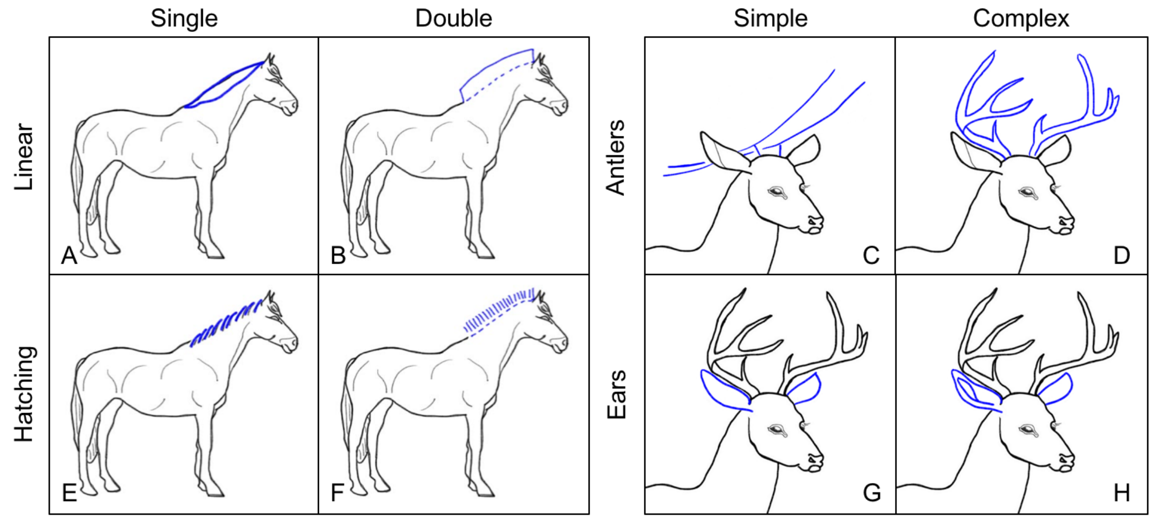


Figure 5.1. Example of design elements recorded for equid and cervid representations. The blue parts show the possible variations: A. Single linear mane, B. Double linear mane, C. Simple antlers, D. Complex antlers, E. Single hatching mane, F. Double hatching mane, G. Simple ears, and H. Complex ears.

Dataset Formatting. Due to breakage and to artist choices, the representations varied in their completeness. To capture the variability in the assemblage, while reducing the level of error in the statistical results, I separated the data in 2 categories: 1. Head: includes the face and the mane, but not the neck, and 2. Body: includes the neck, legs and tail, but not the mane. Representations with elements from both categories were analyzed in both.

Analyzing these 2 categories separately had the advantage of capturing the stylistic similarities of broken and complete representations, as representations that were restricted to bodies due to breakage were compared to all the bodies from broken and complete representations. Moreover, this formatting produced relatively large sample datasets for both categories – which would not have been the case if I had compared only the broken bodies with one another.

Statistical Analyses. To produce statistically significant results, I analyzed each animal type separately (see discussion in Plog, 1978). I first cleaned the dataset by computing the correlations between all pairs of design elements to identify and remove highly correlated ones. For example, this step showed that the element *Mixed Outlines* (OMx) correlated strongly with the presence of facial and body hair – because it was present when the general outline was linear but the body hair was depicted as hatching. I removed this design element, and re-classified the outlines of all representations into *line* or *hatching* elements, based on their main characteristic.

I explored the uses of different statistical tools to group similar representations. I used Correspondence Analysis (CA) to define general style clusters because this method is increasingly popular in stylistic studies (Rivero and Sauvet, 2014). However, I found that the results of this analysis were not useful for this research, because it created clusters that were heavily influenced by the rarest design elements, which did not help identifying the similarity level between representations using more common elements. Therefore, the results of the CA are not presented here. Instead, I relied on a combination of Gower dissimilarity index, Ward clustering, and *k*-means clustering.

Gower Dissimilarity Index. To quantify the stylistic similarities of pairs of representations, I calculated their Gower dissimilarity index, which is a standardized value ranging from 0 (identical) to 1 (completely different). For a pair of representations, it calculates the number of similar variables, divides it by the total number of variables, and subtracts the result from 1. In this case, both presence and absence of each design element are independent variables. For this research, all attributes were weighted equally to limit biases.

As the Gower dissimilarity indices vary based on the number of variables there is no clear threshold under which two representations can be deemed similar or different. Moreover, as there were more design elements in head representations than body-representations, I used Ward and *k*-means clustering methods to define the threshold that best captured similarity.

Ward Clustering. Ward is a hierarchical clustering method that minimizes the within group sum of squares – the distance of each point to the centroid of each created cluster. This method is often used in archaeology and produces relatively satisfying results (Aldenderfer, 1982). However, it requires making a subjective decision as to where one should draw the line to distinguish between clusters of similar representations (see Fig. 5.2). Therefore, to reduce the level of subjectivity in identifying clusters of similar representations, I complemented this method with *k*-means clustering.

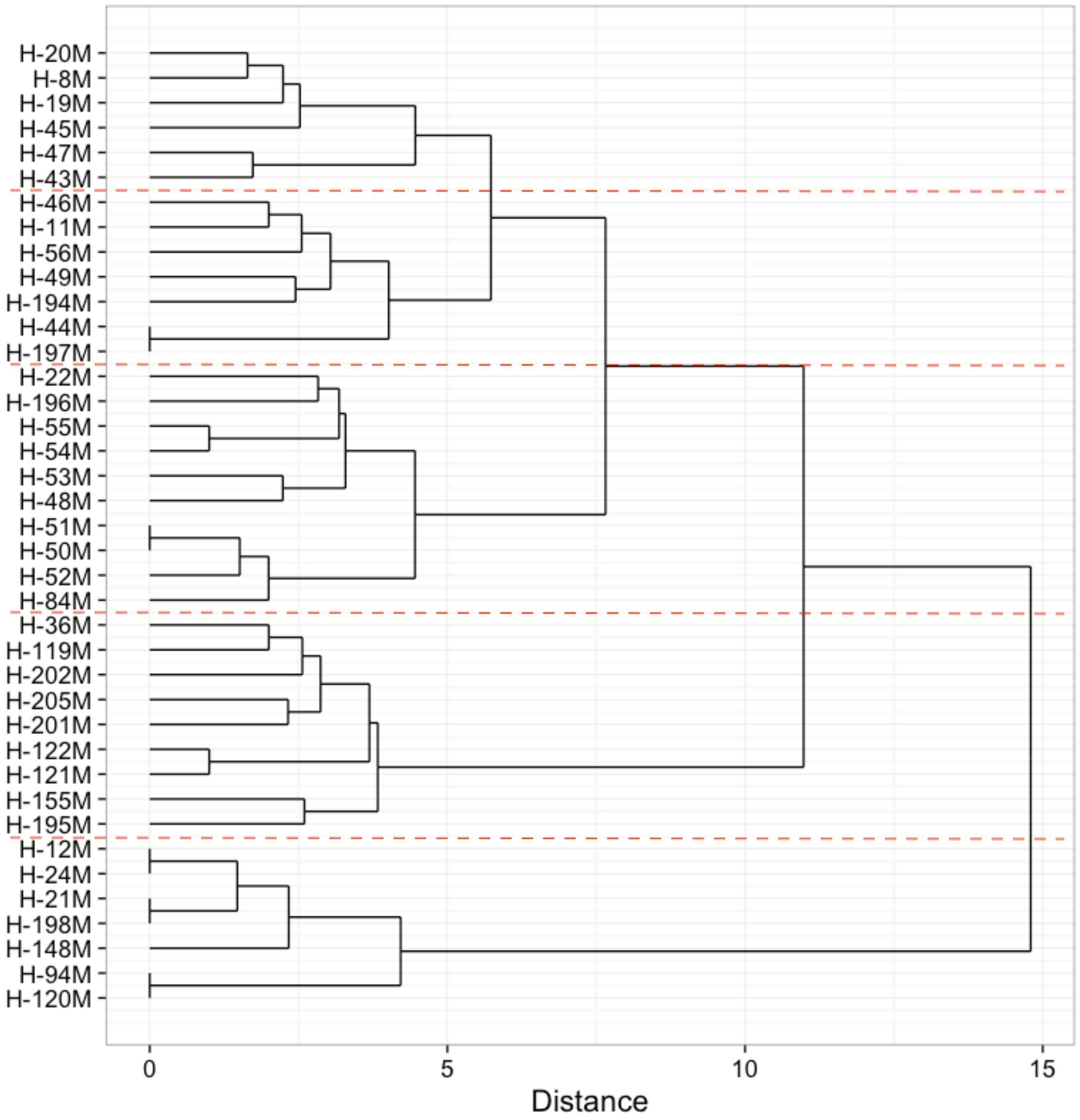


Figure 5.2. Ward hierarchical clusters identified for Middle Magdalenian equid heads. The red lines represent arbitrary clustering at distance < 5.

k-Means Clustering. *k*-means clustering differs from Ward in that it is a divisive and non-hierarchical method. It starts by creating one group and computing the within- and between-groups sum of squared distance (SSE). It then moves points that are closer together to separate groups, and recalculates the ESS. The goal of this method is to minimize the SSE while producing a given number of clusters. However, as it requires the user to define the number of clusters to compute, this method is not appropriate to find the number of clusters that best characterizes a population. To circumvent this problem, I iterated through all possibilities to find the number that best explained the data. I produced a scree plot showing the relationship between cluster numbers and their resulting within group sum of squares. I looked for elbows in the line to identify the cluster number that best reduced this value. In the example provided in Figure 5.3, 5 clusters reduce the SSE of Middle Magdalenian equid heads considerably.

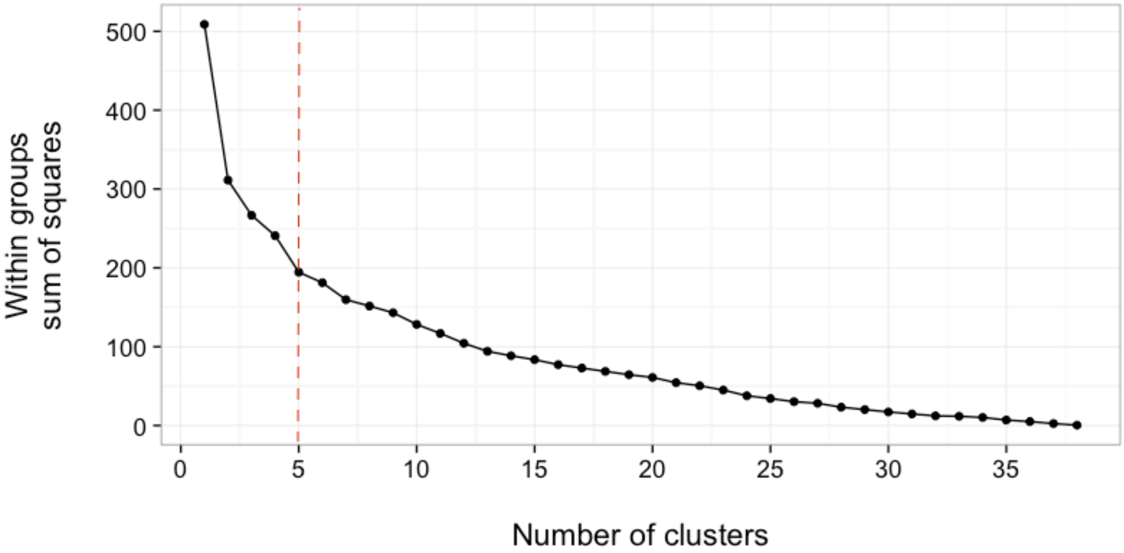


Figure 5.3. k-means plot of the within sum of squares created for each possible cluster number. The red line shows the chosen number of cluster to best reduce SSE.

I then separated the representations by the chosen number of clusters (Table 5.3), and compared their pattern to the clusters identified by Ward.

Table 5.3. Middle Magdalenian equid head clusters created using k-means with 5 clusters. For each cluster, the representations in bold, italic, and underlined are also found together in the ward hierarchical clusters at distance < 5 (Fig. 5.2).

Cluster n.	Representations
1	H-11M, **H-119M**, **H-121M**, **H-122M**, H-194M, **H-195M**, *H-196M*, **H-205M**, **H-36M**, *H-48M*, H-49M, *H-53M*, *H-54M*, *H-55M*, *H-22M*
2	H-197H, H-198M, H-50M, H-155M
3	*H-120M*, *H-21M*, *H-24M*, **H-19M**, **H-20M**
4	H-202M, **H-52M**, **H-84M**, H-94M
5	H-201M, H-43M, **H-44M**, H-45M, **H-46M**, H-47M, H-51M, **H-56M**, *H-148M*, *H-12M*, H-8M

Combining Methods. Combining the results of Ward and *k*-means allowed identifying sets of representations that were statistically similar using both methods. I narrowed down the Gower dissimilarity indices of these representations to identify which index best distinguished between statistically similar and dissimilar representations. I compared images of a few of these representations to fine-tune the threshold, which were defined at < 0.2 for heads and < 0.15 for bodies. Using these thresholds, I transformed the Gower indices into 1 (similar) and 0 (different). I grouped the similar representation pairs per site, which reduced the representation matrix to a site matrix providing the sum of similar representations by site pairs. I placed those onto maps, as links between sites sharing similar representations. The strength of cultural transmission between sites is represented as the sum of similar representation pairs between the two.

Spatial Analysis of Artistic Similarities. For each period and region, sites sharing similar representations were linked on a topographical map, following previously used methods (see Bahn, 1982; Schwendler, 2004, 2012). However, my method differed in that I used least-cost paths between sites to show the impact of topography on distances.

The maps were created on an Azimuthal projection of Europe in GRASS, at a 90m resolution. I used the GRASS *r.walk* tool to calculate the anisotropic cumulative cost of walking between each pair of connected sites. I used the default walking cost values (Aitken, 1977; Langmuir, 1984) shown below, with a friction map with value 0, and using the Knight's move, which takes into consideration grid cells that are one cell removed from the center (slower but more accurate). *r.walk* uses the well-known Tobler hiking function, based on the following equation to calculate the cost in seconds to move from one site to another.

$$T = 0.72 \cdot \Delta_S + 6 \cdot \Delta_{HU} + 1.9998 \cdot \Delta_{HMD} - 1.9998 \cdot \Delta_{HSD}$$

where T stands for the cost of movement in seconds, Δ_S is the horizontal distance covered in meters, and Δ_H is the altitude difference in meters affected by slope (Δ_{HMD} = [slope > 5° and < 12°], and Δ_{HSD} = [slope > 12°]). This step was followed by *r.drain* to identify the path with the lowest T value. For each inter-site paths, I calculated the distance traveled in km.

To evaluate the networks in their social and environmental contexts, I created buffers of 2 and 6 hours of travel-time around the connected sites. For each site, the 2h buffer represents its daily foraging radius, whereas the white buffer represents its possible minimal band territory – based on Whallon's (2006) estimates of Magdalenian populations in Germany. Here, the sites with overlapping foraging radii were assumed to represent the archaeological results of the seasonal mobility of one band, as well as the palimpsest of multiple generations of their descendants. I used the clear separations in the 2h buffers to separate the 'territories' of different minimal groups and compare their resources. In GRASS, I used each independent buffer to clip the relevant biome distribution map (presented in Chapter 3). I then used χ^2 tests on the relative coverage of the biomes to determine if the environments of linked territories were significantly different. As χ^2 uses integers and provides inaccurate results when dealing with very large values, I used it on rounded up percentage coverage of each biome in each territory. Moreover, I focused only on the biomes that were present in at least one of the two compared territories. The results of the χ^2 tests are presented within the figures of connected biomes. Statistically significant differences between connected territories are represented as uninterrupted links between the two, whereas the non-significant differences are shown as hatched links. I used the results of this section to test the hypothesis that networks were created between groups living in different environments to safeguard against environmental insecurities. The results show that, for the most part, linked territories within one region (Spain OR France) were significantly different. This suggests that some of the networks may have been used to cope with the resource fluctuations brought by the Late Glacial.

Below, I present the results by period and region. In all figures, the sites with similar representations are presented in red, whereas the sites with art representations that were not similar to any other are in yellow. The width of the lines connecting sites is scaled to represent the number of similar representations between them. The white buffer area represents the minimal band territory buffer, whereas the grey area is the foraging radius around a site. All topographical networks are accompanied by a non-spatial network, which allows for easier observation of the connections between sites.

Lower Magdalenian.

Cantabria (Site n = 10, Representation n = 50). Given the lack of portable art objects dated to the Lower Magdalenian in the Dordogne, only Cantabria gives us insights on the social behavior of that period. Figure 5.4 shows the presence of a few site clusters with overlapping foraging radii, such as Altamira (*Al*), El Juyo (*EJ*), El Pendo (*EP*), and El Castillo (*EC*). The strongest link is found between Altamira and El Castillo, which are also the two sites with the highest degree centrality measures of the network. This is interesting because these two sites have been interpreted as important symbolic centers and aggregation sites (Cabrera Valdés, 1984; Conkey, 1980). The results of this research thus suggest that, as important centers, they may have played a pivotal role for inter-group communication and cultural transmission. El Castillo shares artistic conventions with the most sites (n = 6), which could be explained, in part, by its long record of occupation (Straus, 1992), which provided more opportunities to create networks with other sites than sites with shorter occupation spans. It is surprising that both El Cierro (*ECi*) and Güelga (*Gu*) share networks with the central cluster but not with one another, but radiocarbon dates for their Lower Magdalenian layers show that their occupations did not overlap – calibrated at 95.4% CI, El Cierro F dates to 18,880-18,560 cal BP (Álvarez-Fernández et al., 2016), and Güelga Zone A 3C to 17,491-16,836 cal BP (Ménendez Fernández et al., 2000, 2005, 2007).

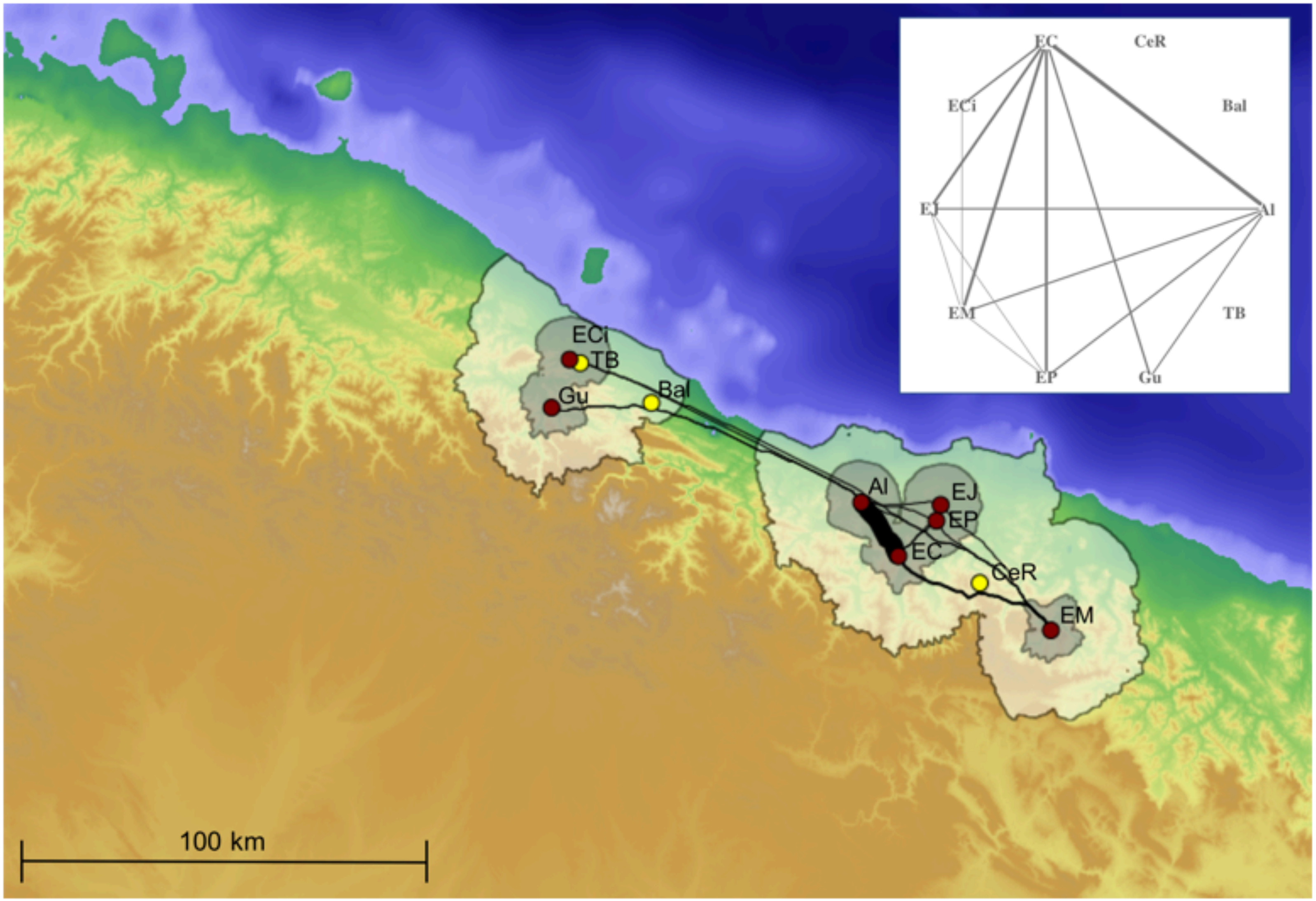


Figure 5.4. Reconstructed social network for the Lower Magdalenian of Cantabria.

As discussed in Chapter 4, we cannot analyze the metrics associated with these networks as they are not fair representations of their latent social networks. Therefore, the values of each network metric are not discussed here, but can be found in Appendix K. However, while the longest links – between El Cierro (*ECi*) and El Miron (*EM*) – may represent indirect transmission of cultural information through El Castillo (*EC*) rather than direct contact, the links between El Cierro and the central sites still cover distances of up to 100km. Following Whallon's (2006) estimates of population territories, this remains within the maximal or regional band territory, which suggests that the links between El Cierro and the central sites had an important purpose.

Based on the range of linked sites' foraging radii, I divided the territories into 3 parts (Fig 5.5). These territories were used to clip the Lower Magdalenian biome maps recreated in Chapter 3 (Lower Magdalenian A and B) to evaluate the environmental diversity of the linked sites. The χ^2 results – represented as uninterrupted links for significant differences, and hatched links for non-significant ones – show that the biome composition of all connected territories were significantly different (Fig. 5.5), which suggests that the networks may have been created to exchange environmental information between territories, thus creating safety nets.

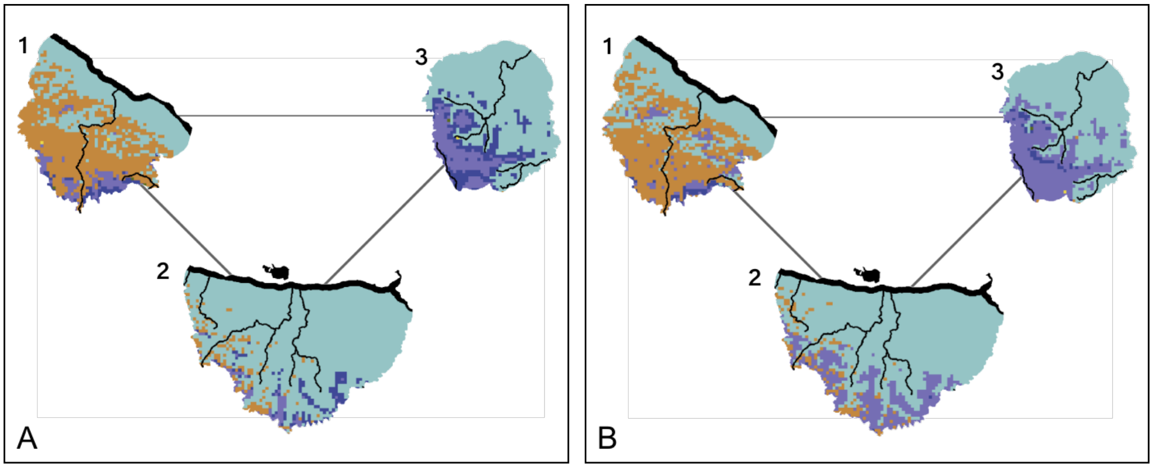


Figure 5.5. Territorial Lower Magdalenian A and B biomes of the linked Cantabrian sites. The width of the lines represents the number of similar representations between territories. All biome distributions are statistically different.

Middle Magdalenian. During the Middle Magdalenian, a few sites with portable animalistic art appeared in the Dordogne, whereas the number of Cantabrian sites and artistic representations decreased.

Cantabria (Site n = 6, Representation n = 36). The inter-connectivity of the networks dated to this cold and arid period decreases slightly (see Fig. 5.6 and Appendix K). Moreover, most links are rather weak – the maximum number of similar representations is 7 – which suggests that regional inter-group contact decreased during that time.

Keeping in mind that links represent the presence of similar pairs of representations in connected sites, the links found between Las Caldas (*LaC*) and La Garma – Galeria Inferior (*LGGI*) is likely to result from each site's direct contact with an intermediate site such as Tito Bustillo rather than from direct contact between these two geographically remote locations.

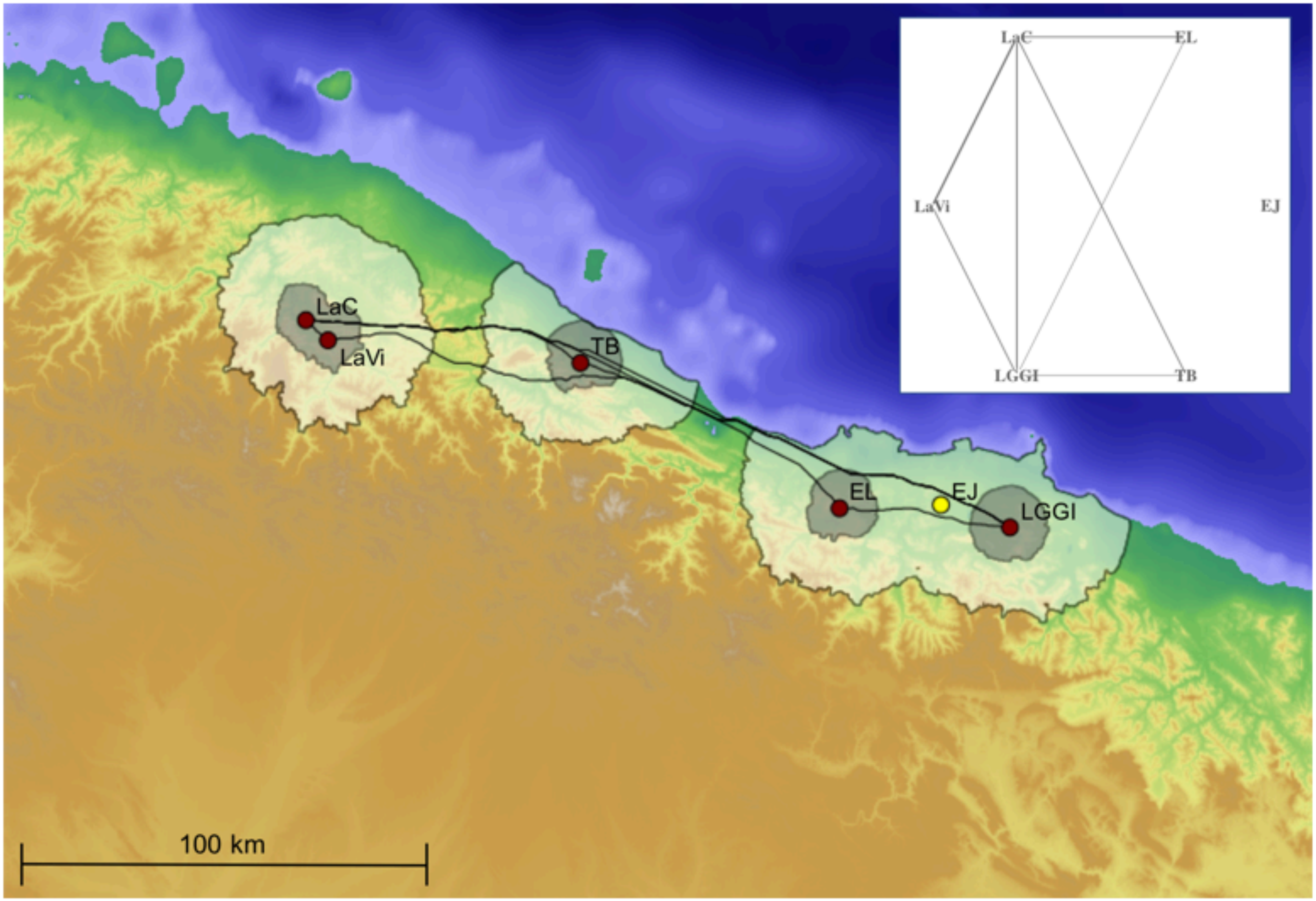


Figure 5.6. Reconstructed network of the Middle Magdalenian in Cantabria.

The differences in biome composition of all linked territories are statistically significant (Fig. 5.7). In fact, the only non-significant $\chi 2$ p-value (0.09) is found between the only two territories that are not sharing similar representations (Territories 2 and 3). While the absence of similar art in the two most similar territories could be due to the small sample size rather than an intentional choice, the links found between the different territories suggests that, similarly to the Lower Magdalenian, Middle Magdalenian intra-Cantabrian links may have been created to safeguard against environmental insecurities.

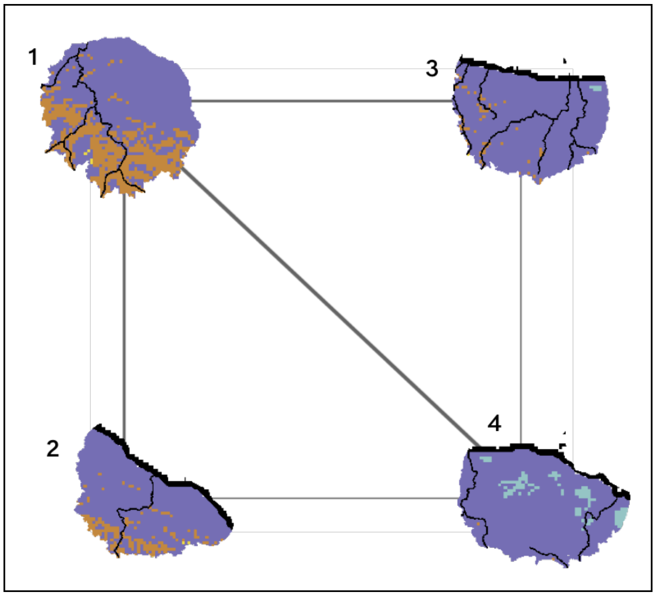


Figure 5.7. Territorial biomes of the Middle Magdalenian Cantabrian linked sites.

Dordogne (Site = 4, Representation n = 26). The network reconstructed for the Dordogne (Fig. 5.8) connects only 3 sites; however, due to the low number of sites *with* portable art representations during this period, this network encompasses most sites, suggesting relatively strong shared cultural conventions. It is important to remember that an important decrease in the occupation of Southwest France (Barshay-Szmidt et al., 2016) might have played a role in the reduced number of portable art objects found

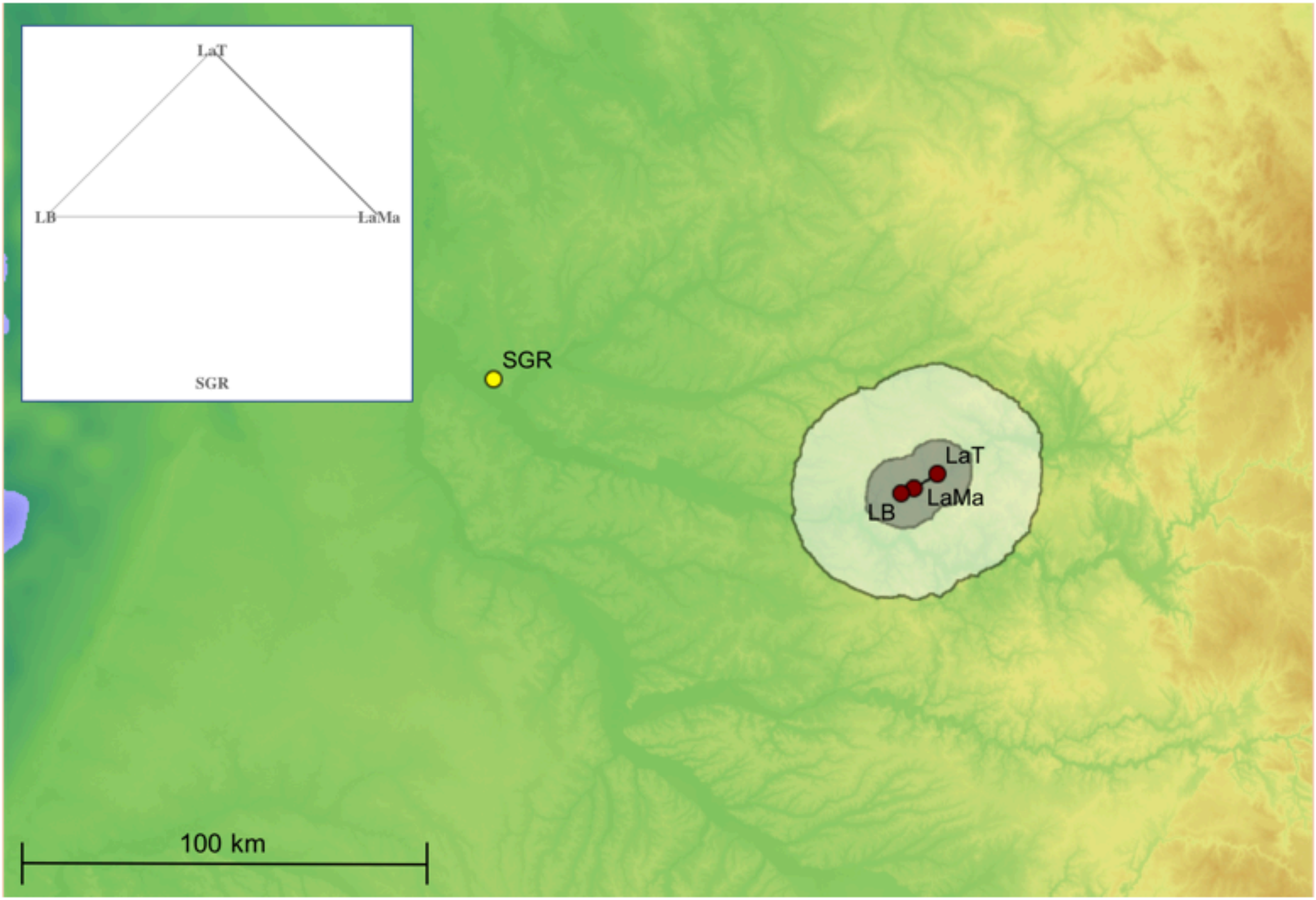


Figure 5.8. Reconstructed network of the Middle Magdalenian in the Dordogne.

therein. Given the proximity of the linked sites, they are considered as part of the same territory, which precludes from comparing their biomes statistically.

Inter-Regional (Site n = 10, Representation n = 62). Several of the portable art representations found in the Dordogne are similar to the representations found in Cantabria, suggesting the presence of strong links between the two regions (Fig. 5.9). All sites linked inter-regionally are also linked to other sites within their region; therefore, inter-regional links likely represent wide cultural sharing of information rather than direct contacts between remote sites.

As mentioned in Chapter 2, the Middle Magdalenian was the coldest and most arid subperiod of the Magdalenian, bringing a decline in the number of sites throughout the European Southwest. Despite this, people continued making artistic representations and expanded the sharing of their artistic conventions further than before. This suggests that these inter-regional networks could represent classic safety nets created between people living in different environments. The results of the χ^2 tests on connected territories support this interpretation, as they show that all connected territories have significantly different biome compositions (Fig. 5.10).

It is important to stress that, while the least costly way to travel between the Dordogne and Cantabria may have been to remain close to the Atlantic Ocean – as seen in the least-cost paths of Fig. 5.9 – this may not have been the path used by Magdalenian hunter-gatherers, who may have stopped or met at convenient half-way points provided by Western Pyrenees occupations (Barshay-Szmidt et al., 2016; Clottes, 1989; Delpech, 1983; Sacchi, 1987, 1988; Straus, 1991a, 1991b, 1995). The artistic record of the

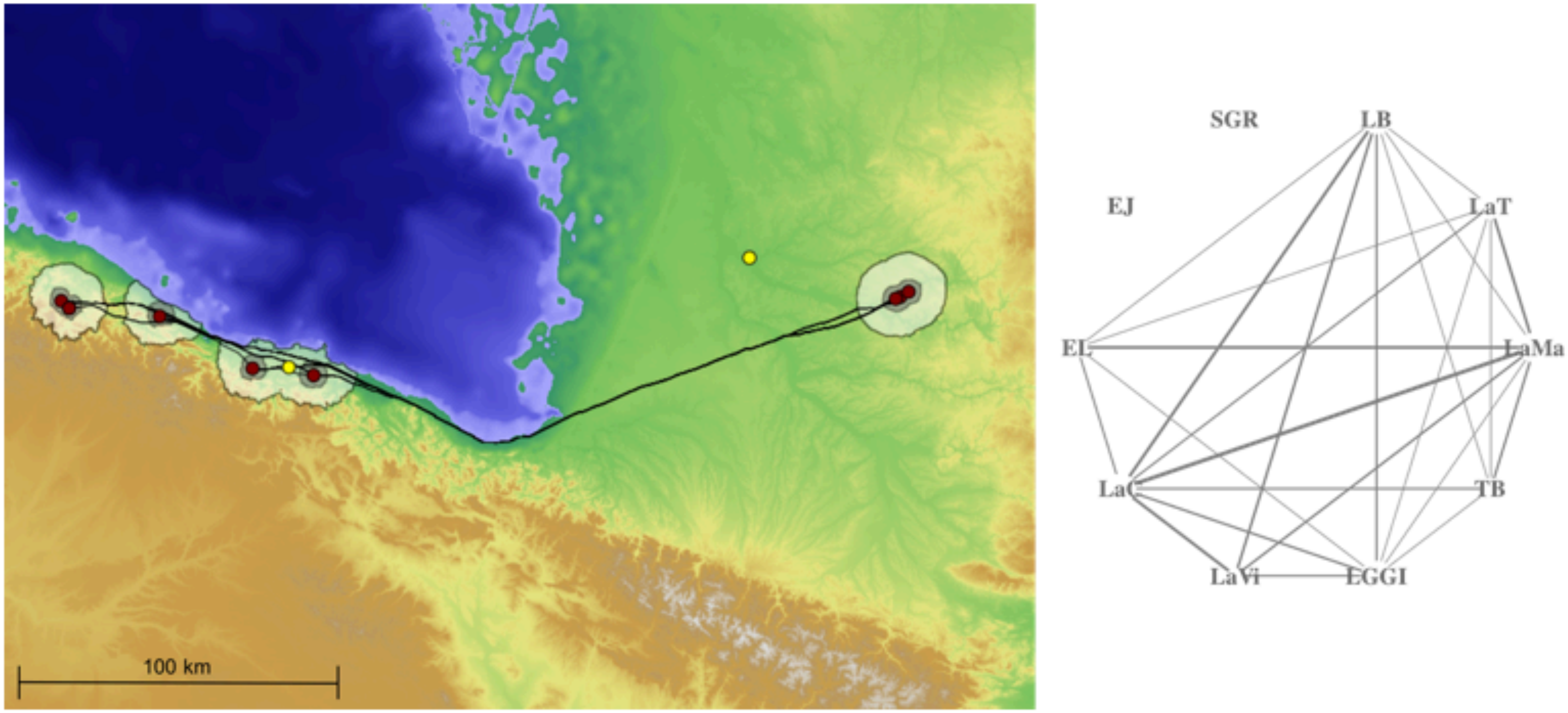


Figure 5.9. Inter-regional network reconstructed for the Middle Magdalenian. For site names on the geographical map, refer to Figures 5.7 and 5.8.

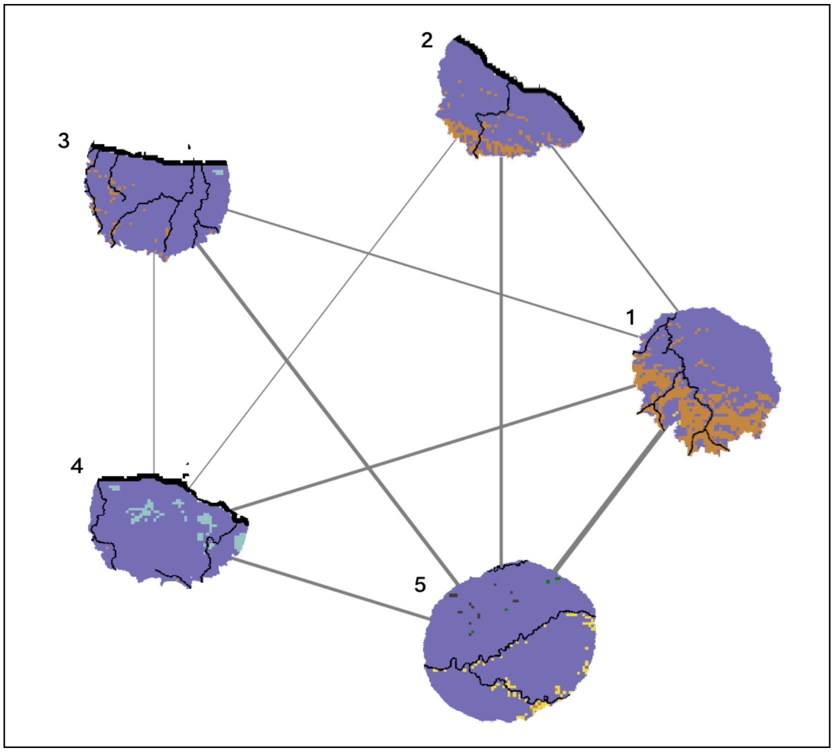


Figure 5.10. Territorial biomes of all Middle Magdalenian linked sites.

Pyrenees was not studied here, but documented similarities between the Pyrenean art and the representations found in the two regions studied (Buisson et al., 1996; Dachary, 2002, 2006; Fritz et al., 2007; Schwendler, 2004, 2012) have shown that Cantabria and the Dordogne might in fact have been linked through the Pyrenees. As including the Pyrenean artistic record could change the results of this study considerably, it will be studied in future research.

Upper Magdalenian.

Cantabria (Site n = 12, Representation n = 41). While the number of sites and artistic representations expanded considerably in the Dordogne during the Upper Magdalenian, it remained somewhat restrained in Cantabria (Figure 5.11). The network reconstructed for this period is well connected as ¾ of the sites with art share at least one similar representation. The fact that the art of Las Caldas (*LaC*) – located more than 150km from any other site – is similar to the art of 5 other sites suggests that the creation of strong inter-maximal band alliances served an important purpose during this period.

The biomes composition of the linked territories vary by temporal subdivisions (Upper Magdalenian A and B), but in both cases the differences between territories 1 and the other two are statistically different, whereas territories 2 and 3 do not differ significantly (represented as a dashed line in Fig. 5.12). Therefore, most inter-site links could still have been created to serve as safety nets. However, the strength of the link between the two similar territories suggests that parts of the network may have been created for other social reasons.

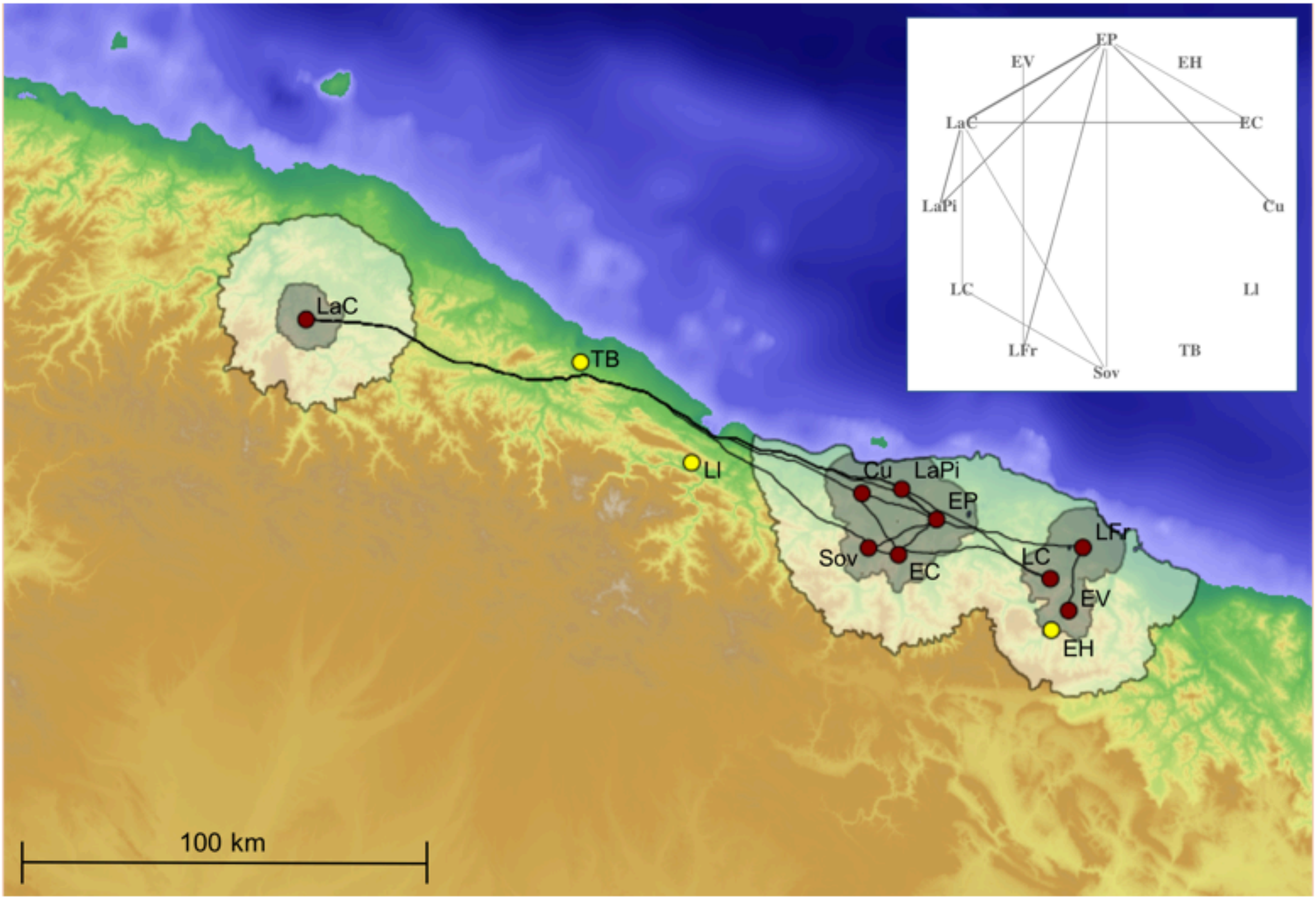


Figure 5.11. Upper Magdalenian reconstructed networks in Cantabria.

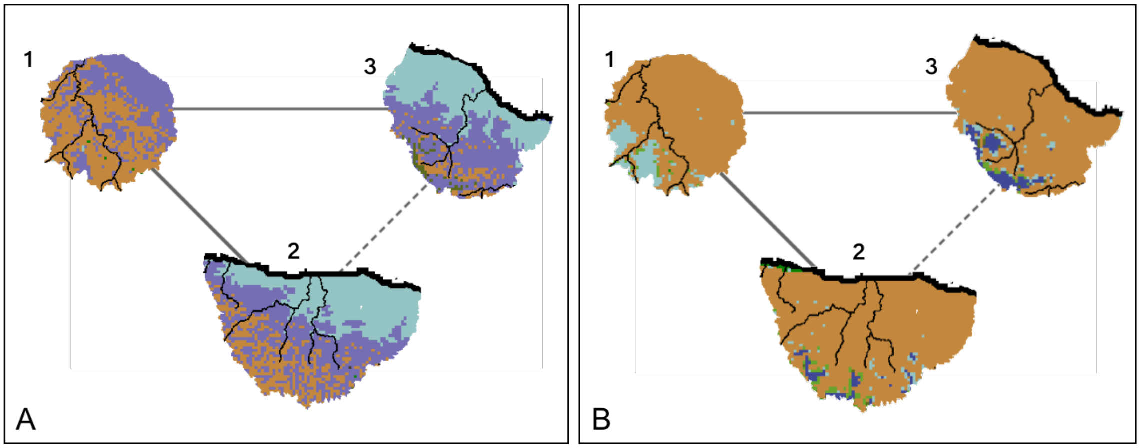


Figure 5.12. Territorial biomes of Upper Magdalenian A and B linked Cantabrian sites. The dashed lines show that the biome composition of the two territories are not statistically different.

Dordogne (Site n = 16, Representation n = 247). The explosion in the number of artistic representations in the Dordogne during the Upper Magdalenian, as well as their high similarity leads to the reconstruction of a tightly connected network (Fig. 5.13).

I divided the linked territories into 8 parts. Similarly to Cantabria, most linked territories of the Dordogne have significant differences in their biome composition (Fig. 5.14). However, the number of statistically different territories vary by temporal subdivision. The Upper Magdalenian A territories are more often statistically different than the biomes of the Upper Magdalenian B. While this difference can be problematic, the *majority* of linked territories are statistically different for both Magdalenian subdivisions, which suggests that most networks might have been created to use as safety nets, but that many others may have served different social purposes.

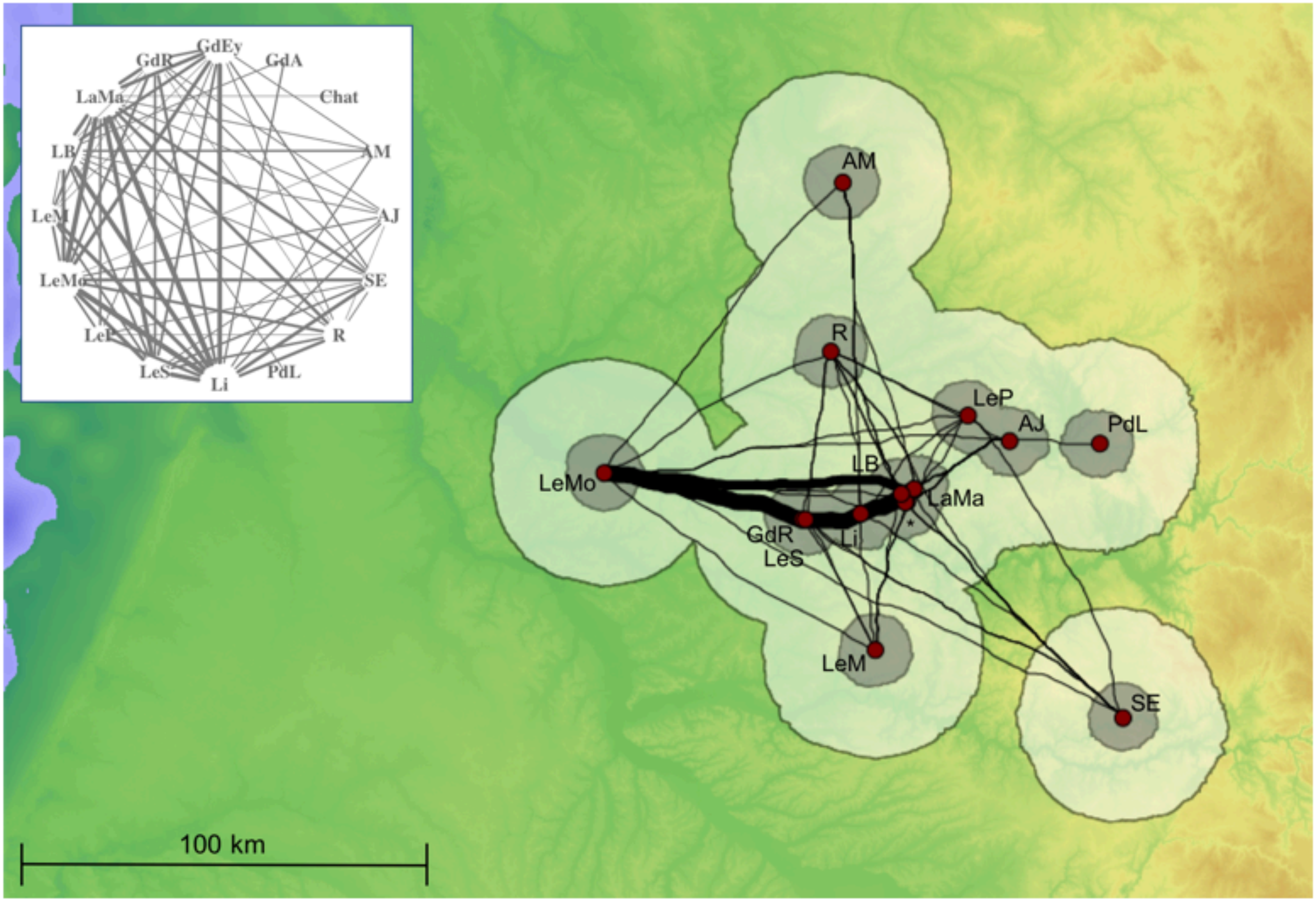


Figure 5.13. Upper Magdalenian reconstructed networks in the Dordogne. *Chat, GdEy, and LeS.

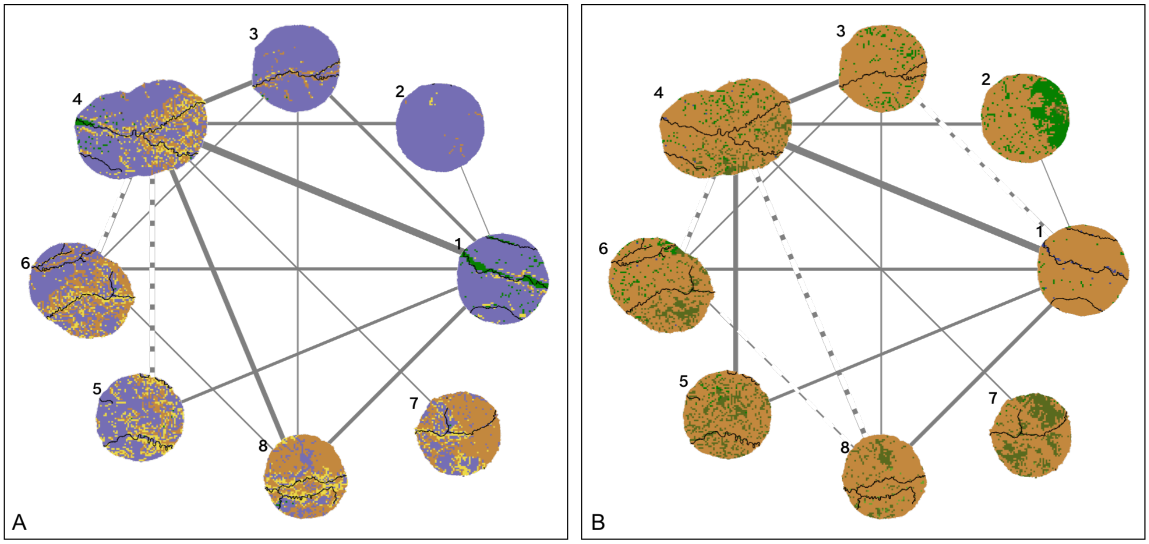


Figure 5.14. Territorial biomes of Dordogne linked sites. Dashed lines represent territories with biome compositions that are not statistically different.

Inter-Regional (Site n = 28, Representation n = 288). The number of inter-regional links increased during the Upper Magdalenian, while their individual strength decreased slightly. Most of the sites considered here shared at least one similar representation (Fig. 5.15), which confirms the held assumption that Magdalenian artistic conventions were widely transmitted (Bahn, 1982; Pigeaud, 2007; Schwendler, 2004, 2012). In turn, the presence of these links suggests the widespread sharing of information between groups of hunter-gatherers, which would have provided a good safety net to safeguard against the environmental changes of the Bölling.

Contrary to the social networks reconstructed for the Middle Magdalenian, a few Upper Magdalenian Cantabrian sites that are not connected to their neighbors share similar representations with French sites (e.g., El Horno (*EH*) shares similar art with Limeuil only (*Li*), whereas Tito Bustillo (*TB*) only has art similar to the representations of La Madeleine (*LaMa*)). This might be the archaeological trace of a relationship between two sites that were not part of the larger network, which could suggest an increase in the

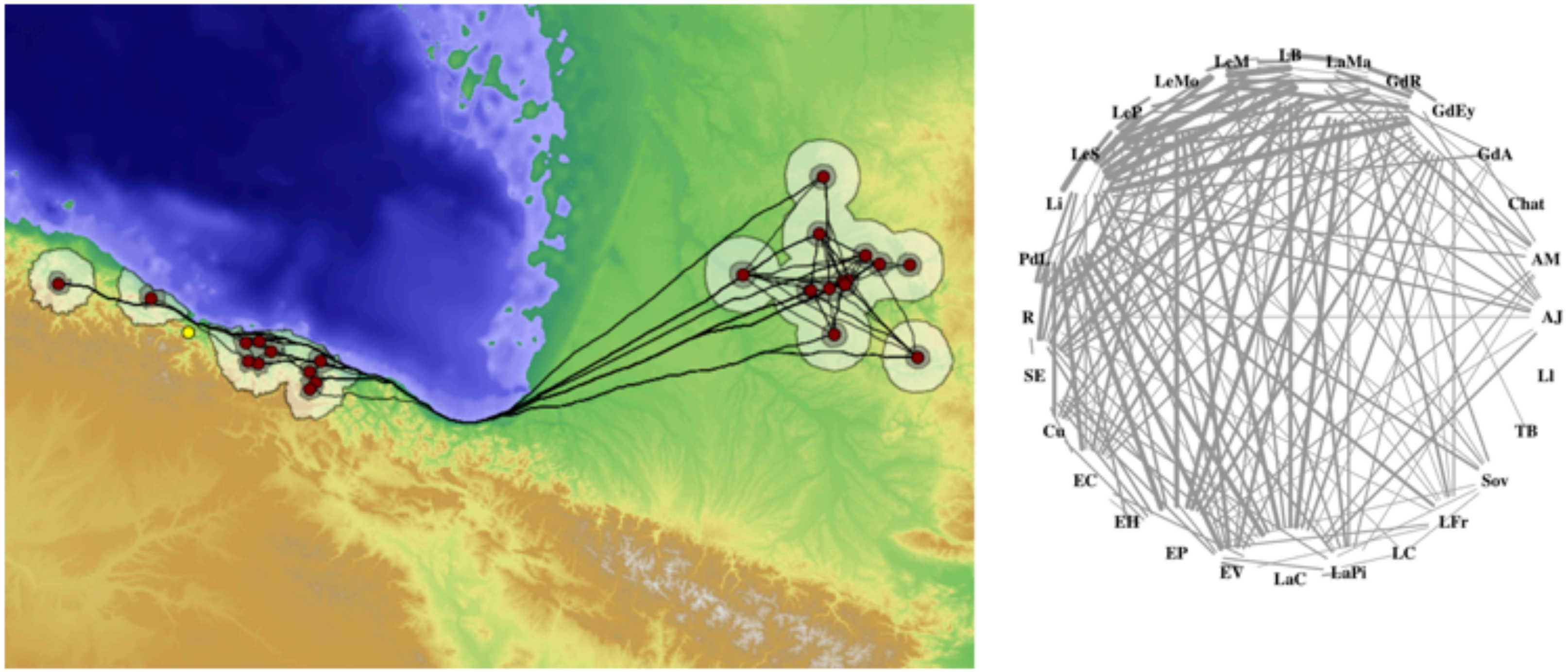


Figure 5.15. Upper Magdalenian inter-regional reconstructed networks. For site names, refer to Figures 5.11 and 5.13.

creation of local artistic styles transmitted directly between two sites through long-distance travel.

As for other Magdalenian temporal subdivisions, the biome composition of most linked territories are statistically significant (Figure 5.16), and the differences are stronger for the biomes of the Upper Magdalenian A than B. Given how different the resources are *within* regions, it is surprising to see the creation of high-cost inter-regional alliances, as shorter-distance alliances might have provided similar resources variety at a lower energy cost. This peculiarity implies that those social networks were not created to deal with resource fluctuation alone.

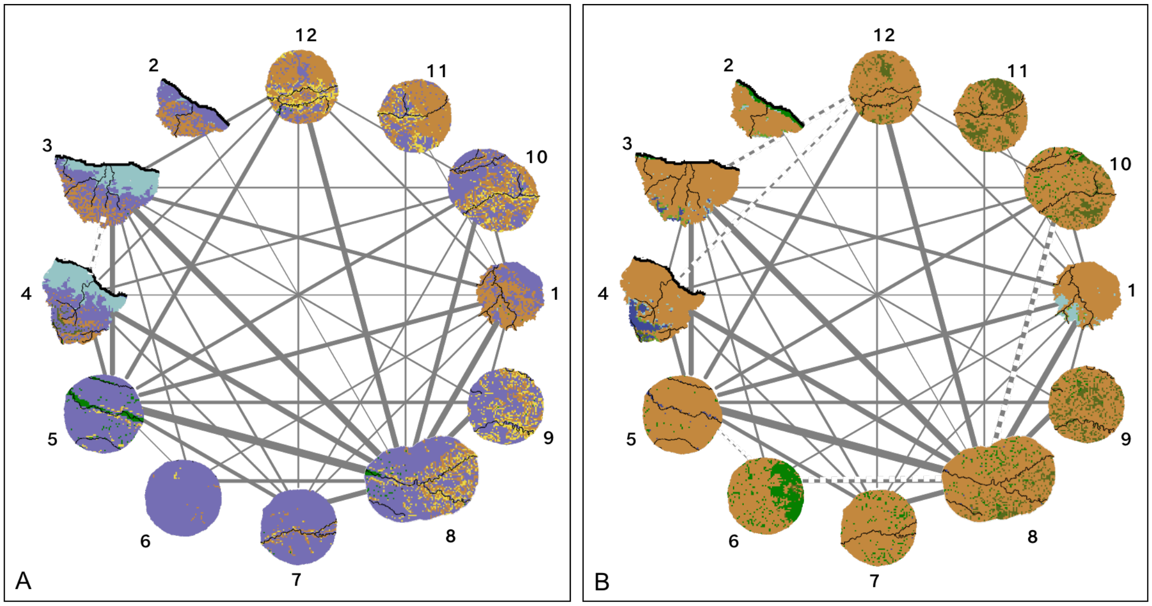


Figure 5.16. Territorial biomes of inter-regionally linked sites. Dashed lines represent territories with biome compositions that are not statistically different.

Connected Territories

As discussed in Chapter 4, I cannot use the metrics of the reconstructed networks to infer changes in social behavior over time. Even graph density, identified as a relatively reliable metric, could lead to erroneous results given that this metric requires including all the sites that were contemporaneous to the use of the network – even if they were not connected, and even if they did not produce art – which is impossible for the Magdalenian. Therefore, in this section, I focus on the connected biomes, as comparing their biome distribution show that most connections are formed between territories with significantly different resources. This supports the assumption that social networks were created and maintained to transmit environmental information and safeguard against resource shortage, as is practiced in modern populations (Kelly, 1995, 2013; Rautman, 1993; Wiessner, 1982; Whallon, 2006; Wobst, 1974).

To evaluate if the strength of links was based on the level of differences between the resources of its territories, I calculated the Euclidean distance between the biome composition of all territory pairs and plotted that value against the strength of their connection – the number of similar art objects (Fig. 5.17). All values were logged. I also calculated the regression R^2 for each log-log relationship (Table 5.4).

Table 5.4. Adjusted R^2 and p-value (in parentheses) of the log strength and log difference values of linked territories.

	LMA	**LMB**	**MM**	**UMA**	**UMB**
Cantabria	0.41 (0.56)	0.50 (0.50)	0.70 (0.08)	0.00 (0.97)	0.00 (0.95)
Dordogne	N/A	N/A	N/A	0.08 (0.31)	0.15 (0.15)
Inter-regional	N/A	N/A	0.31 (0.12)	0.01 (0.55)	0.17 (0.01)

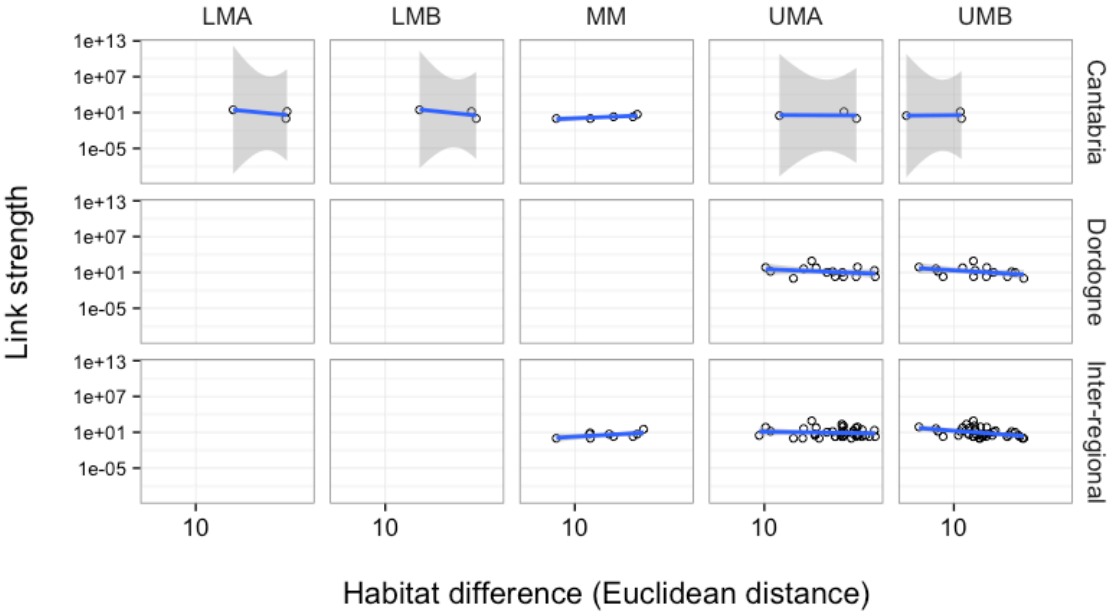


Figure 5.17. Log link strength (y axis) vs. log habitat difference measured as the Euclidean distance between the biome composition of linked territories (x axis).

This shows that the relationships between resource difference and strength of alliance are not statistically significant – apart from the Upper Magdalenian B inter-regional networks. The Cantabrian Middle Magdalenian relationship is significant at σ 0.10, which suggests that the creation of social networks during this cold and arid Oldest Dryas may have been used to safeguard against resource insecurity, as the stronger alliances are created between the territories that differ the most.

Discussion

None of the social network metrics produced in this chapter can be analyzed to test the hypotheses since they come from the reconstruction of networks that are not good representations of their latent networks. In Chapter 6, I use those metrics to identify which set of the model's simulations (from Chapter 4) produced the best fitting reconstructed networks. I then use the characteristics of the modeled observed networks from these best-fitting simulations as estimates of Magdalenian latent networks to test the hypotheses presented in Chapter 1. Finally, in Chapter 7, I summarize the new data created through this research and analyze them briefly in the context of the background knowledge presented in Chapter 2.

CHAPTER 6. COMPARING MODELED RESULTS TO THE EMPIRICAL DATA

Introduction

In Chapter 4, I presented the structure of my agent-based model and discussed how its outputs could be used to show the impact of topography and resources on social networks. I also demonstrated how the model refuted the assumption that social networks reconstructed from archaeological assemblages are good representations of the latent networks that produced them. As a reminder, the agent-based model showed the presence of important differences between the metrics of reconstructed networks and their observed (latent) networks (see examples in Figure 6.1). This led me to conclude that the social networks reconstructed through Magdalenian portable art similarities (Chapter 5) could not be analyzed directly to infer social behavior.

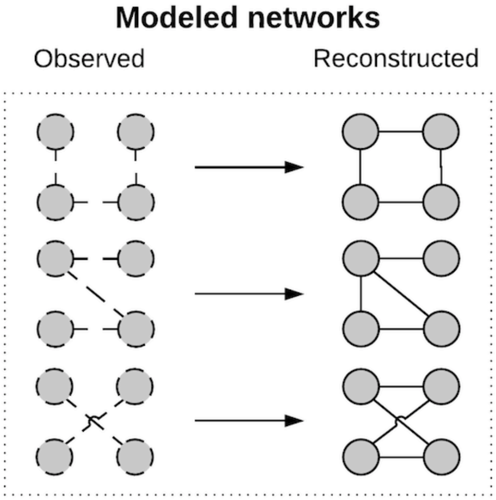


Figure 6.1. Example of differences found between observed and reconstructed modeled networks.

In this chapter, I combine the results of the agent-based model to the results of the empirical art analysis to estimate the Magdalenian latent social networks' characteristics. The method I use derives from experimental archaeology, where researchers experiment with different techniques to recreate artifacts and features in order to learn about the invisible processes behind their production (e.g., Fritz, 1999; Mesoudi, 2008; Schoville and Brown, 2010). Similarly, I use the agent-based model to experiment on the impact of cultural transmission on reconstructed social networks, and show the link between social interactions and the archaeological record they produce. I can then obtain the characteristics of an observed network from the characteristics of its reconstructed network. To document the invisible processes behind the empirically reconstructed Magdalenian networks, I identify the simulations that produced reconstructed networks most similar to the empirical networks, and use their observed networks as estimates of the latent social networks' characteristics (Fig. 6.2).

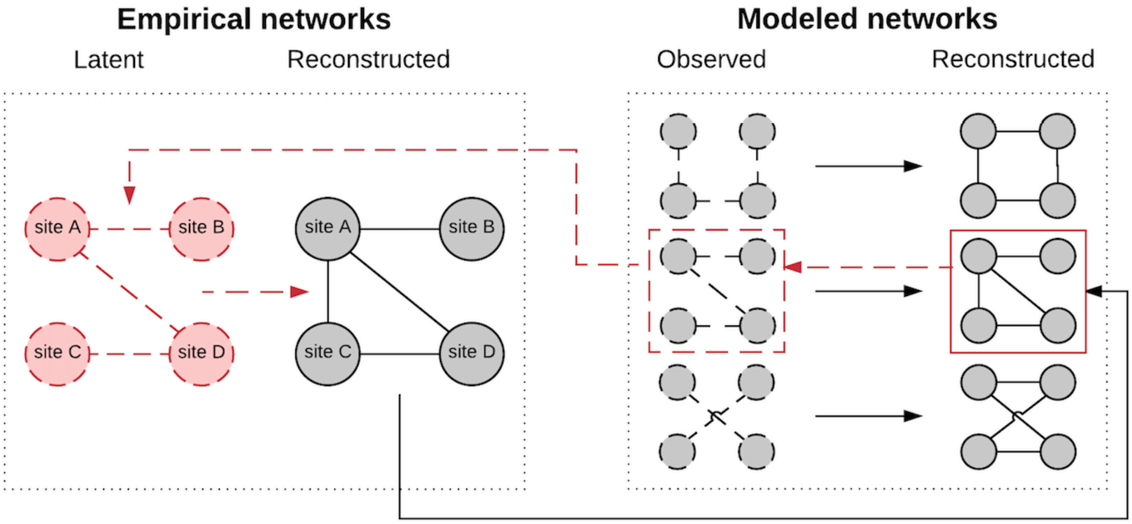


Figure 6.2. By comparing the characteristics of the Magdalenian empirically reconstructed networks to the characteristics of the modeled reconstructed networks, I can obtain an estimate of the Magdalenian latent networks.

Creating Estimates

To reduce the modeled dataset to the simulations that produced reconstructed networks best fitting the empirically reconstructed networks, I computed the Euclidean distance between the metrics of each empirically reconstructed network and the metrics of all modeled reconstructed networks. As I did not know which cultural transmission method was used during the Magdalenian, I focused on the simulations using both *Prestige* and *Conformism* methods at 25% transmission – ignoring the simulations set at 100% transmission, as research has shown that this was not a realistic value (Boyd and Richerson, 1987). Using the outputs of those simulations allowed representing the impact of mixed transmission methods on the creation of style palimpsests.

To calculate the similarities of network characteristics, I used the following metrics: mean degree centrality, cluster coefficient, shortest path, and Pearson *r* and covariance of alliances' length and strength. I did not use graph density because its accuracy is contingent on including all sites present when the network was used, which is not feasible for the Magdalenian. Similarly, I did not use extent metrics such as the longest alliance and the length of the strongest alliance because those were calculated in different ways – direct line in the modeled reconstructed networks vs. least-cost path in the empirically reconstructed ones – which could have led to some important misclassifications. Using correlation and covariance of length and strength was deemed satisfactory as those values are standardized; the different ways of calculating distances do not affect them.

I standardized all metric values into z-scores that included the range of both modeled and empirical data, and calculated the Euclidean distance between the metrics of empirically reconstructed and modeled reconstructed networks. I then standardized these similarity values into z-score, and retained only the simulations with a Euclidean similarity value < -1, identified as the simulations that produced reconstructed networks that were the most similar to each empirical network. Table 6.1 shows the sample size of the datasets selected for each region and period.

Table 6.1. Sample sizes of selected best-fitting simulations.

	Lower Magdalenian	Middle Magdalenian	Upper Magdalenian
Cantabria	165	156	279
Dordogne	0	233	271
Inter-regional	0	225	264

Empirically-Informed Networks to Test Hypotheses

In this section, I focus on the simulations that provided the best fit for each region and period. I use the characteristics of their observed networks as an estimate of the structure and extent of the latent Magdalenian social networks. I test the main hypotheses of this research using these estimates. I then present the estimates for the inter-regional networks to provide a more comprehensive picture of the network changes over time. I summarize, contextualize, and interpret the general patterns provided by those results in the discussion.

To relate to the three hypotheses, I separated the metrics of the modeled observed networks into those that provided information on the geographical extent of the networks (lengths of the longest and the strongest alliances, and the Pearson correlation coefficient (*r*) between length and strength of alliances: Fig. 6.3), their structure (mean betweenness centrality and shortest path: Fig. 6.4), and the connectivity between sites (number of linked sites and number of times alliances were used: Fig. 6.5). Mean betweenness centrality was used to complement shortest path, as it measures how many shortest paths go through each connected camp. High betweenness centrality suggests the presence of heterogeneous networks, where the majority of shortest paths go through a few important sites. Moreover, to evaluate the intensity with which alliances were used, I divided the number of alliances by the number of times they were used (Fig. 6.5). The following figures present the temporal and geographical changes in these metrics. As a reminder, the boxplot notches show the 95% confidence interval around the median. Therefore, when the notches of two boxplots overlap, the difference in their median is not statistically significant at $\alpha = 0.05$.

Hypothesis 1. Magdalenian social networks in the Dordogne were in general, more extensive spatially than the networks created in Cantabria. SUPPORTED

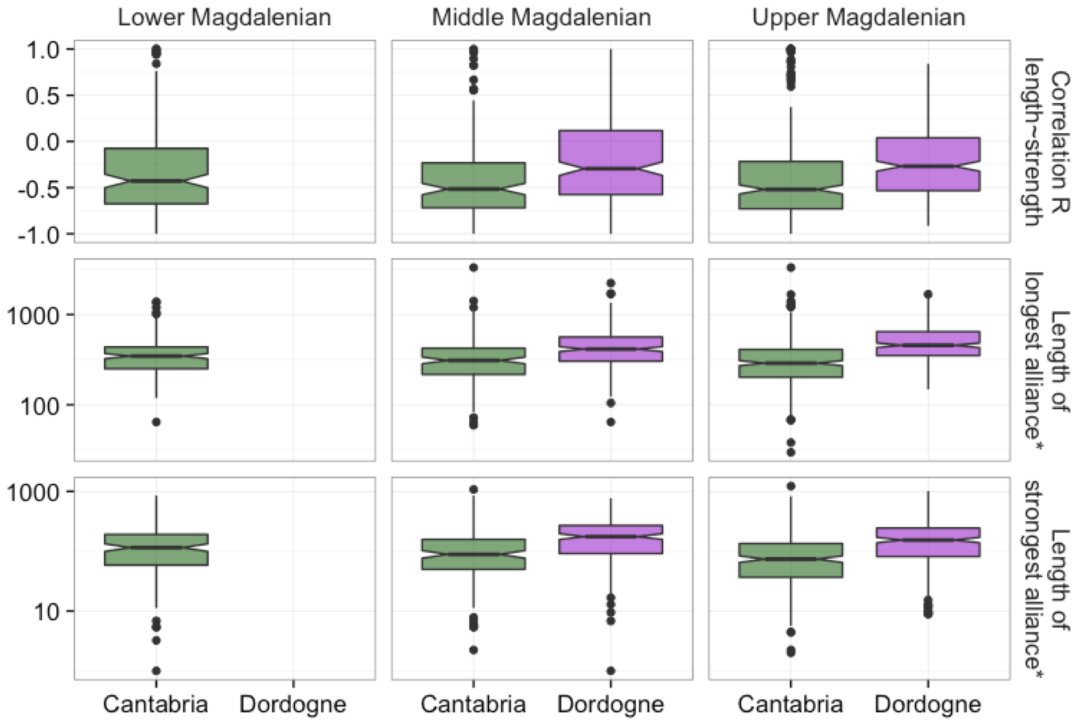


*Figure 6.3. Estimated network extent over time and space. *Logged*

For all extent metrics, the median values of Dordogne social networks are significantly higher than those of Cantabrian networks, which supports the hypothesis.

Therefore, Dordogne networks were more geographically extensive than Cantabrian ones, and their long-distance alliances were used more often than the ones in Cantabria, as seen in the weaker negative correlation *r*. This could be explained by the impact of topography on mobility, as well as the populations' different subsistence patterns, which led Dordogne populations to travel further distances to hunt large herds than Cantabrian hunters who relied mostly on local forested taxa (Kuntz and Costamagno, 2011; Straus, 1977, 1986).

Hypothesis 2. The Magdalenian sites in the Dordogne were 'homogeneously connected' whereas they were 'heterogeneously connected' in Cantabria. REFUTED

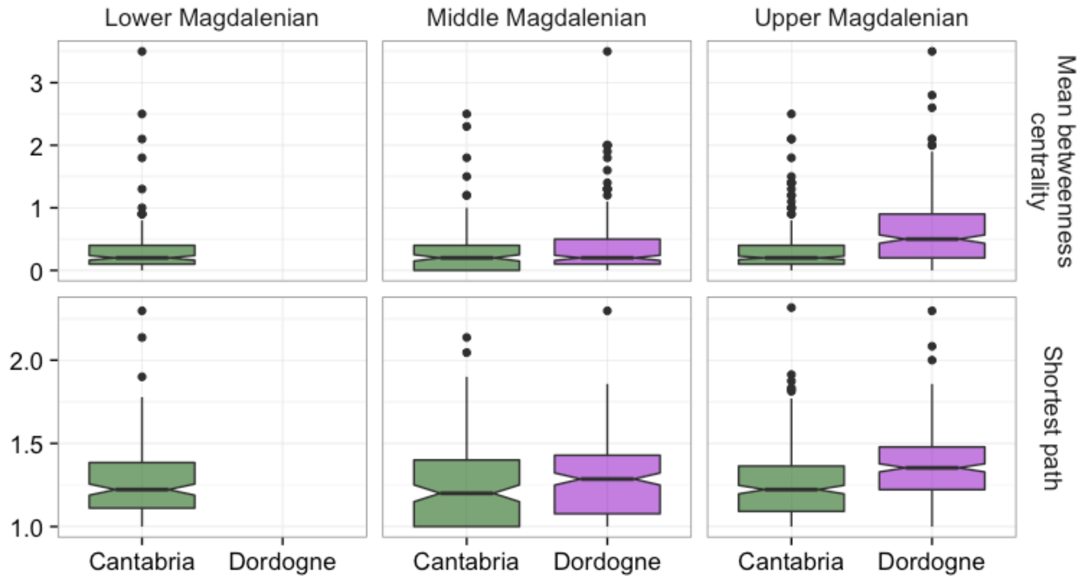


Figure 6.4. Estimated network structure over time and space.

Both the shortest path and mean betweenness centrality values of the estimates show that Cantabrian sites were more directly connected than the sites of the Dordogne, which refutes the hypothesis. Therefore, according to this data, Cantabrian social networks were more homogeneously connected than Dordogne networks.

Hypothesis 3. The intensity of use of the social networks in the Dordogne varied more over time than in Cantabria. SUPPORTED

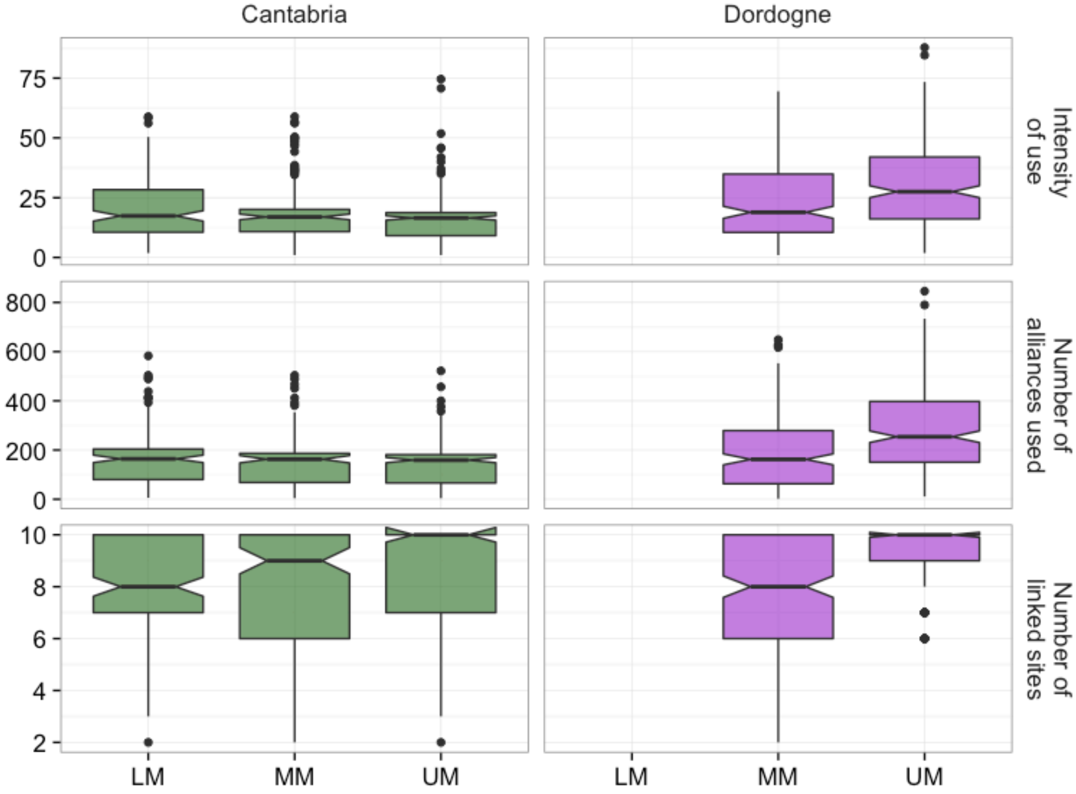


Figure 6.5. Estimated network connectivity over time and space.

This hypothesis is difficult to test due to the absence of Lower Magdalenian portable art objects in the Dordogne, which reduces the comparison to only two time periods. However, the metrics of the modeled networks set in the Middle and Upper Magdalenian support this hypothesis, as the temporal changes of all connectivity metrics are significantly stronger in the Dordogne than in Cantabria.

I review the implications of these results, as well as the networks' general pattern in the discussion.

Inter-Regional Networks

While inter-regional networks are not used to test the hypotheses, their pattern must be taken into consideration to gain a proper understanding of the Magdalenian social organization.

The estimated network metrics are presented in Figure 6.6. They show the presence of a significant temporal increase in the number of connected sites as well as a non-statistically significant increase in their usage. Other metrics show that the networks were highly connected in a relatively homogeneous manner – inferred from the low shortest path. The relatively low but increasing mean betweenness centrality suggests that the importance of key sites – or cultural transmission hubs – may have increased slightly over time, but not to the point that it created societal inequalities. The extent metrics show that most contacts were made between sites of the same maximal band – using territory sizes from Whallon (2006) – but that a few important long-distance alliances were also created beyond. In general, none of the metrics other than the number of linked sites show statistically significant temporal differences, which suggests that, while the regional networks may have varied over time, the general network remained relatively stable throughout.

Discussion

Following protocols used by experimental archaeology to document archaeological-invisible processes, I used an agent-based model to estimate the characteristics of the latent social networks that produced the networks reconstructed through stylistic

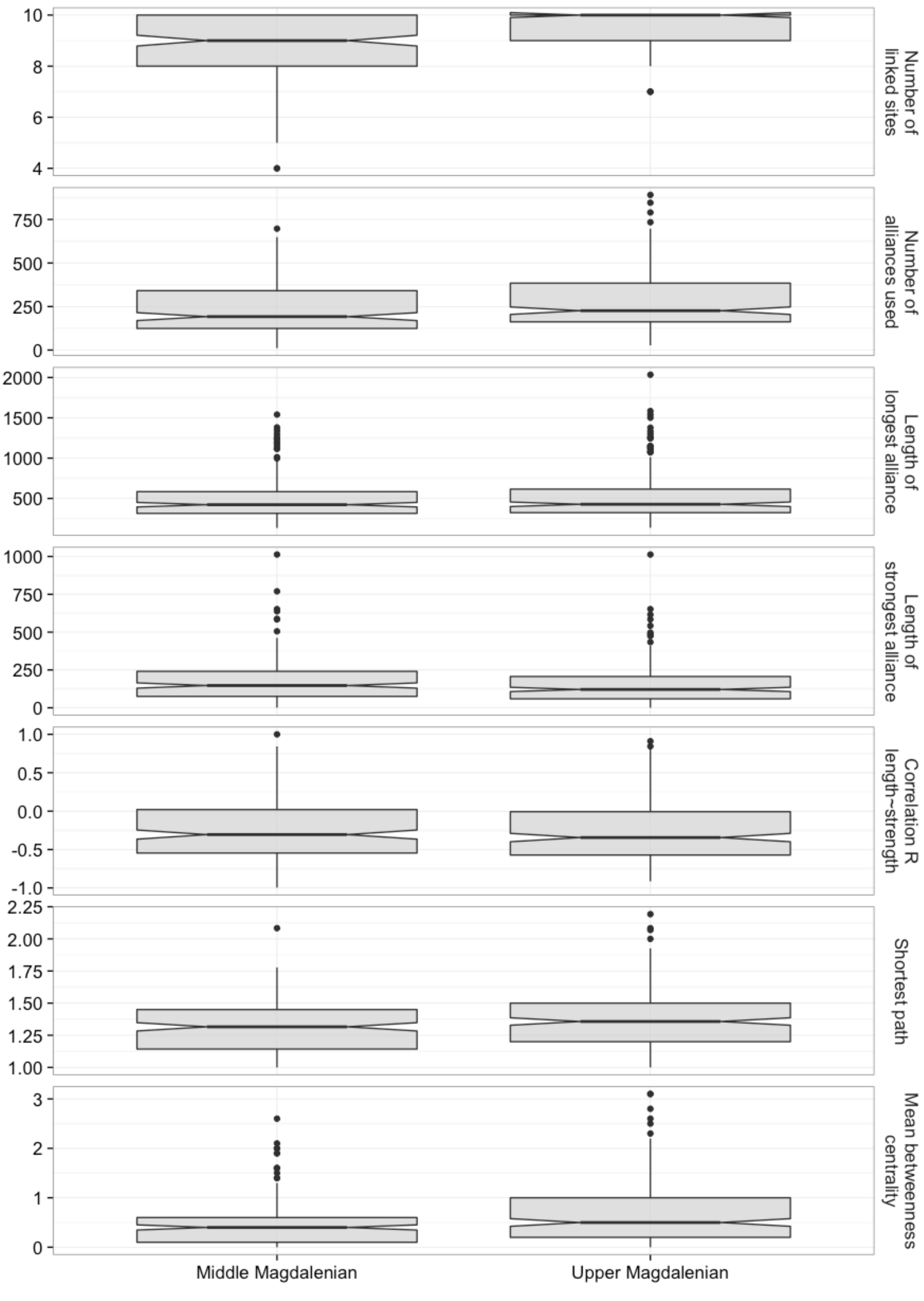


Figure 6.6. Estimated social network metrics for the whole Magdalenian.

similarities in portable art objects. These estimated Magdalenian network characteristics show that the structure and extent of social networks likely changed considerably throughout the Magdalenian. In most cases, these results conform to the patterns seen in the archaeological record through different proxies, as discussed here.

All metrics of Cantabrian networks remained relatively stable throughout the Magdalenian. As the archaeological record shows that site density increased during the Upper Magdalenian, leading to reduced residential mobility (Álvarez Alonso et al., 2016; Marín Arroyo, 2009; Straus, 2005), the lack of change in social networks suggests that the social organization of the population was resilient to climatic and demographic changes. I interpret this as the result of the high resource level and biodiversity found in the region.

According to the network estimates, many Lower Magdalenian Cantabrian sites were likely in constant contact with their nearby neighbors, creating a network that was well inter-connected, as seen in the relatively strong negative Pearson *r*. This complies with archaeological data, which suggests that mobility was reduced at the time (Risetto, 2009; Straus, 2012), as tools and most ornaments were made on local raw material (Álvarez-Fernández, 2002; Straus, 2012). Moreover, the network estimates suggest that most long-distance alliances were created between adjacent maximal bands, but were not used often. This could explain how the strict artistic conventions were shared throughout the Cantabrian region (Álvarez Alonso et al., 2016; Dachary, 2002; Utrilla, 2004; Corchón Rodríguez, 2005). The presence of a few Mediterranean pierced shells in Cantabrian sites hint at the presence of rare long-distance networks (Álvarez-Fernández, 2002; Schwendler, 2012), which also fits the results of the estimated networks.

The highly productive and varied environment of the warm and humid Lower Magdalenian Cantabrian coast (Altuna, 1992) can explain the restricted mobility of the time, as the mosaic environment allowed hunter-gatherers to take advantage of varied resources over short distances (Conkey, 1980; Marín Arroyo, 2009; Rensink, 1995; Straus, 1986). Moreover, their reliance on species with reduced mobility – ibex, red deer – prevented the need for large-scale movement. This supports the idea that populations were socially organized in small bands mainly confined to specific valleys who moved their camp seasonally, occupying coastal camps intensively during the winter, and using smaller sites in the mountains during the summer (Clark, 1986; Costamagno and Fano, 2006; Altuna, 1992; Álvarez Alonso et al., 2016; Freeman, 1973; Marín Arroyo, 2009; Straus, 1977, 1986, 1992, 2005, 2012). However, it also shows that the few long-distance alliances created were important paths for cultural transmission.

The Cantabrian network estimates suggest that the cold and arid climate of the Middle Magdalenian likely increased the proportion of sites sharing connections, but restricted slightly the geographical extent at which contact occurred. However, this pattern coincides with the increase in the use of non-local raw material to make stone tools (Álvarez Alonso et al., 2016; Corchón Rodríguez, 1986, 1995, 2005; Corchón Rodríguez and Rivero, 2008; Corchón et al., 2008; Straus et al., 2002), the spread of specialized designs originating from the Pyrenees (Buisson et al., 1996; Dachary, 2002; Fullola et al., 2012; Montes and Utrilla, 2008; Sauvet et al., 2008b; Schwendler, 2004; Straus, 2012), and the diffusion of harpoon technology from Cantabria to the Pyrenees (Álvarez Alonso et al., 2016; Julien, 1982), which all indicate that Cantabrian populations broadened their mobility pattern, thus seemingly contradicting the results of the estimates. However, these estimates relate only to the networks created within Cantabria. When taking into consideration the characteristics of the estimated inter-regional networks, we can see that the few long-distance alliances created beyond adjacent maximal band territories were likely used more often than the alliances created within adjacent maximal bands – as seen in the weaker negative correlation *r* of the inter-regional alliances in Figure 6.6. Therefore, combining the network estimates of the Cantabrian and inter-regional networks produces results that fit relatively well with the archaeological record.

Similarly, the advent of the warmer Upper Magdalenian did not affect the structure and extent of the social networks created within Cantabria and inter-regionally. Within Cantabria, this conforms to the archaeological record of that period, which is characterized by the optimization of local resources including small mammals (Altuna, 1985, 1995; Straus et al., 1981) and shellfish used as ornaments (Gravel-Miguel, 2011). This also coincided with an important widening of the subsistence pattern, leading to the creation of specialized tools for hunting smaller taxa (Álvarez Alonso et al., 2016; Costamagno and Laroulandie, 2004). While Cantabrian hunter-gatherers relied on local material to make general tools, they still used exotic material to make specialized ones (Álvarez Alonso et al., 2016; Dachary, 2002; Fullola et al., 2012; Sacchi, 1988; Straus, 2005). This conforms to the inter-regional networks estimates, which show an increase in the number of linked site, but not in their usage.

In general, the network estimates for Cantabria show stability, despite important climatic and resource changes. If this represents reality, it would suggest that the high biome diversity and fragmentation of this rugged region allowed Cantabrian prehistoric societies to remain resilient in the face of resource fluctuations. We already know that the region's geography favored the distribution of a wide range of animal taxa that could be hunted yearlong without the need for large-scale mobility (Marín Arroyo, 2009; Mellars, 1985; Straus, 1986, 1991; Yravedra, 2010). It is also logical to think that Cantabrian hunter-gatherers' efficient logistical mobility system (Clark and Barton, 2017; Straus, 1986) allowed them to gather all necessary resources from the different parts of their valleys, without the need to rely intensively on other groups for safety. To this, I would add that this high biodiversity may have created a natural safety net that strengthened the role of Cantabria as a temperate refugium. In such a context, the presence of long-distance alliances documented in the archaeological record may have been the result of outside groups relying on Cantabrian populations rather than the other way around. While this interpretation is supported by the uninterrupted occupation of this region – in contrast to the Pyrenees, which were not occupied until the Middle Magdalenian, and the Dordogne which may have been unoccupied during that time (Barshay-Szmidt et al., 2016; Dachary, 2002) – it needs to be tested further.

The Dordogne network estimates are different, as they show the presence of important changes in social organization between the Middle and the Upper Magdalenian.

According to the estimates, the Middle Magdalenian networks created within the Dordogne were wider than the ones found in Cantabria, which is not surprising given that Dordogne hunter-gatherers relied on migratory taxa (Fontana, 1999; Kuntz and Costamagno, 2011), whereas Cantabrian hunters preferred less mobile, forest taxa (Altuna, 1992; Álvarez Alonso et al., 2016; Straus, 1992). The numbers of Dordogne linked sites, as well as their usage, were relatively low. The low shortest path values of Middle Magdalenian networks combined with the relatively high lengths of strongest alliances suggest that most of these inter-site contact would have occurred within maximal band territories, but also that strong and important long-distance alliances were created beyond adjacent maximal band territories. This could have been due to the lower fragmentation of their biome (see Table 3.11 in Chapter 3), which would have forced hunter-gatherers to travel long distances to find potential allies. This conforms to the archaeological record, which shows a reduced population size (Barshay-Szmidt et al., 2016), an emphasis on local raw material to make stone tools (Demars, 1998; Lenoir, 1992), as well as the introduction of new artistic and technological conventions shared with the Pyrenees and Cantabria (Blanchard, 1972; Buisson et al., 1996; Capitan and Peyrony, 1928; Dachary, 2002; deSonneviles-Bordes, 1960; Fritz et al., 2007; Fullola et al., 2012; Langlais et al., 2012; Montes and Utrilla, 2008; Reverdit, 1878; Schwendler, 2004; Sieveking, 1971; Straus, 2012).

All connectivity metrics increased significantly after the Middle Magdalenian, which suggests that Dordogne populations changed their social organization with the advent of the Bölling. In particular, the significant increase in mean betweenness centrality of Dordogne networks suggests that a few sites may have gained more importance over time. This conforms to the important territory expansion, as well as the subsistence and technology diversification documented archaeologically from that period (Costamagno and Laroulandie, 2004; deSonneville-Bordes, 1960; Dachary, 2002; Delpech, 1983, 1992; Fontana, 1999; Jones, 2007; Langlais et al., 2012; Langley and Street, 2013; Otte, 2012; Sacchi, 1988), as well as the increase in the occupation intensity of a few important sites such as Laugerie-Basse and Limeuil (Breuil, 1936; Peyrony and Maury, 1914; Tosello, 1992).

Therefore, the structure of the networks may have changed from a tightly-knit network without important hubs during the Middle Magdalenian to a more heterogeneous pattern of sites linked through a few important hubs in the Upper Magdalenian. The increased site density, increased occupation intensity (Álvarez Alonso et al., 2016; Debout et al., 2012; Jones, 2007; Miller, 2012; Otte, 2012; Sacchi, 1988; Straus, 1991, 2005) and the reduction of large-mammal distribution (Costamagno et al., 2016; Delpech, 1983, 1992) that occurred during that time may have played a part in this re-organization. With the increase in the number of occupied sites on the landscape, using a few of those as meeting points could have alleviated stress, and insured the proper and less costly transmission of important conventions. With time, the separation of those important sites could have led to the emergence of heterogeneous styles, restricted to certain areas of the European Southwest, that were found towards the end of the Upper Magdalenian (Langlais et al., 2012; Langley and Street, 2013).

Finally, comparing the estimated network connectivity metrics shows that Dordogne groups may have used alliances more often than Cantabrian groups. This conforms to the idea that Dordogne played a more important role than Cantabria in the northern expansion that took place during the Upper Magdalenian through the intensive use of inter-group connections (Schwendler, 2004, 2012; Straus, 2012), an idea based on studies of raw material and artistic representations, which show the appearance of strong networks between the Dordogne and northern regions during that period (Bosinski, 2011; Langlais et al., 2016; Rivero and Sauvet, 2014). However, this pattern could also result from the strong impact of climate change on Dordogne's main source of meat (Costamagno et al., 2016; Straus, 2013), which may have increased hunters' need for safety nets. Here again, more research is necessary to shed light on those questions.

As I evaluated the changes in the intra-regional networks of Cantabria and the Dordogne in their social and environmental contexts, I came to think that Cantabria may have been the ultimate refugium. As discussed in Chapter 3, while the occupants of the Dordogne seem to have transformed their environment to protect the extent of the steppes, thus insuring that they could hunt reindeer all year round, Cantabrian hunter-gatherers may not have altered theirs to the same extent. This could be explained by the natural diversity of the Cantabrian environment, which provided such a wide range of resources that it protected its occupants from shortages. Surprisingly, however, these results suggest that despite their best effort, hunter-gatherers living in the Dordogne may have reduced their own resilience to climate change through their continued reliance on reindeer. In fact, this choice may have contributed to the important decrease in their demographic distribution during the cold and arid Middle Magdalenian. This is important because it shows that even prehistoric hunter-gatherers may have fell prey to the thought that manipulating the environment to facilitate resource intensification would protect them against hunger, when they actually should have diversified to remain flexible. While this thought is tangential to this project, it is important for past and modern societies alike and should be studied further.

CHAPTER 7. DISCUSSION

Introduction

In this research, I combined the outputs of three projects – environmental reconstructions, agent-based model, and social network reconstruction through artistic similarities – to estimate the characteristics of Magdalenian social networks, evaluate if they were used as safety nets, and assess how they were affected by environmental and climate changes. I focused my research on the networks of Cantabria and the Dordogne, two regions that served as temperate refugia for people and large-bodied mammals during the Last Glacial Maximum and the Late Glacial (Altuna, 1972, 1992; Freeman, 1973, 1981; Jochim, 1987; Straus, 1991).

To contextualize the networks, I reconstructed the biome distribution of the different Magdalenian periods, using an ecological model. The resulting environmental maps allowed me to evaluate how biome diversity and fragmentation affected the structure and extent of social networks over time. I then created an agent-based model where camps formed alliances within the reconstructed Magdalenian environments of Cantabria and the Dordogne. Every camp had 6 campers who produced daily sets of artistic traits, which were affected by the chosen mode of cultural transmission. This model created outputs of the alliances created between camps – observed networks – and palimpsests of artistic traits that could be used to produce their related reconstructed networks. I used the modeled networks as a bridge to estimate the characteristics of the empirical latent Magdalenian networks reconstructed through similarities of portable art representations.

The results of this research supported hypotheses 1 and 3, and refuted hypothesis 2, suggesting that both topography and climate change had important – and sometimes unexpected - impacts on social networks.

1. Magdalenian social networks were more extensive in the Dordogne than in Cantabria. SUPPORTED
2. Magdalenian sites in the Dordogne were *homogeneously* connected whereas they were *heterogeneously* connected in Cantabria. REFUTED
3. The intensity of use of the social networks in the Dordogne varied more over time than in Cantabria. SUPPORTED

The contextualization of the Magdalenian reconstructed networks also allowed me to determine that most of the long-distance alliances created between sites were likely used to exchange environmental information to cope with resource fluctuation.

Individual parts of the research brought important contributions to the study of human-environment interactions, history of hunter-gatherer cooperation, archaeological usage of agent-based model and social network analysis, and Magdalenian research. I summarize and discuss these contributions below.

Contributions

Humans Impacted Their Environment. Using MaxEnt on climate and pollen data, I reconstructed the distribution of Magdalenian biomes. However, the results did not fit the empirical pollen and faunal data; for most of the Magdalenian, the reconstructed biomes included extensive forested areas where the empirical evidence showed it should have been steppe-tundra. This discrepancy between modeled vegetation and empirical data has been observed in other research (e.g., Harrison and Prentice, 2003; Huntley et al., 2003) and suggests that ecological models are missing important variables. Recent research has shown the potential of human-induced small fires to reduce tree growth and increase the production of grasses (Kaplan et al., 2016). When added to an ecological model of the LGM, these anthropogenic fires improved considerably the accuracy of the reconstructed biomes, suggesting that Southwest European hunter-gatherers may have impacted their environment as early as the LGM.

I followed this method and added human impacts to my own ecological model, which improved its results significantly. In the Dordogne, this change transformed the previously reconstructed forests into large extents of steppe-tundra, which provided a better fit to the zooarchaeological record dominated by steppe species such as reindeer, bison, and horses (Delpech, 1990; Jones, 2007; Kuntz and Costamagno, 2011). As steppes allowed a year-round reliance on reindeer (Costamagno et al., 2016; Langlais et al., 2012), it is possible that Magdalenian hunter-gatherers intentionally used fire to maintain this highly productive environment.

The advent of the Bölling's warmer temperatures coincided with a decrease in the reliance on reindeer (Grayson et al., 2001; Kuntz and Costamagno, 2011; Langlais et al., 2012), followed by its complete disappearance from the Dordogne ~ 14 cal. kya (Costamagno et al., 2016). The reconstructed biomes showed that forests were expanding during the Upper Magdalenian, which suggests that, as temperature and precipitations increased, the environment reached the tipping point at which the impacts of small anthropogenic fires became weaker than the impacts of climate changes. Unable to preserve their productive steppes, hunter-gatherers were then forced to adapt by increasing their subsistence diversity (Dachary, 2002; Langlais et al., 2012; Sacchi, 1988).

Furthermore, human impact on the environment did not seem to have been as important in Cantabria as in the Dordogne, as some of the Cantabrian biomes reconstructed using climate only were a better fit to the archaeological and pollen records than the reconstructions made with human impact. In particular, the human-climate reconstructions showed a lower biome fragmentation than was expected for Cantabria, where archaeological research has demonstrated the persistence of small pockets of temperate vegetation in mountain river valleys (Straus, 1986, 1991). I believe that, as Cantabrian hunter-gatherers relied on the varied set of resources offered by the mountain flanks and the ocean (Mellars, 1985; Straus, 1986, 1991), they did not need to modify their environment. This interpretation still needs to be tested, and thus will be the focus of future research.

Environmental Changes Occurred in 'Temperate' Refugia. The climate data and the ecological model used in Chapter 3 showed that, while Cantabria and the Dordogne remained more temperate than other regions (Clark et al., 1996; Jochim, 1987), their environment and resources changed significantly throughout the Late Glacial. The climatic data supported the notion that the Lower Magdalenian temperatures of both regions were relatively warm (Langlais et al., 2012), thus providing safe refugia for northern human and mammal populations (Jochim, 1987; Straus et al., 2000). The data also confirmed previous interpretations (Altuna, 1992; Corchón Rodríguez, 2012; Muñoz Sobrino et al., 2007) that the Middle Magdalenian was the coldest and driest period in both regions, which could explain the decline in French population dated to that time

(Barshay-Szmidt et al., 2016). In both regions, the pollen and faunal records, as well as the reconstructed biomes, showed that steppes dominated the landscape (Aubry et al., 2012; Dachary, 2002; Fullola et al., 2012), even during the quick climatic changes brought by the Bölling. In other words, climate change impacted the resources found in these temperate refugia.

These changes did not affect Cantabria as much as the Dordogne. While Cantabrian temperature and precipitation fluctuated more in Cantabria than the Dordogne, temperature remained generally warmer (see Figure 2.3 in Chapter 2). Combined to the Cantabrian topography, which created sheltered valleys with high biome diversity and fragmentation (see Tables 3.10 and 3.11 in Chapter 3, and Straus, 1986, 1991), this led to higher and more stable resource levels that may explain why Cantabria remained occupied throughout the Magdalenian (Barshay-Szmidt et al., 2016; Clark et al., 1996; Jochim, 1987). The biodiversity of the Cantabrian region was reflected in the higher diversity of the Cantabrian faunal assemblages (see Figure 2.6 in Chapter 2, as well as Marín Arroyo, 2009 and Langlais et al., 2012), as hunter-gatherers took advantage of the varied resources offered by that environment mosaic (Conkey, 1980; Marín Arroyo, 2009; Rensink, 1995; Straus, 1986). This pattern did not hold for the Lower Magdalenian, however, as the biome fragmentation and faunal assemblage diversity of that period were higher in the Dordogne than Cantabria. In both regions, fauna diversity correlated strongly with biome fragmentation, which confirmed the validity of the biome reconstructions, as well as the assumption that diverse environments allowed hunter-gatherers to rely on several different types of resources rather than focus on only a few species. However, these values did not correlate linearly with the social networks metrics, suggesting that their effect on the creation of alliances was less direct than their effect on subsistence.

Topography and Resources Impacted Social Networks. The outputs of the agent-based model simulations with socially-driven alliances showed that sites' geographical placement impacts the structure and extent of the networks created between them. In particular, the placement of sites along the Cantabrian coast reduced the geographical extent of the created networks (see Figure 4.15 in Chapter 4), as topography directed movement to follow the coastal shelf, increasing the chances that an agent would stop at a neighboring camp on its way to a remote goal. This differed from the networks created in the Dordogne, where mobility was less incumbent on topography and where movement could be done in all directions relatively easily. In that situation, agents stumbled upon random camps less often, and thus their remote goals were reached more often. Therefore, the model showed that rugged topography favors the creation of alliances between chains of neighboring sites, creating strong local networks that may be linear in structure, whereas rolling hills allow for more extensive and diverse inter-site connections. Incidentally, combined with the reconstructed networks of Chapter 5, these results suggested that the impact of topography on mobility may have played a role in the formation and location of aggregation sites, as several least-cost paths between remote sites intersected along or near important mega-sites such as Altamira, El Castillo, Laugerie-Basse, Limeuil, and La Madeleine (see Figures 5.4 and 5.13 in Chapter 5).

The model also showed that resource-driven alliances are found in higher numbers in environments with highly fragmented biomes due to the increased facility of finding allies who rely on different resources.

Reconstructed Networks Differ from Observed Networks. The outputs of the agent-based model showed that archaeologists studying social behavior through reconstructed social networks should proceed with caution, because indirect cultural transmission can easily lead researchers to infer the presence of links between sites that were never in direct contact. This problem affects mostly the network extent metrics, as well as the metrics that are path based – i.e., that refer to the structure of connections. In fact, this research showed that only the temporal and geographical changes in graph density could be trusted to represent realistic social changes, but only when that value takes into consideration all the sites – connected or not – that are contemporaneous to the network analyzed. However, as this assumption is highly problematic when dealing with the incomplete prehistoric record, this ultimately shows that none of the social network metrics of reconstructed networks can be assumed to directly indicate prehistoric behavior.

While this problem may not affect all studies of archaeological social networks alike, it was of particular importance for the present study of the Magdalenian due to the well-documented homogeneity of its culture (Barandiarán, 1994; Dachary, 2002; Montes and Utrilla, 2008; Pigeaud, 2007; Rivero, 2010; Rivero and Sauvet, 2014; Schwendler, 2004, 2012), which suggests the presence of regular cultural transmission that blurred the individual inter-site interactions. Previous research has shown that parts of the Magdalenian homogeneous artistic record were created by the transmission of locally invented designs – e.g., Pyrenean bone disks and *contours découpés* – to other regions through small successive contacts (Buisson et al., 1996; Dachary, 2002; Fullola et al., 2012). As I demonstrated here, such small successive contacts ultimately lead to the creation of reconstructed networks where most sites are connected with each other, which is incorrect. Incidentally, this suggests that the art similarities found across Cantabria and the Dordogne (Chapter 5) should not be interpreted as signs of direct contact occurring between the two regions, as those are more likely the results of shared alliances with common Pyrenean sites. Future research on Magdalenian social networks should include the Pyrenean artistic record to test this interpretation.

This discovery has important ramifications for studies of prehistoric social behavior. However, it may not impact all research similarly. For one thing, it should not affect research that aims to document the *diffusion* of traits and/or objects because indirect transmission is an important component of such studies. Moreover, this may not affect social networks reconstructed through sourcing of pottery or lithic raw material, as the identification of stable material sources may reduce the impact of indirect transmission on certain metrics. This should be clarified through new research.

Agent-Based Models Can Act as Bridges Between Scales to Shed Light on the Invisible Past. In this research, I also used the agent-based model to conduct multiple experiments at a low cost, in ways similar to Kohler et al. (2005). Each simulation was a separate experiment producing a reconstructed network linked to its observed network. Using statistics, I identified the simulations that produced reconstructed networks most similar to the empirically reconstructed ones, and used those simulations' observed social networks as estimates for the latent Magdalenian social networks. I confirmed the validity of these estimates by analyzing their temporal and geographical changes within their known Magdalenian context. Most of the results supported previous interpretations of the archaeological record.

Therefore, while the agent-based model identified important differences between reconstructed and latent networks, it also provided a solution. Through this research, I thus provided a new example of how an agent-based model can serve as a heuristic tool to estimate the processes behind the creation of the archaeological palimpsests we study today (see Axelrod, 2006; Axelrod and Tesfatsion, 2005). I created a simple methodology that reconciles formal social network methods with the incomplete archaeological record, and thus, that could be applied to research on the evolution of cooperation.

However, one should keep in mind that latent networks can only be estimated through their reconstructed networks if inter-site cultural transmission occurred, as demonstrated by the model. This is discussed below.

Cultural Transmission is Archaeologically Visible Even at Low Levels. I computed the Quadratic Assignment Procedure (QAP) on the reconstructed and observed modeled networks of each simulation to evaluate if their general structure was similar enough to statistically determine that they came from the same population. The QAP test showed the presence of general structural similarities in reconstructed and their observed networks only for simulations using cultural transmission (*Conformism* and *Prestige*). The *Autodidact* method resulted in reconstructed networks that differed completely from their observed networks, which was not entirely surprising. What was surprising was that the QAP test identified linked networks even when cultural transmission was low (only 25% of the time). This is important because it demonstrates that using an agent-based model to estimate the characteristics of latent social networks is a robust method when it is used on societies where some form of cultural transmission took place, which is the case for the Magdalenian (see Álvarez-Fernández, 2006, 2009; Fullola et al., 2012; Langlais et al., 2012; Schwendler, 2012).

Biodiversity Creates Resilient Societies. Environment Manipulation Does Not. Finally, compiling all the results of this research showed that Cantabrian social networks remained relatively stable over time, whereas the Dordogne networks fluctuated significantly. Analyzed within their social and environmental contexts, these results suggest that the geographical characteristics of Cantabria created a stable refugium in which populations were resilient to changes. This may explain why Cantabrian hunter-gatherers may not have changed their environment to the same extent as Dordogne populations (see discussion in Chapter 3). In contrast, the Dordogne hunter-gatherers may have reduced their own resilience to change by transforming their environment and relying heavily on reindeer. In fact, I believe that the manipulation of the Dordogne environment to preserve steppes contributed to the important decrease in its population during the cold and arid Middle Magdalenian. This is important because it shows that even prehistoric hunter-gatherers may have fallen prey to the thought that manipulating their environment to satisfy their immediate needs would protect them against hunger, when they should rather have diversified to remain flexible in the face of important environmental changes. While this thought is tangential to this project, it is important for past and modern societies alike and should be studied further.

Conclusion

This research contributes several new results, most of which point to the advantages of using an inter-disciplinary approach to the study of the archaeological record. It demonstrates the benefits of using an agent-based model to deal with one of archaeologists' biggest problems: how to parse social data from long-term palimpsests. It shows that geographical and environmental context affects the structure of social networks, which in turn affects the transmission of ideas and goods that flow through it. This shows the presence of human-environment interactions that not only affected our ancestors' reaction to resource insecurities, but also led them to innovate and improve the productivity of their own environment. However, it also shows that such alterations may not have been enough to counter the strong climatic changes of the time, and that the region with diverse resources provided a more stable and resilient environment than the region transformed to satisfy the immediate needs of its population. Modern populations who strive to produce more and diversify less should keep this in mind. With its multiple parts, this research offers a baseline to study different questions such as the evolution of cooperation, the extent of human impact on their environment, the ways in which we can distinguish between direct and indirect cultural transmission, and why population expansion led to a decrease in the strength of long-distance alliances in the European Southwest.

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APPENDIX A

PREHISTORIC FAUNA PER SITE

[CONSULT ALSO ATTACHED FILES]

Lower Magdalenian A

Site	Longitude	Latitude	Type	Bos Bison	Capra sp	Capreolus capreolus	Cervus elaphus	Elephas primigenius	Equus sp	Lepus sp	Rangifer tarandus	Rupicapra rupicapra	Saiga tatarica	Sus scrofa	References
Cueva el Rascano	-3.703507	43.294543	MNI	2	93		16		4	1					1,3,7
El Castillo	-3.965257	43.29228	MNI	10	1	1	167		9		1	10		4	5
La Riera	-4.854958	43.426223	MNI	1	15	1	39		2			1			2
Le Roc de Marcamps	-0.504519	45.041623	MNI	7			1		3	1	2		5		6
Les Jamblancs	0.742732	44.798252	NISP						3		60	1	1		4

Legend references: 1. Altuna 1981; 2. Altuna 1986, 3. Cabrera-Valdes 1984; 4. Drucker et al. 2000; 5. Landry and Burke 2006; 6. Slott-Moller 1988; 7. Straus 1992.

Lower Magdalenian B

Site	Longitude	Latitude	Type	Bos Bison	Capra sp	Capreolus capreolus	Cervus elaphus	Elephas primigenius	Equus sp	Lepus sp	Rangifer tarandus	Rupicapra rupicapra	Saiga tatarica	Sus scrofa	References
Altamira	-4.123474	43.378202	MNI	2		3	14		1						3,9,15
Combe Cullier	1.5667	44.85	NISP		7				5		230	10			6
Cueva el Rascano	-3.703507	43.294543	MNI	2	79		16		3	1		1			1,15
El Juyo	-3.889	43.431	MNI	6	6	8	122		4					2	8,10,14,15
Flageolet II	1.0833	44.85	NISP	4	1		18		8		694	3	9		5,6
La Riera	-4.854958	43.426223	MNI		7	1	23		1			1			2
Las Caldas	-5.912015	43.337027	NISP		36		265		47						13
Laugerie-Haute	1.003417	44.953278	NISP	17	9		13	1	104	3	2143	12	34		6
Le Roc de Marcamps	-0.504519	45.041623	MNI	13			2		7	1	7	1	13		12
Les Jamblancs	0.742732	44.798252	NISP	8					4		106				7
Saint-Germain-la-Riviere	-0.331229	44.949175	MNI	2					4		3		17		4
Tito Bustillo	-5.073512	43.46057	MNI	4	8	1	22		5			3			11,15

References legend: 1. Altuna 1981; 2. Altuna 1986; 3. Alvarez-Fernandez 2009; 4. Costamagno 2001; 5. Delpech 1970; 6. Delpech 1983; 7. Drucker et al. 2000; 8. Freeman and González-Echegaray 1995; 9. Freeman et al. 1988; 10. Janssens and González-Echegaray 1958; 11. Moure Romanillo 1979; 12. Slott-Moller 1988; 13. Soto and Meléndez Hevia 1981; 14. Straus 1977; 15. Straus 1992.

Middle Magdalenian

Site	Longitude	Latitude	Type	Bos Bison	Capra sp	Capreolus capreolus	Cervus elaphus	Elephas primigenius	Equus sp	Lepus sp	Rangifer tarandus	Rupicapra rupicapra	Saiga tatarica	Sus scrofa	References
Combe Cullier	1.5667	44.85	NISP		7				5		230	10			4
El Juyo	-3.889	43.431	MNI	6	6	8	122		4					2	6,7,12,13
Flageolet II	1.0833	44.85	NISP	4	1		18		8		725	3	9		3,4
La Garma - Galeria Inferior	-3.6667	43.4333	NISP	60			164		286		14				1
La Garma A	-3.6667	43.4333	NISP	20	6	6	29		63		9				1
La Madeleine	1.033503	44.968179	NISP	7					142	25	258	1	1		2,4
Las Caldas	-5.912015	43.337027	NISP	2	63		316		58						11
Laugerie-Haute	1.003417	44.953278	NISP	17	9		13	1	104	3	2143	12	34		4
Le Roc de Marcamps	-0.504519	45.041623	MNI	9			2		4	1	4	1	8		10
Les Jamblancs	0.742732	44.798252	NISP	6	1				26	1	364	5	3		5
Tito Bustillo	-5.073512	43.46057	MNI	6	11	1	39		8			4			8,9,13

References legend: 1. Arias Cabal et al. 2005; 2. Bouvier 1979; 3. Delpech 1970; 4. Delpech 1983; 5. Drucker et al. 2000; 6. Freeman and González Echegaray 1995; 7. Janssens and González Echagaray 1958; 8. Marín-Arroyo 2013; 9. Moure Romanillo 1979; 10. Slott-Moller 1988; 11. Soto and Meléndez Hevia 1981; 12. Straus 1977; 13. Straus 1992.

Upper Magdalenian A

Site	Longitude	Latitude	Type	Bos Bison	Capra sp	Capreolus capreolus	Cervus elaphus	Elephas primigenius	Equus sp	Lepus sp	Rangifer tarandus	Rupicapra rupicapra	Saiga tatarica	Sus scrofa	References
Comarque	1.01667	44.933	MNI	1	1					1	14				9
Cueva el Rascano	-3.703507	43.294543	MNI		15		4		1			1		1	1,17,21
El Castillo	-3.965257	43.29228	MNI	14	7	4	114		78			23			5,17
El Horno	-3.450989	43.243331	MNI		16	1	6		2	2		2		1	8
El Miron	-3.453424	43.245813	MNI		14	3	11		2			5		1	5,17
Faustin	-0.168526	44.732527	MNI	2		1	1		3		1			1	10,15
Gare de Couze	0.73	44.83	NISP	7	1				2		613	2	1	1	12
Grotte XVI	1.20333	44.802222	NISP	2	2	10	24		30		2049	27	26	2	14
La Fragua	-3.433386	43.440804	MNI	2	5	3	8					1		3	16,17
La Garma - Galeria Inferior	-3.6667	43.4333	NISP	60			164		286		14				3
La Madeleine	1.033503	44.968179	MNI	1					5	1	1	1		1	4,12
La Riera	-4.854958	43.426223	MNI	2	13	6	41		4			7		4	2
Las Caldas	-5.912015	43.337027	NISP	2	31		54		11						6,7,20
Le Morin	0.079956	44.817143	NISP	334		5	101		183	28	710			41	11,12
Le Roc de Marcamps	-0.504519	45.041623	MNI	9			2		4	1	4	1	8		19
Moulin-du-Roc	0.927527	44.863849	NISP	3		17	34		11		115			23	13
Tito Bustillo	-5.073512	43.46057	MNI	2	3		17		3			1			18,21

References legend: 1. Altuna 1981; 2. Altuna 1986; 3. Arias Cabal et al. 2005; 4. Bouvier 1979; 5. Cabrera Valdés 1984; 6. Corchón Rodríguez 1992; 7. Corchón Rodríguez 1995a; 8. Costamagno and Fano Martínez 2005; 9. Delluc and Delluc 1981; 10: Delpech 1971; 11. Delpech 1979; 12. Delpech 1983; 13. Detrain et al. 1996; 14. Grayson and Delpech 2003; 15. Lenoir 2003; 16. Marín 2004; 17. Marín-Arroyo 2013; 18. Moure Romanillo 1979; 19. Slott-Moller 1988; 20. Soto and Meléndez Hevia 1981; 21. Straus 1992.

Upper Magdalenian B

Site	Longitude	Latitude	Type	Bos Bison	Capra sp	Capreolus capreolus	Cervus elaphus	Elephas primigenius	Equus sp	Lepus sp	Rangifer tarandus	Rupicapra rupicapra	Saiga tatarica	Sus scrofa	References
Cueva el Rascano	-3.703507	43.294543	MNI		15		4		1			1		1	1,9,10
El Horno	-3.450989	43.243331	MNI		16	1	6		2	2		2		1	3,9
El Miron	-3.453424	43.245813	MNI		11	1	9		1			5		1	3,9
Faustin	-0.168526	44.732527	MNI	2		1	1		3		1			1	4,8
Gare de Couze	0.73	44.83	NISP	13	1	10	15		7		918	2	1	5	6
Grotte XVI	1.20333	44.802222	NISP	2	2	10	24		30		2049	27	26	2	7
La Riera	-4.854958	43.426223	MNI	2	13	6	41		4			7		4	2
Le Morin	0.079956	44.817143	NISP	210		5	97		133	25	481			40	5,6

Reference legend: 1. Altuna 1981; 2. Altuna 1986; 3. Costamagno and Fano Martínez 2005; 4. Delpech 1971; 5. Delpech 1979; 6. Delpech 1983; 7. Grayson and Delpech 2003; 8. Lenoir 2003; 9. Marín-Arroyo 2013; 10. Straus 1992.

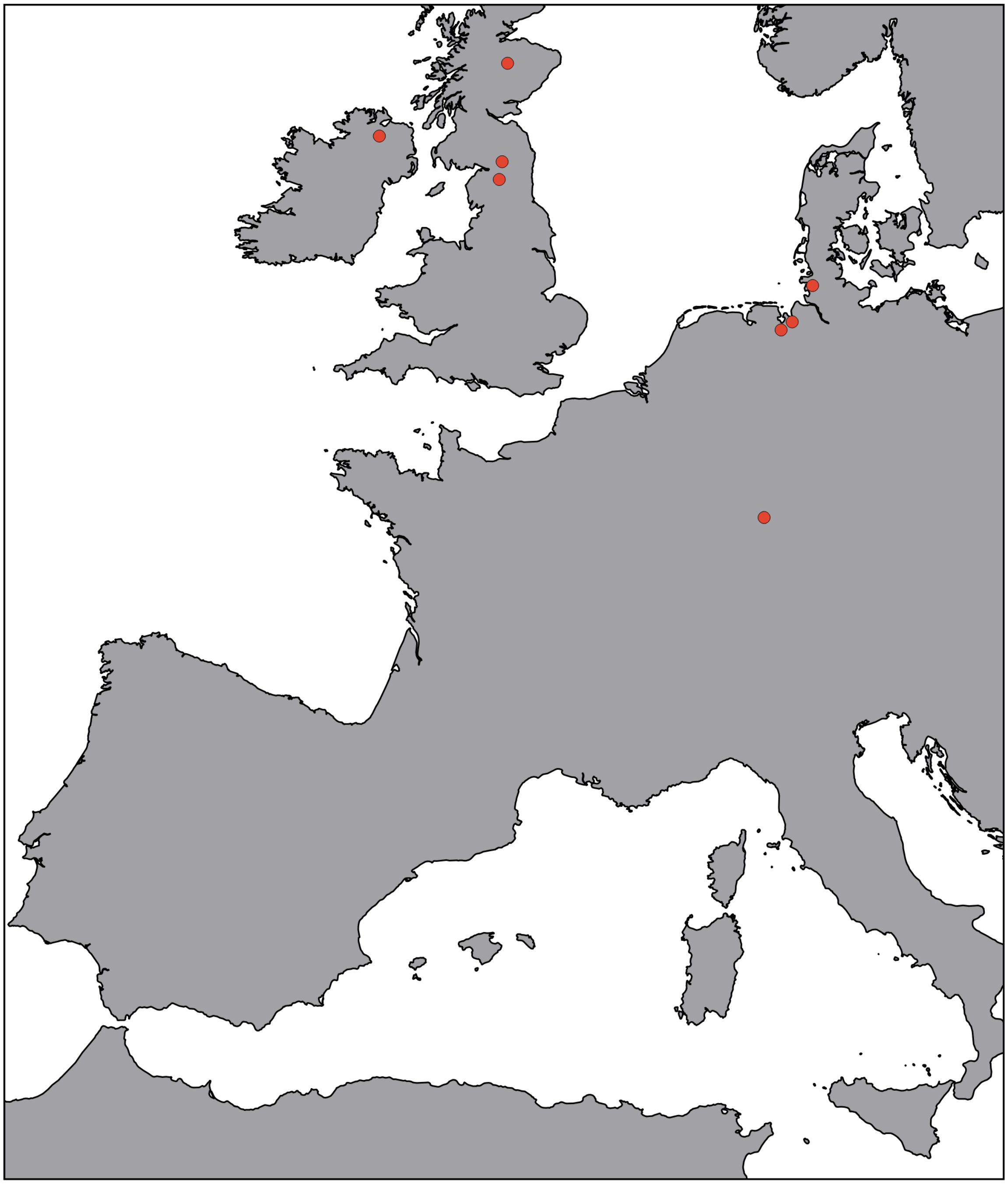
APPENDIX B

MODERN PFT DISTRIBUTION

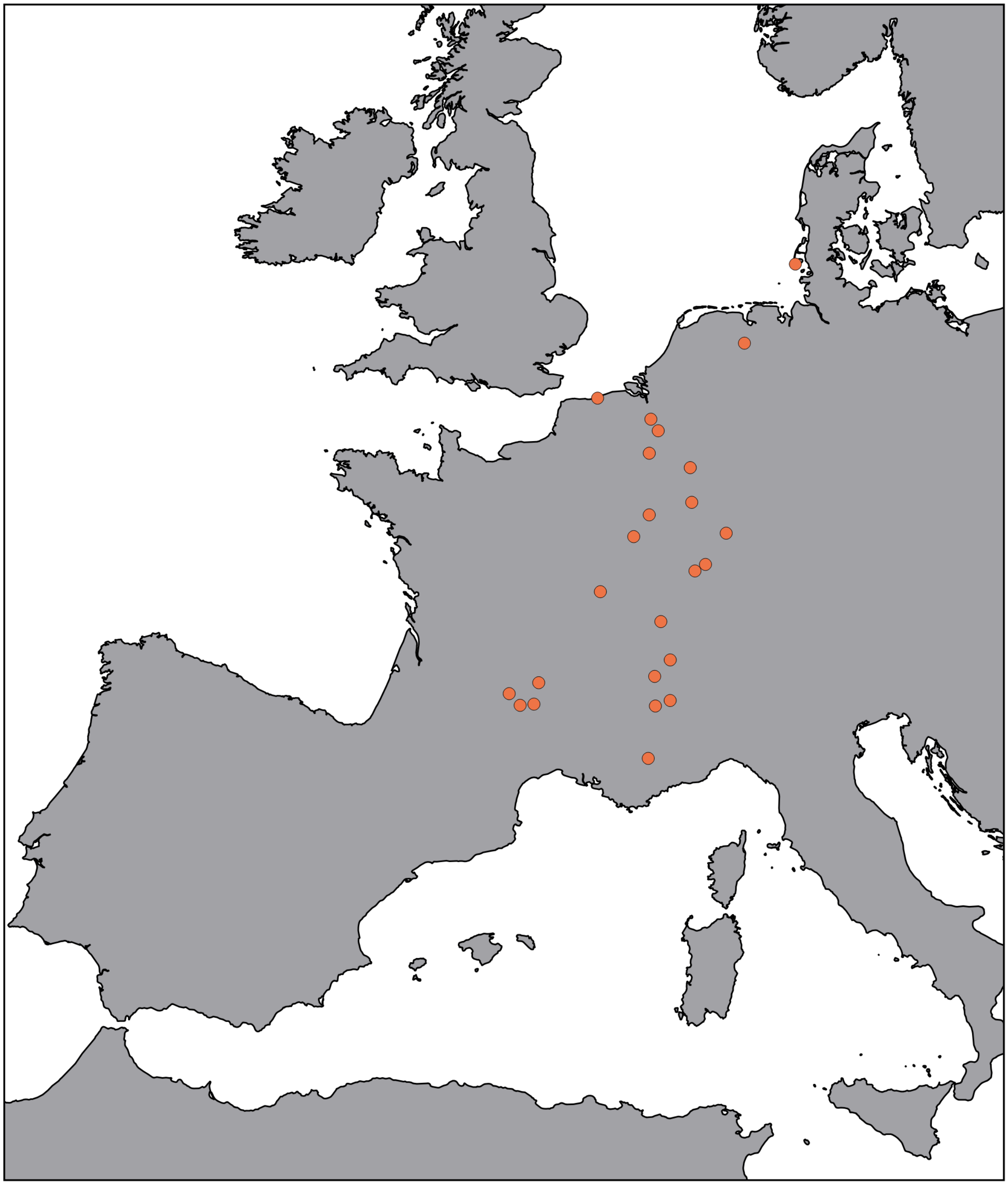
[CONSULT ALSO ATTACHED FILES]

AA modern distribution

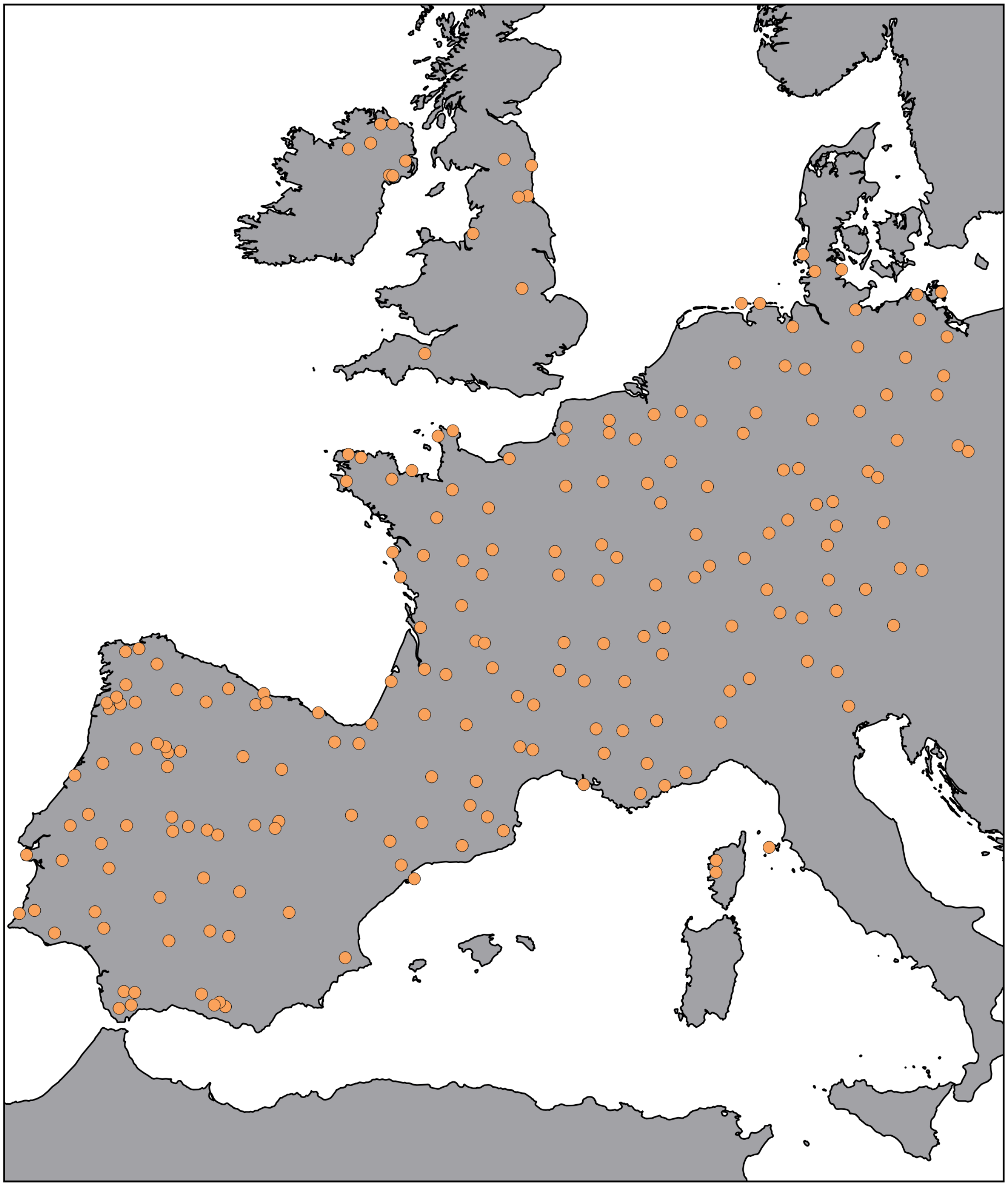
AB modern distribution



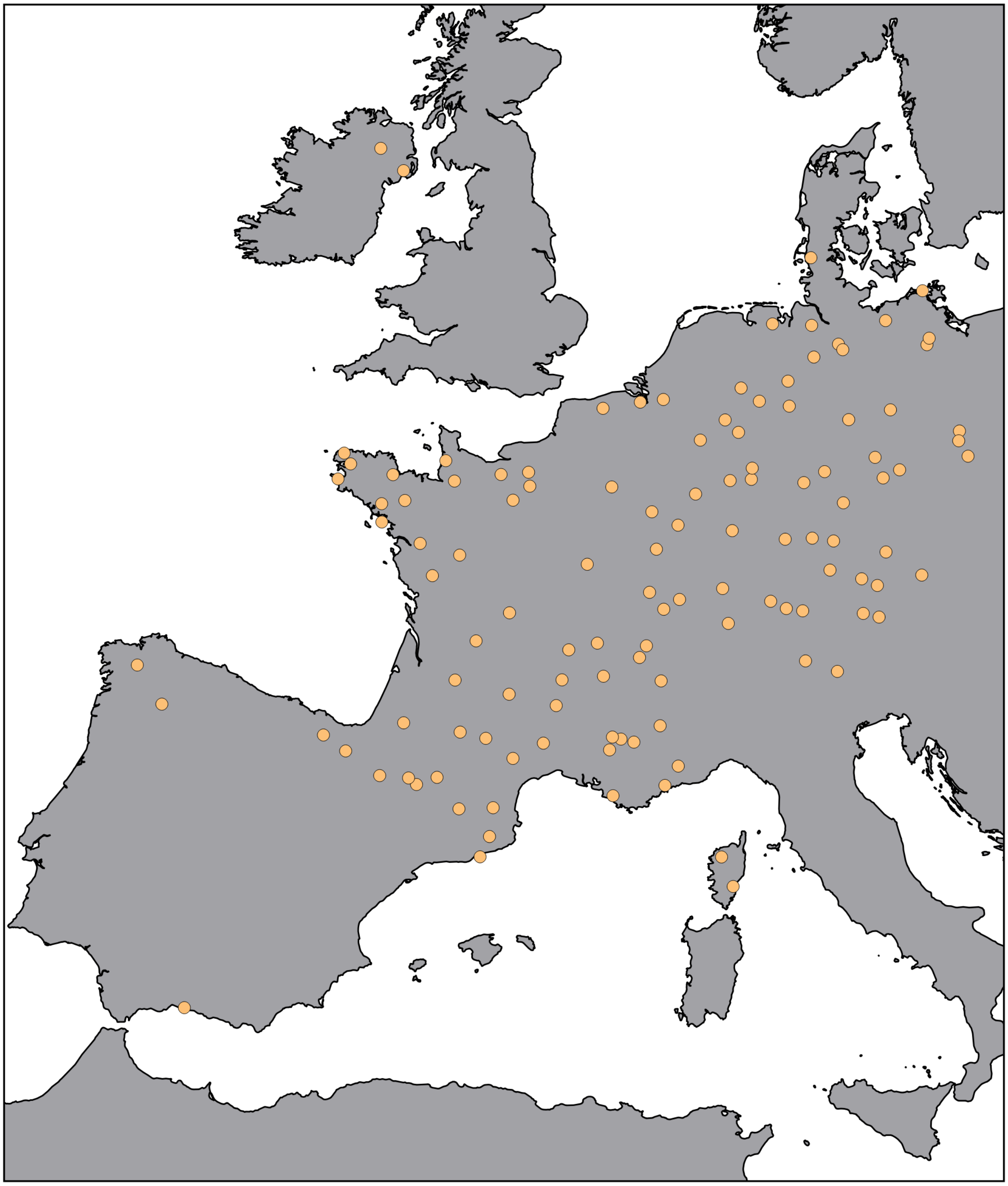
BEC modern distribution



BS modern distribution



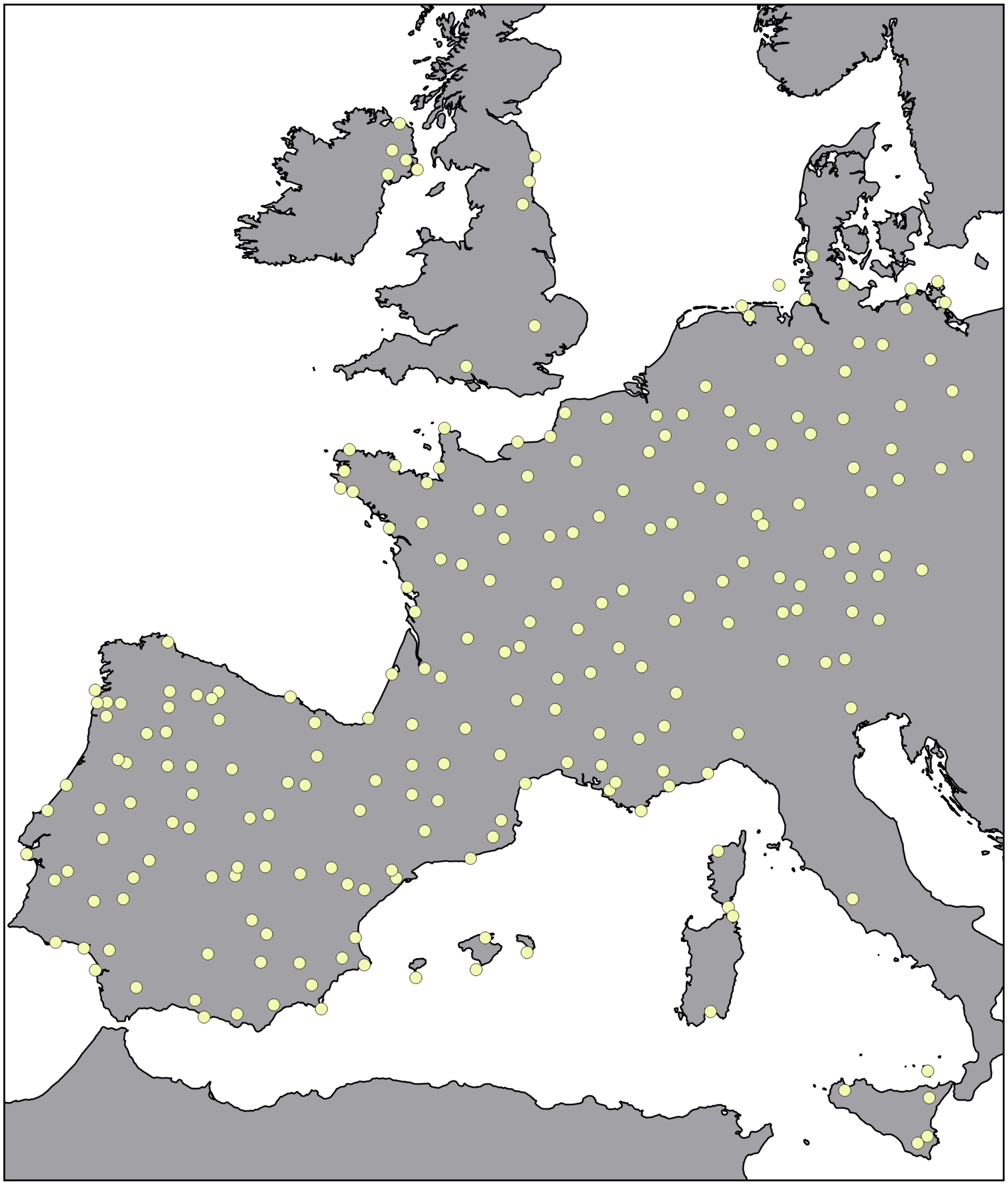
CTC modern distribution



DF modern distribution

EC modern distribution

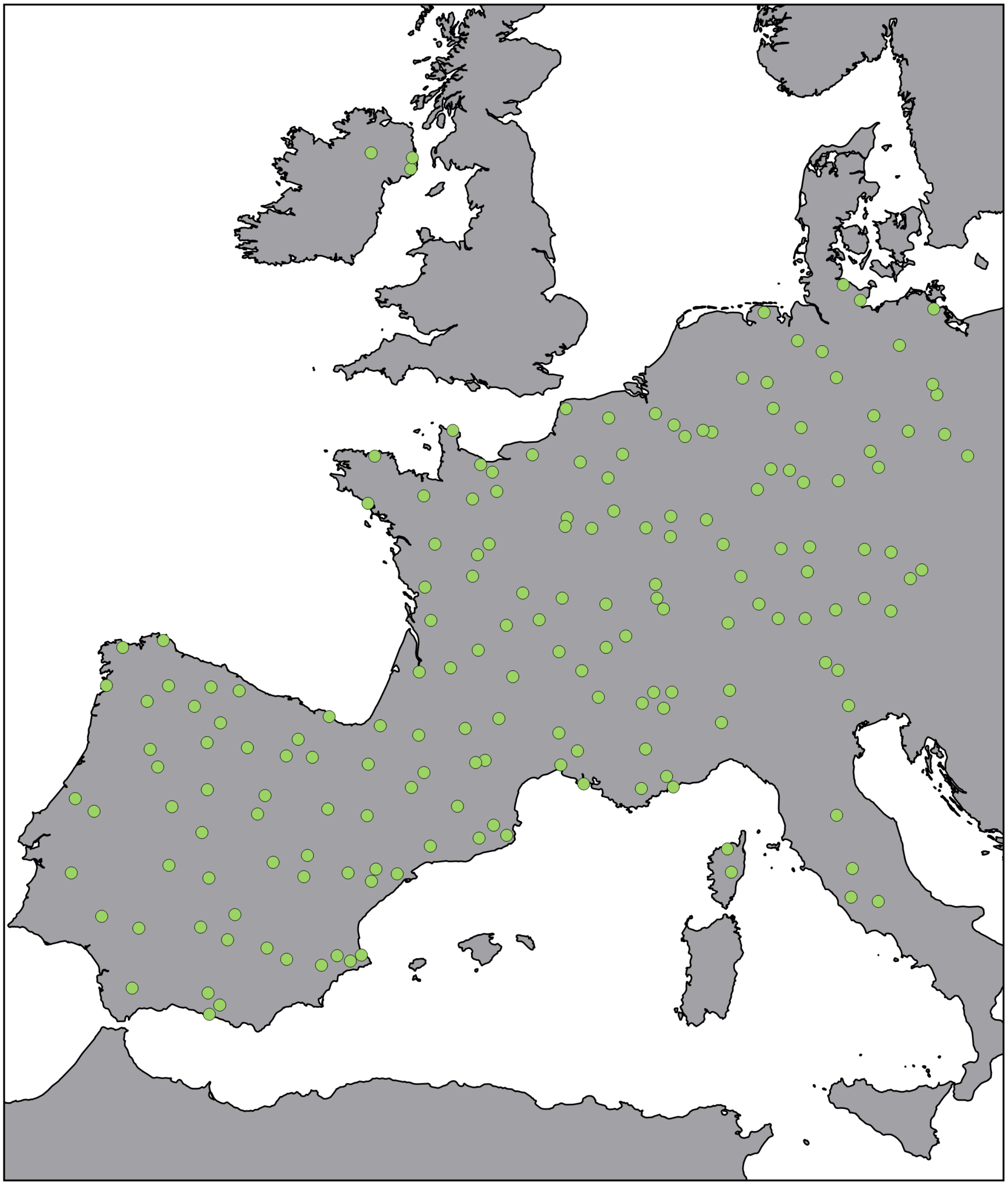
SF modern distribution



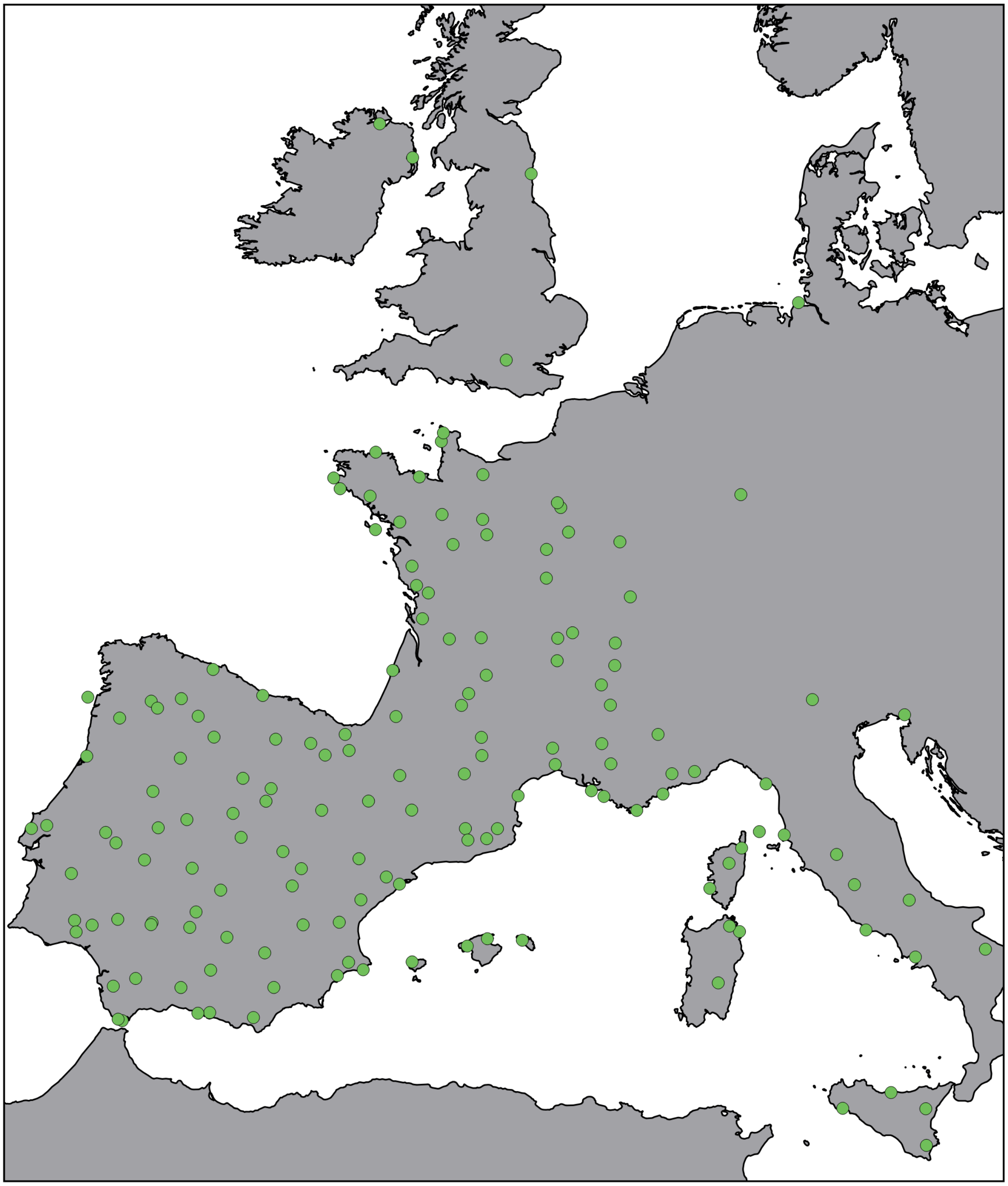
TS modern distribution

TS1 modern distribution

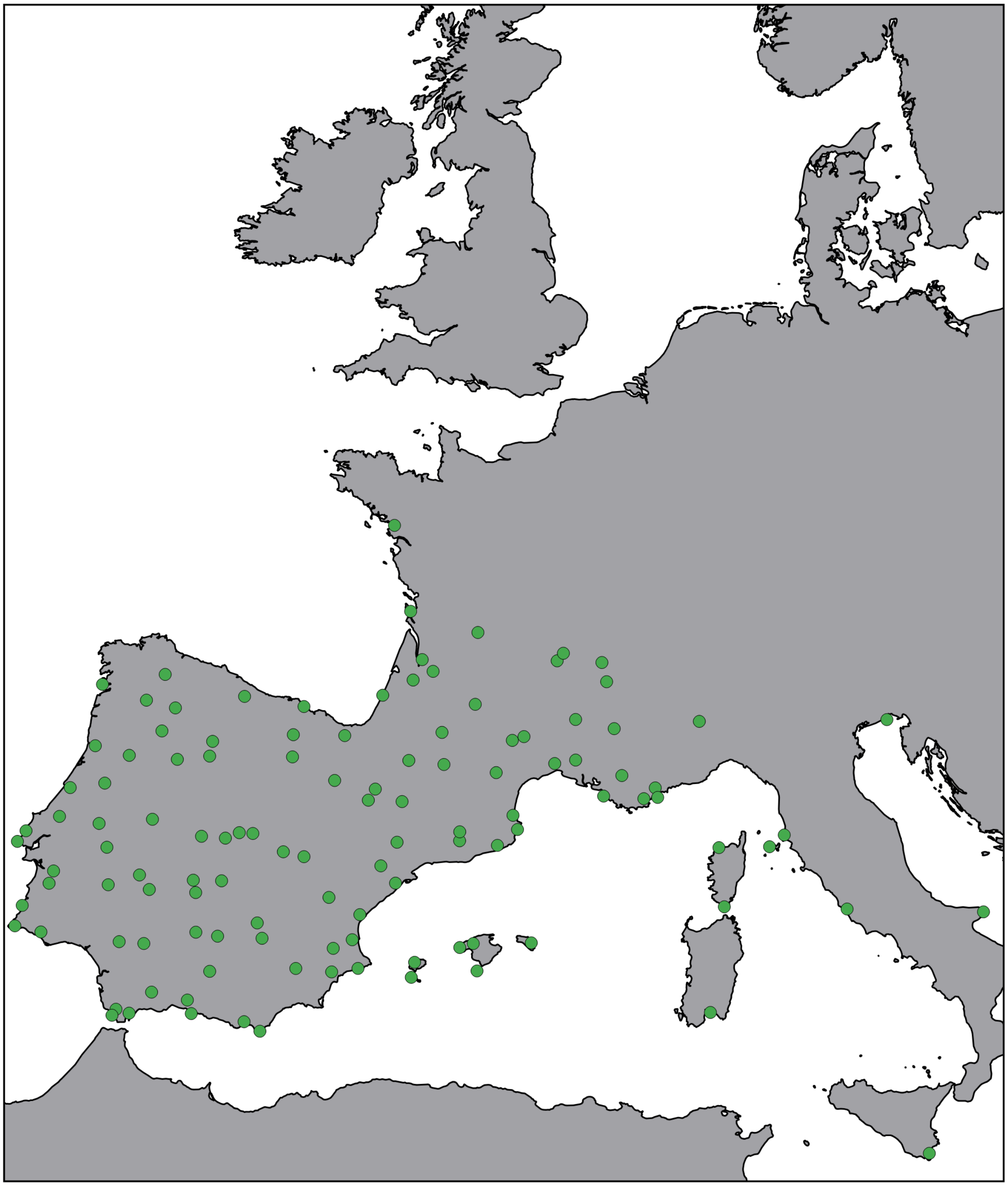
TS2 modern distribution



WTE modern distribution



WTE2 modern distribution



APPENDIX C

PREHISTORIC PFT DISTRIBUTION

[CONSULT ALSO ATTACHED FILES]

Lower Magdalenian A

Site	Latitude	Longitude	AA	AB	BEC	BS	CTC	DF	EC	SF	TS	TS1	TS2	WTE	WTE2
Lac du Bouchet	44.9167	3.7833	.	.	.	.	.	X	.	X	.	X	.	.	.
Brentenlohe	49.7872	12.4625	.	.	.	.	.	.	.	.	.	X	.	.	.
Correo	44.5083	5.9831	.	.	.	.	.	X	.	X	.	.	.	.	.
Feuenried	47.7500	8.9167	.	.	.	.	.	.	.	X	.	.	.	.	.
Lago de Ajo	43.0500	-6.1500	.	.	.	.	.	X	.	X	.	.	.	.	.
Lago Piccolo di Avigliana	45.0533	7.3842	.	.	.	.	.	.	.	X	.	.	.	.	.
Lago Grande di Monticchio	40.9444	15.6000	.	.	.	.	.	.	.	X	.	.	.	.	.

Lower Magdalenian B

Site	Latitude	Longitude	AA	AB	BEC	BS	CTC	DF	EC	SF	TS	TS1	TS2	WTE	WTE2
Lac des Boites	45.0561	5.8853	.	.	.	.	.	.	.	X	.	X	.	.	.
Bondone	46.0144	11.0458	.	.	.	.	.	.	X	X	.	.	.	.	.
Brentenlohe	49.7872	12.4625	.	.	.	.	.	.	.	.	.	X	.	.	.
Correo	44.5083	5.9831	.	.	.	.	.	X	.	X	.	.	.	.	.
Feuenried	47.7500	8.9167	.	.	.	.	.	.	.	X	.	.	.	.	.
Saint Hilaire du Rosier	45.0708	5.2567	.	.	.	.	.	X	.	X	.	.	.	.	.
Lac du Bouchet	44.9167	3.7833	.	.	.	.	.	X	.	X	.	.	.	.	.
Laguna Mesagosa	41.9653	-2.8122	.	.	.	.	.	X	.	X	.	.	.	.	.
Lago de Ajo	43.0500	-6.1500	.	.	.	.	.	X	.	X	.	X	.	.	.
Lago Piccolo di Avigliana	45.0533	7.3842	.	.	.	.	.	.	.	X	.	.	.	.	.
Lago Grande di Monticchio	40.9444	15.6000	.	.	.	.	.	.	.	X	.	.	.	.	.

Middle Magdalenian

Site	Latitude	Longitude	AA	AB	BEC	BS	CTC	DF	EC	SF	TS	TS1	TS2	WTE	WTE2
Lac des Boites	45.0561	5.8853	.	X	.	.	.	.	.	X	.	X	.	.	.
Bondone	46.0144	11.0458	.	.	.	.	.	.	X	X	.	.	.	.	.
Lac du Bouchet	44.9167	3.7833	.	.	.	.	.	X	.	X	.	X	.	.	.
Brentenlohe	49.7872	12.4625	.	.	.	.	.	.	.	.	.	X	.	.	.
La Chaumette	44.7472	3.0850	.	.	.	.	X	X	.	.	.	X	.	.	.
Correo	44.5083	5.9831	.	.	.	.	.	X	.	X	.	.	.	.	.
Feuenried	47.7500	8.9167	.	.	.	.	.	.	.	X	.	.	.	.	.
Saint Hilaire du Rosier	45.0708	5.2567	.	.	.	.	.	X	.	X	.	.	.	.	.
Laguna Negra	42.0003	-2.8483	.	.	.	.	.	X	.	.	.	.	.	.	.
Lago de Ajo	43.0500	-6.1500	.	.	.	.	.	X	.	X	.	X	.	.	.
Lago Piccolo di Avigliana	45.0533	7.3842	.	.	.	.	.	.	.	X	.	.	.	.	.
Lago Grande di Monticchio	40.9444	15.6000	.	.	.	.	.	.	.	X	.	.	.	.	.
San Rafael	36.7736	-2.6014	.	.	.	.	.	.	.	.	.	.	.	X	.
Son Bou	39.9247	4.0272	.	.	.	.	.	.	.	.	.	X	.	X	.
Tanneurs	47.2139	-1.5572	.	.	.	.	.	.	.	X	.	X	.	.	.

Upper Magdalenian A

Site	Latitude	Longitude	AA	AB	BEC	BS	CTC	DF	EC	SF	TS	TS1	TS2	WTE	WTE2
Hieres sur Amby	45.7908	5.2833	.	.	.	.	.	X	.	X	.	.	.	.	.
Lac des Boites	45.0561	5.8853	.	X	.	.	X	.	.	.	.	X	.	.	.
Bondone	46.0144	11.0458	.	.	.	.	.	.	X	X	.	.	.	.	.
Lac du Bouchet	44.9167	3.7833	.	.	.	.	.	X	.	X	.	X	.	.	.
Brentenlohe	49.7872	12.4625	.	.	.	.	.	.	.	.	.	X	.	.	.
Selle di Carnino	44.1500	7.6944	.	.	.	.	X	X	.	X	.	.	.	.	.
La Chaumette	44.7472	3.0850	X	.	X	X	X	X	.	X	.	X	.	.	.
Tourbiere des Granges des Chavants	45.8931	6.7683	.	.	.	.	.	.	.	X	.	X	.	.	.
Correo	44.5083	5.9831	.	.	.	.	.	X	.	X	.	.	.	.	.
Feuenried	47.7500	8.9167	.	.	.	.	.	.	.	X	.	.	.	.	.
Durchenbergried	47.7833	8.9833	.	.	.	.	.	.	.	X	.	.	.	.	.
Saint Hilaire du Rosier	45.0708	5.2567	.	.	.	.	.	.	.	X	.	.	.	.	.
Saint Hilaire du Rosier	45.0708	5.2567	.	.	.	.	.	X	.	X	.	.	.	.	.
Laguna Negra	42.0003	-2.8483	.	.	.	.	.	X	.	.	.	.	.	.	.
Lago de Ajo	43.0500	-6.1500	.	.	.	.	.	X	.	X	.	.	.	.	.
Lago Piccolo di Avigliana	45.0533	7.3842	.	.	.	.	.	.	.	X	.	.	.	.	.
Le Loch Sunart	56.6667	-5.8667	.	.	.	.	.	.	.	.	.	X	.	.	.
Lôttersee	51.5767	10.1617	.	.	X	.	.	.	.	.	.	X	.	.	.

Site	Latitude	Longitude	AA	AB	BEC	BS	CTC	DF	EC	SF	TS	TS1	TS2	WTE	WTE2
Lago Grande di Monticchio	40.9444	15.6000	.	.	.	.	.	.	.	X	.	X	.	.	.
Pezou	47.8708	1.1508	.	.	.	.	.	.	.	X	.	X	.	.	.
San Rafael	36.7736	-2.6014	.	.	.	.	X	.	.	X	.	X	.	X	.
Son Bou	39.9247	4.0272	.	.	.	.	.	.	.	.	.	X	.	X	X
Tanneurs	47.2139	-1.5572	.	.	.	.	.	.	.	.	.	X	.	.	.

Upper Magdalenian B

Site	Latitude	Longitude	AA	AB	BEC	BS	CTC	DF	EC	SF	TS	TS1	TS2	WTE	WTE2
Hieres sur Amby	45.7908	5.2833	.	.	.	.	.	.	.	X	.	.	.	.	.
Altenweiher	48.0133	6.9944	.	.	.	.	.	.	.	X	.	.	.	.	.
Lac des Boites	45.0561	5.8853	.	X	.	.	X	.	.	.	.	X	.	.	.
Bondone	46.0144	11.0458	.	.	.	.	.	.	X	.	X	X	.	.	.
Lac du Bouchet	44.9167	3.7833	.	.	.	.	.	X	.	X	.	.	.	.	.
Selle di Carnino	44.1500	7.6944	.	.	.	.	.	X	.	X	.	.	.	.	.
La Chaumette	44.7472	3.0850	.	.	.	.	X	.	.	X	.	.	.	.	.
Tourbiere des Granges des Chavants	45.8931	6.7683	.	.	.	.	.	.	.	.	.	X	.	.	.
Correo	44.5083	5.9831	.	.	.	.	.	X	.	X	.	.	.	.	.
Saint Hilaire du Rosier	45.0708	5.2567	.	.	.	.	.	X	.	X	.	.	.	.	.
Saint Hilaire du Rosier	45.0708	5.2567	.	.	.	.	.	X	.	X	.	.	.	.	.
Laguna Negra	42.0003	-2.8483	.	.	.	.	.	X	.	.	.	.	.	.	.
Lago de Ajo	43.0500	-6.1500	.	.	.	.	.	X	.	X	.	X	.	.	.
Lago Piccolo di Avigliana	45.0533	7.3842	.	.	.	.	.	.	X	X	.	.	.	.	.
Le Loch Sunart	56.6667	-5.8667	.	.	.	.	X	.	.	.	.	X	.	.	.
Lôttersee	51.5767	10.1617	.	.	X	.	.	.	.	.	.	.	.	.	.
Lago Grande di Monticchio	40.9444	15.6000	.	.	.	.	.	.	.	.	.	X	.	.	.
Pezou	47.8708	1.1508	.	.	.	.	.	.	.	X	.	.	.	.	.

Site	Latitude	Longitude	AA	AB	BEC	BS	CTC	DF	EC	SF	TS	TS1	TS2	WTE	WTE2
Grand Ratz le Pellet	45.4250	5.6083	.	.	.	.	.	X	.	.	.	.	.	.	.
San Rafael	36.7736	-2.6014	.	.	.	.	.	.	.	.	.	.	.	X	.
Tanneurs	47.2139	-1.5572	.	.	.	.	.	.	.	.	.	X	.	.	.

APPENDIX D

SITES AND DATES

[CONSULT ATTACHED FILES]

APPENDIX E

METHODS FLOWCHART – BIOME RECONSTRUCTION

[CONSULT ATTACHED FILES]

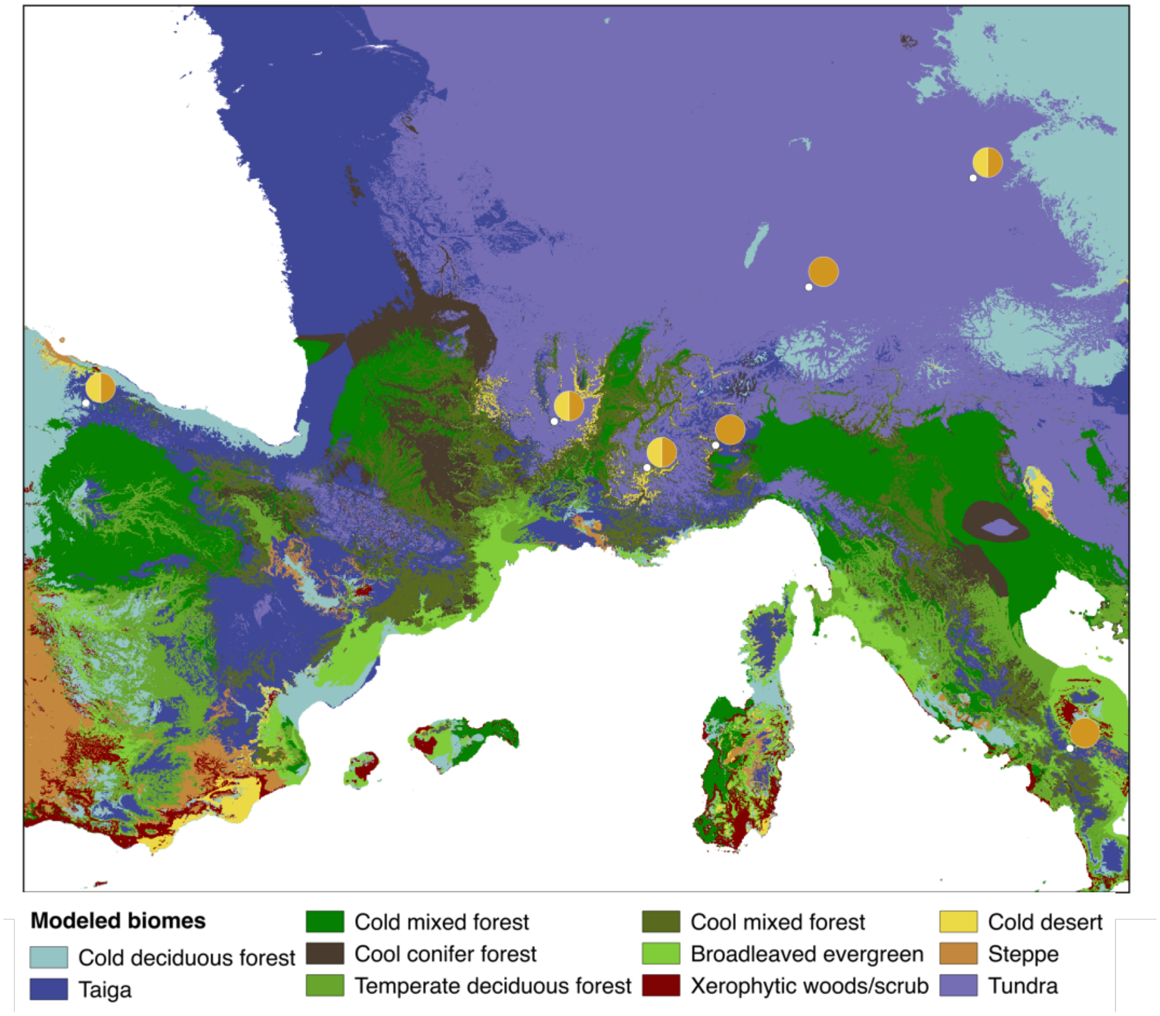
APPENDIX F

RECONSTRUCTED BIOMES

Reconstructions – Climate-only

Pollen records

Lower Magdalenian A



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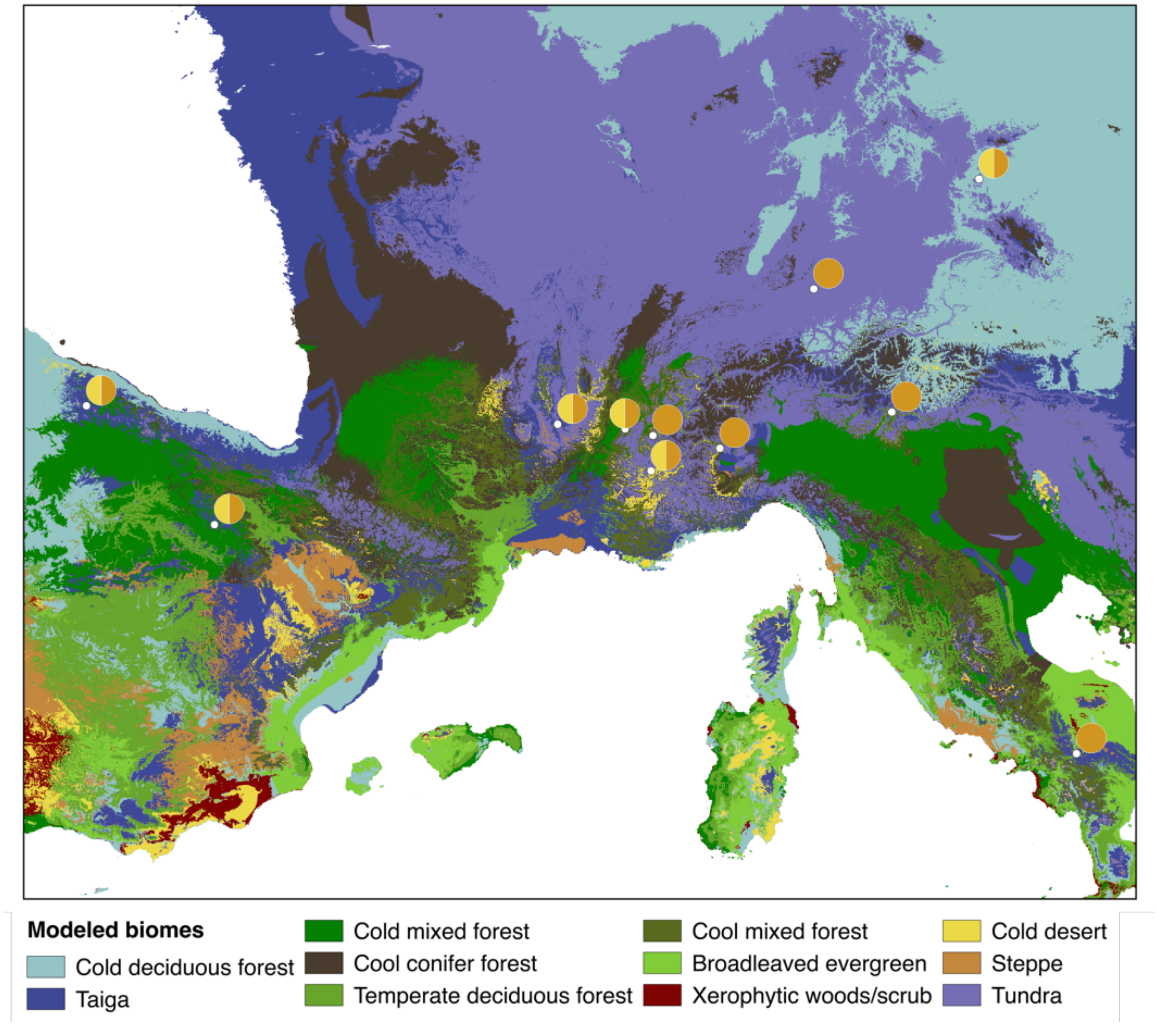

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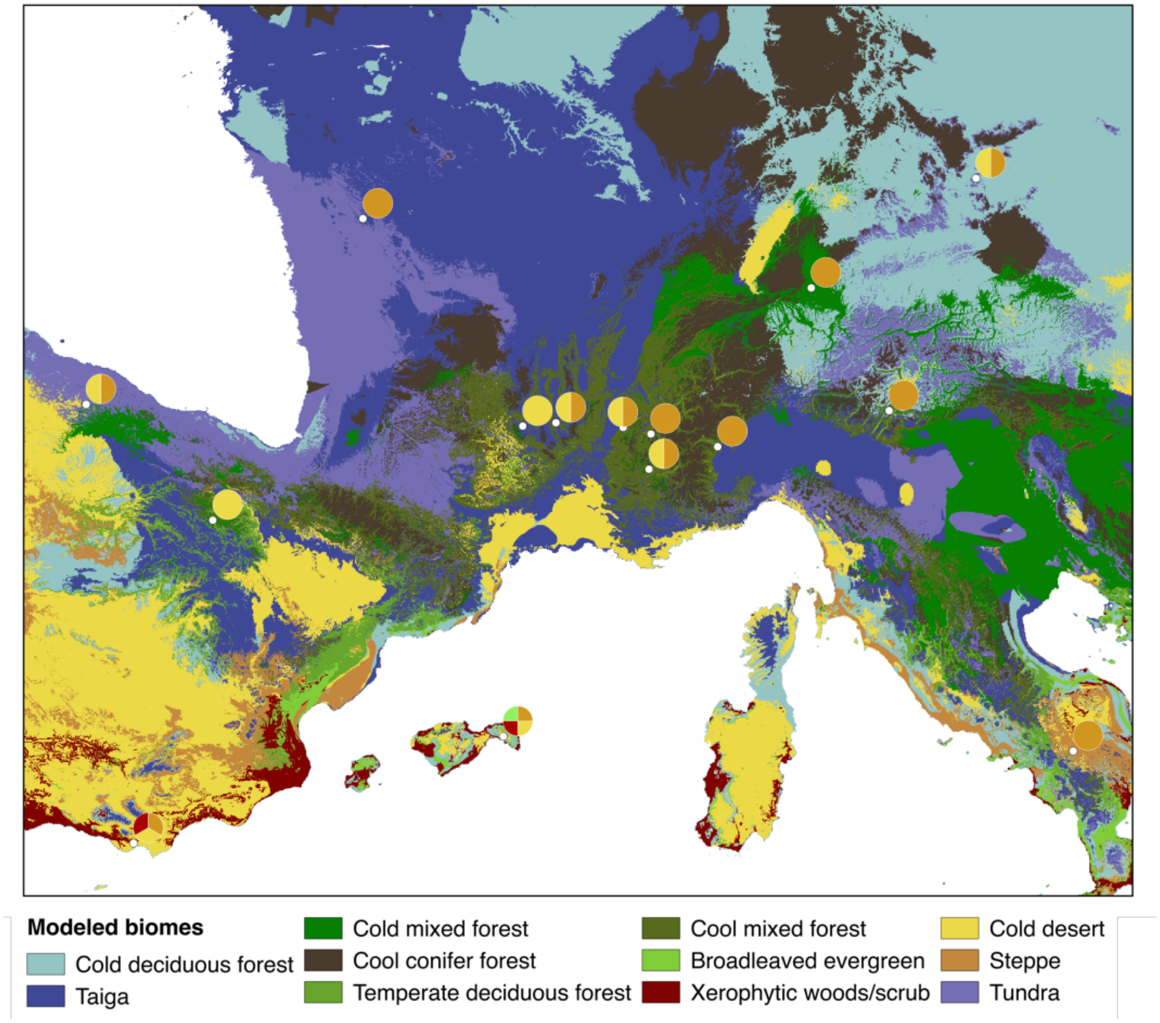
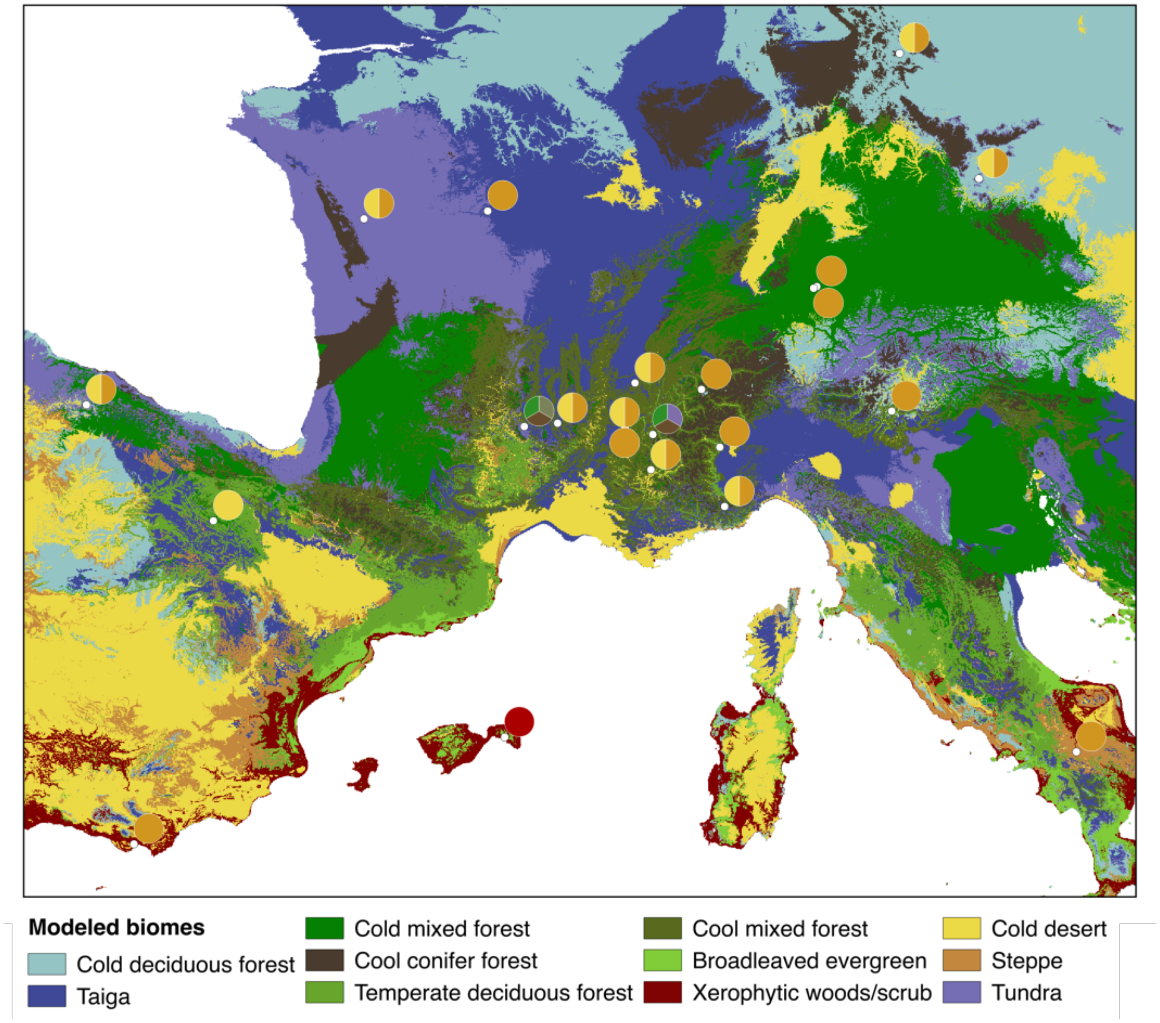


Upper Magdalenian A



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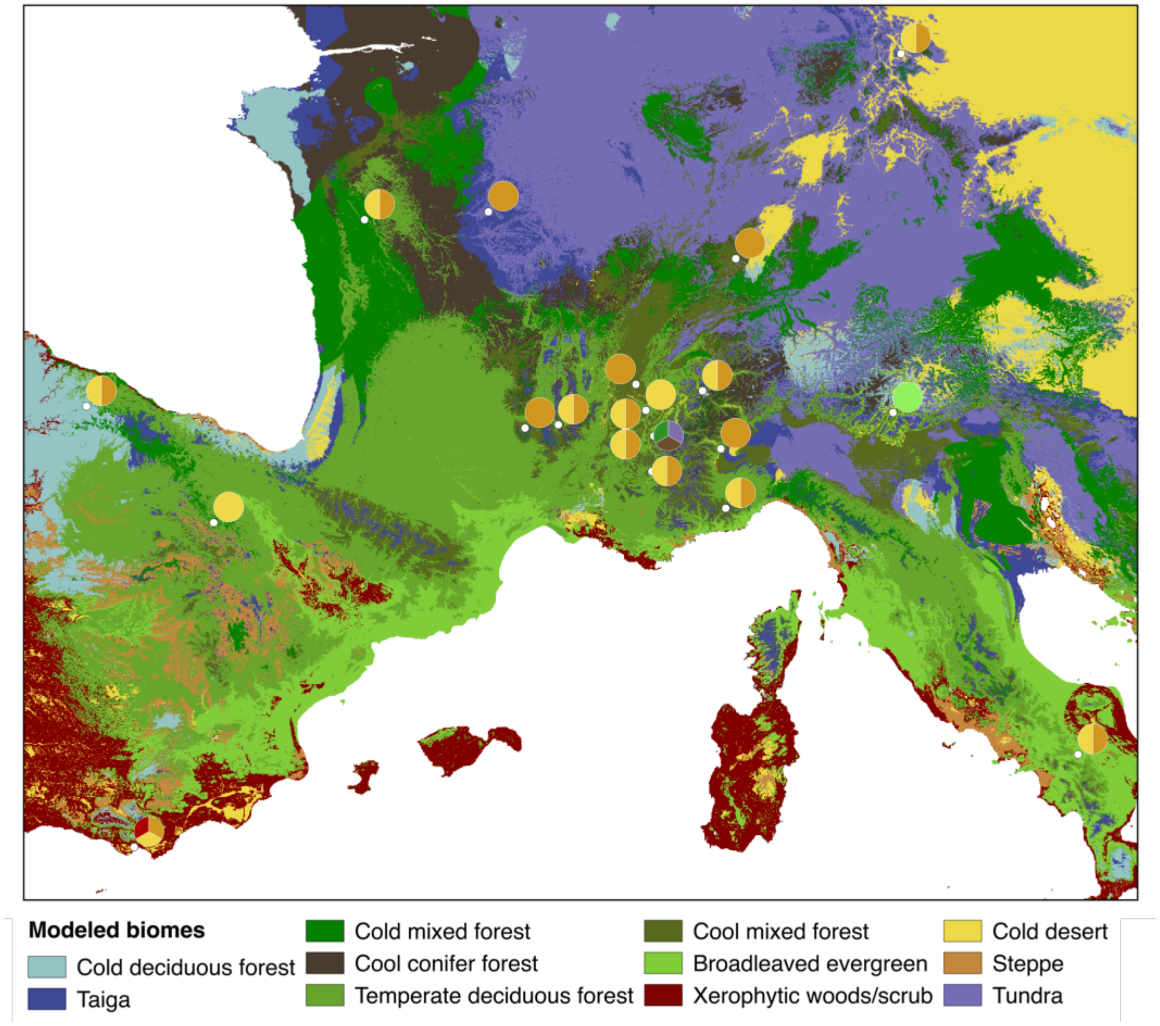
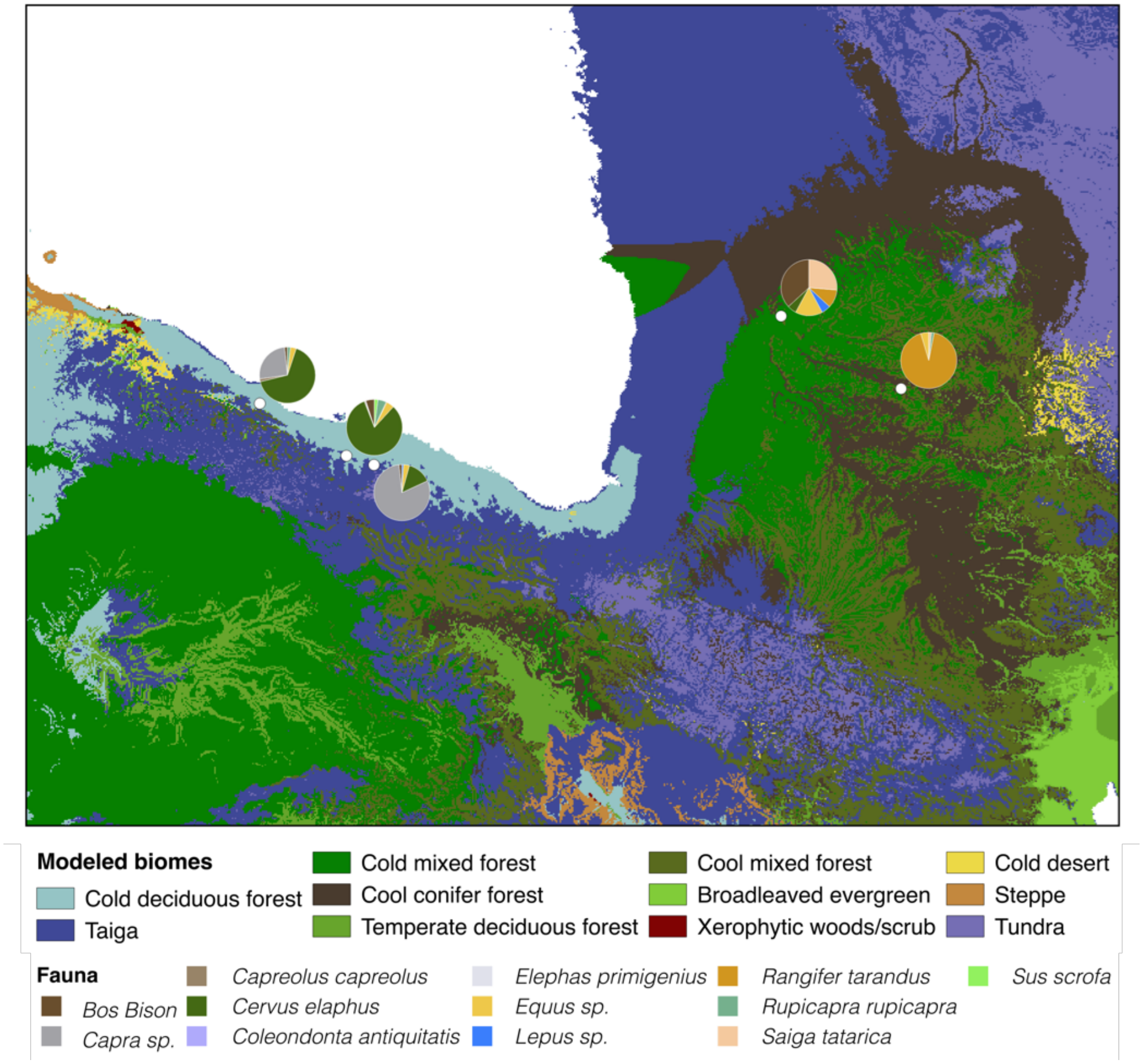


Faunal records

Lower Magdalenian A



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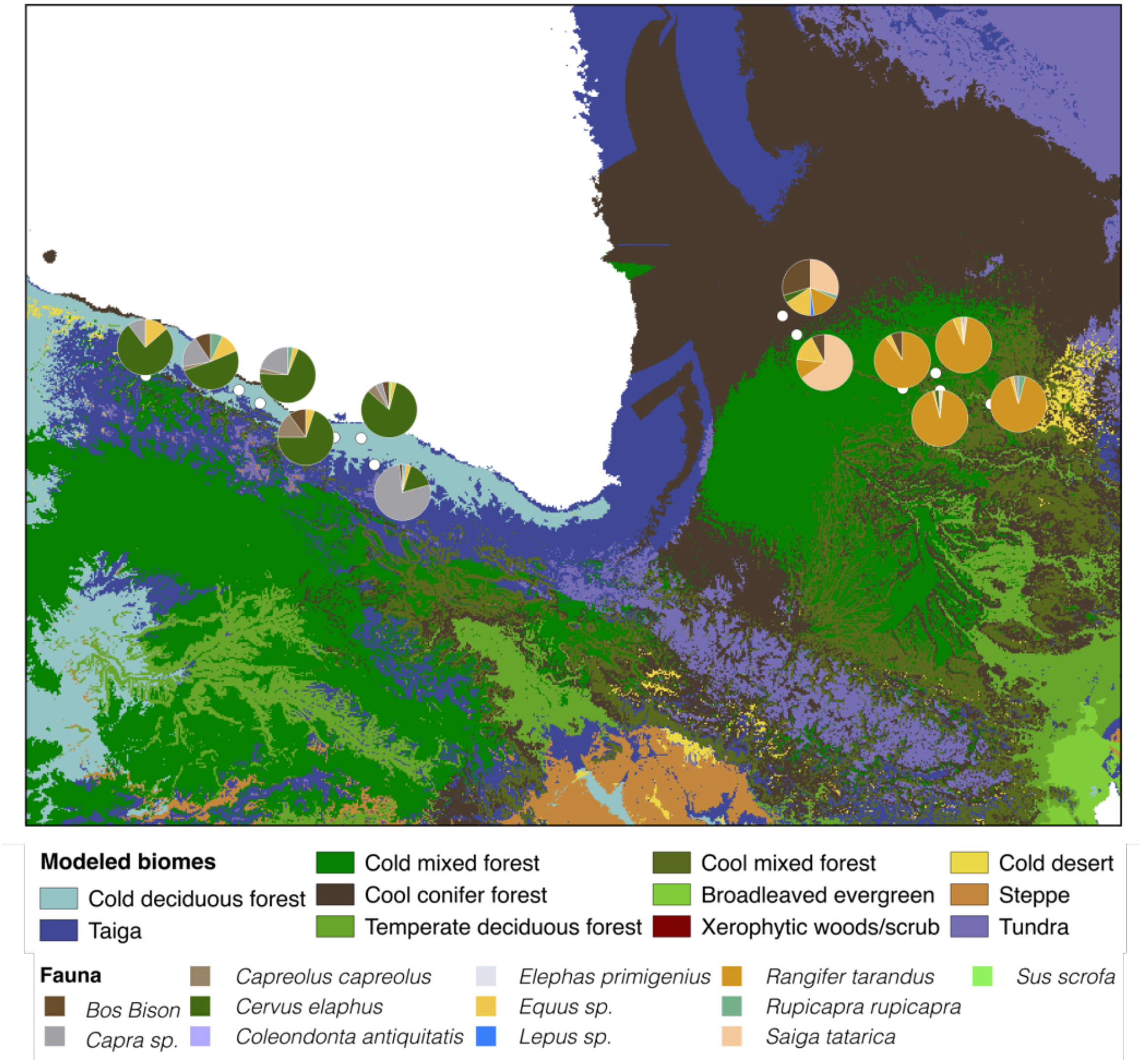
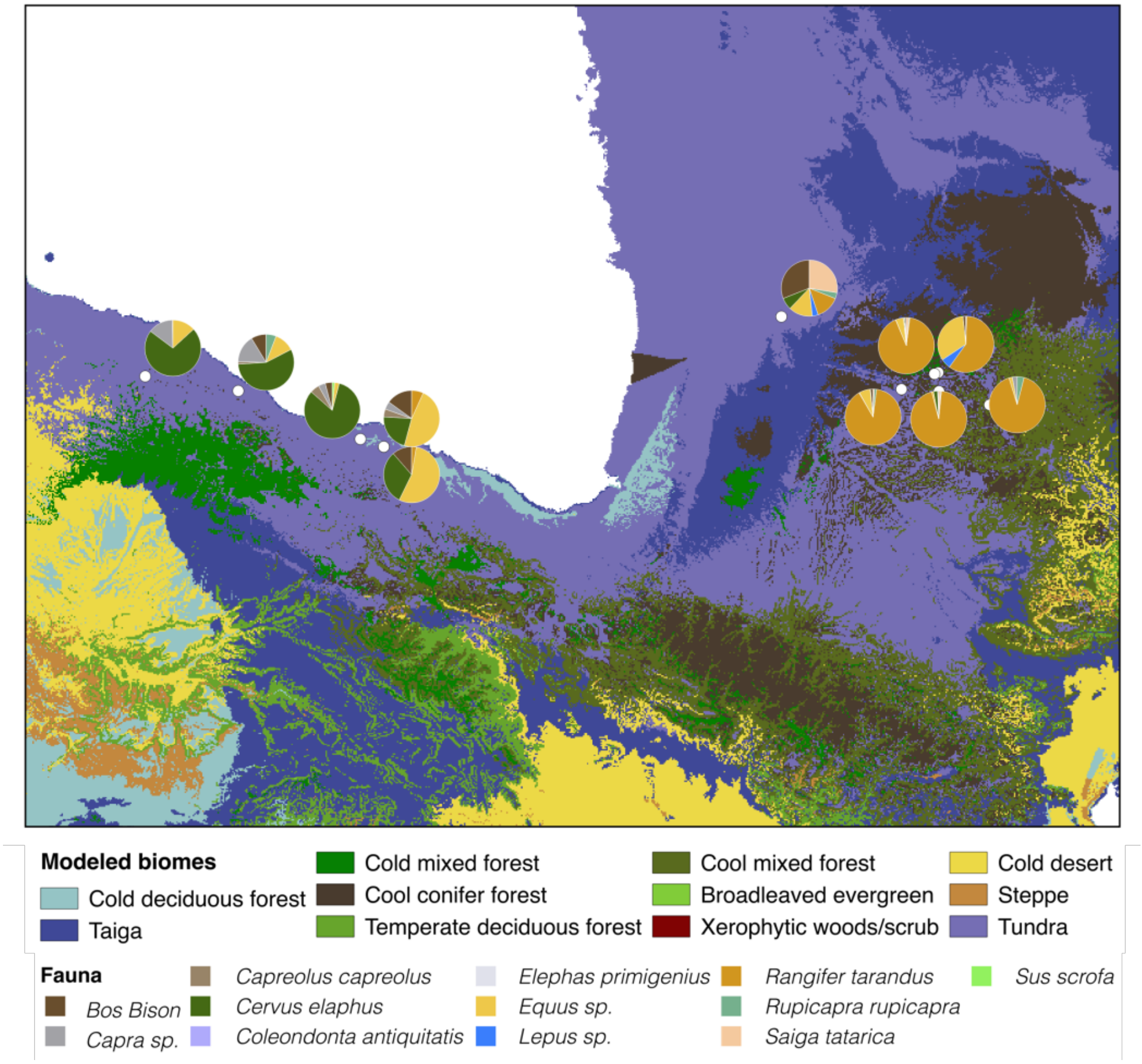
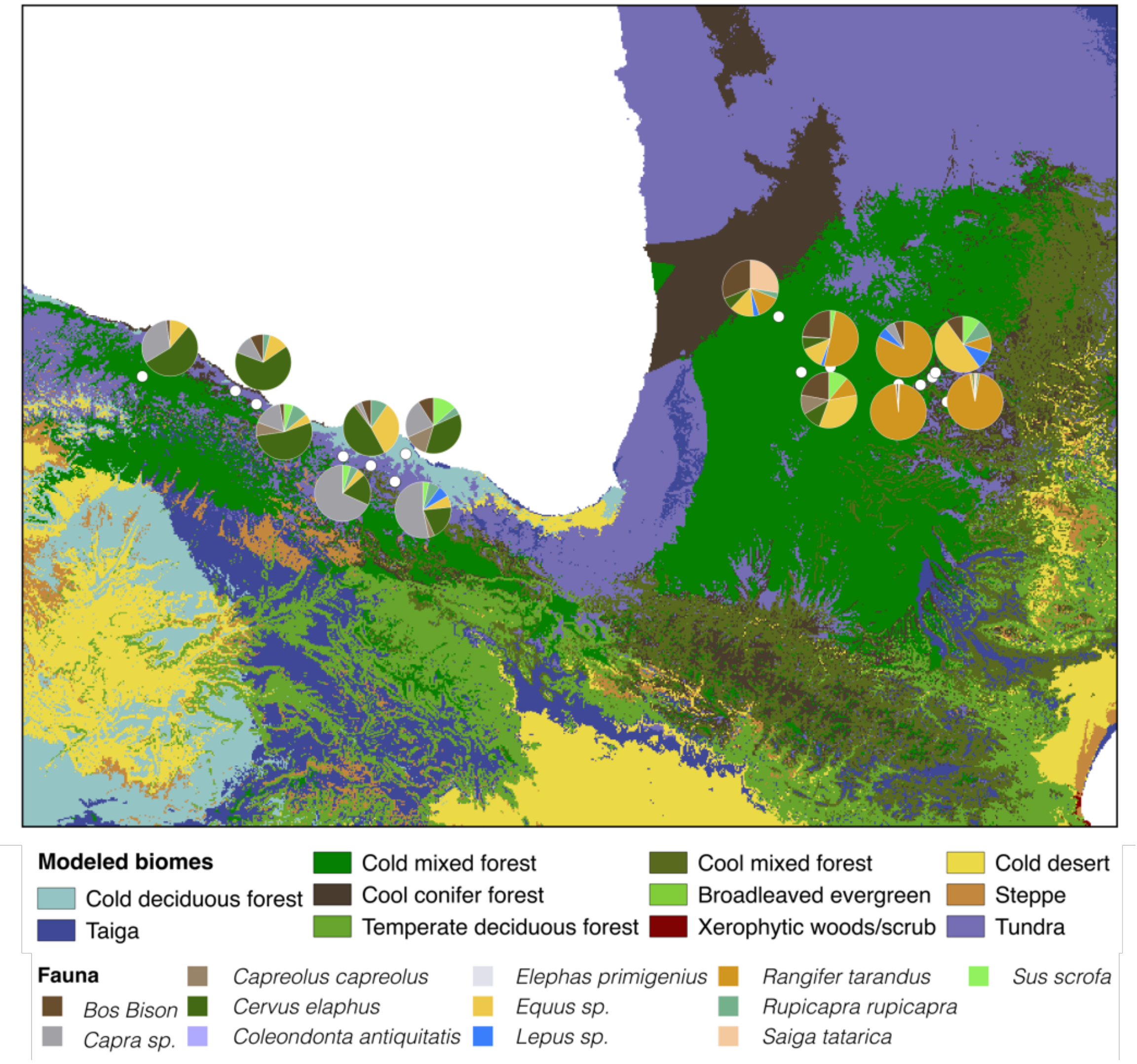


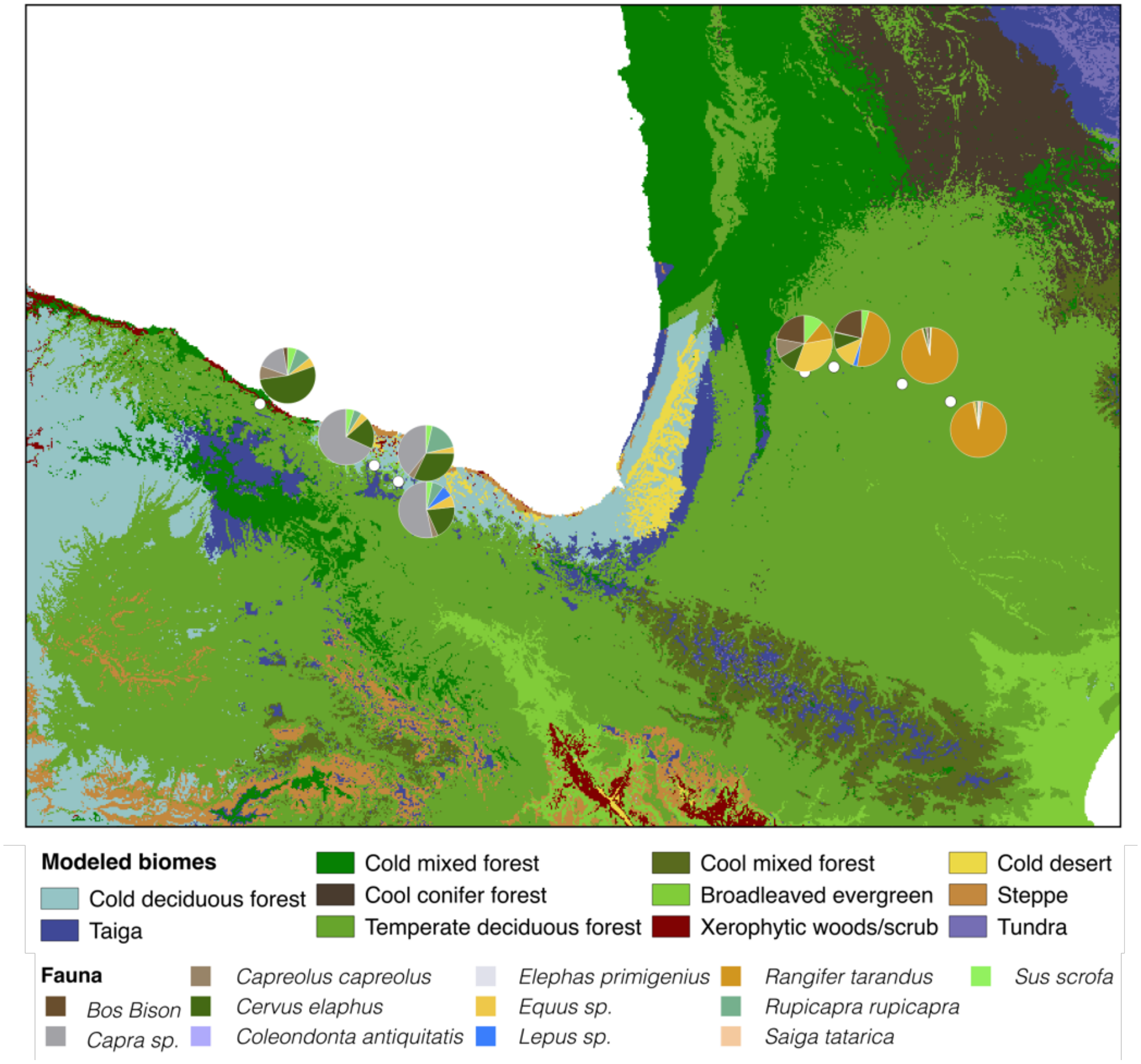
Middle Magdalenian



Upper Magdalenian A



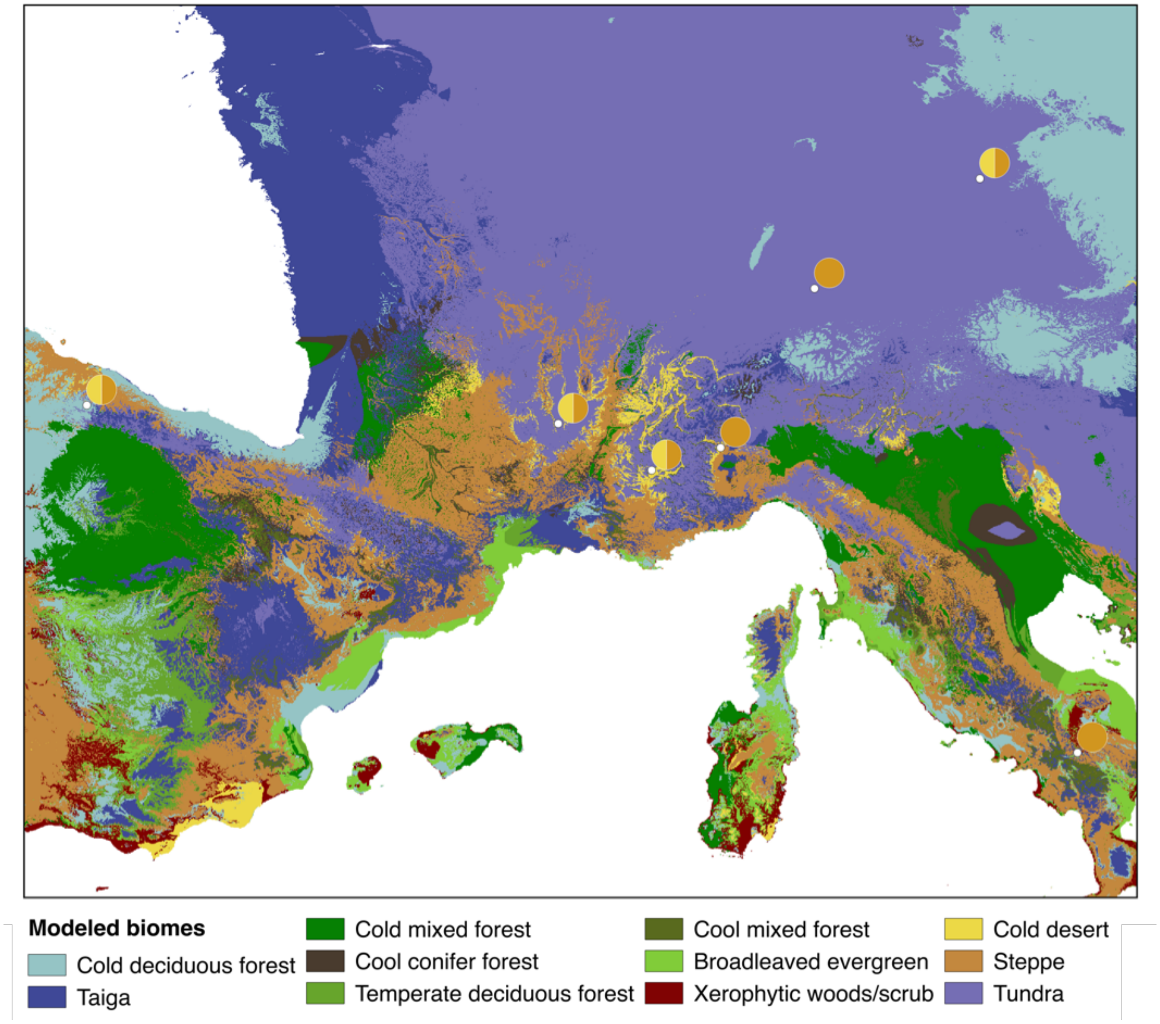
Upper Magdalenian B



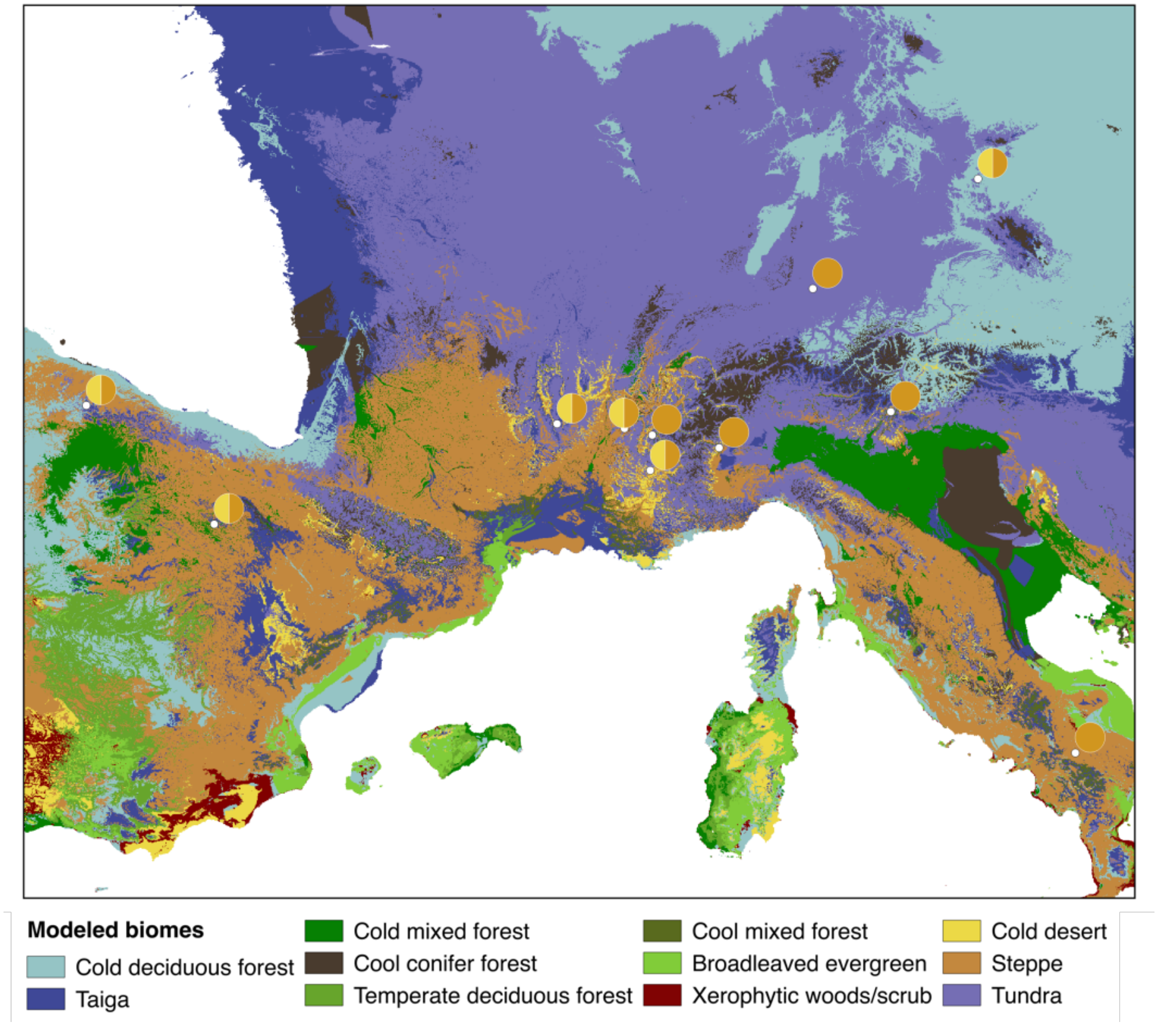
Reconstructions – Human-climate

Pollen records

Lower Magdalenian A



Lower Magdalenian B



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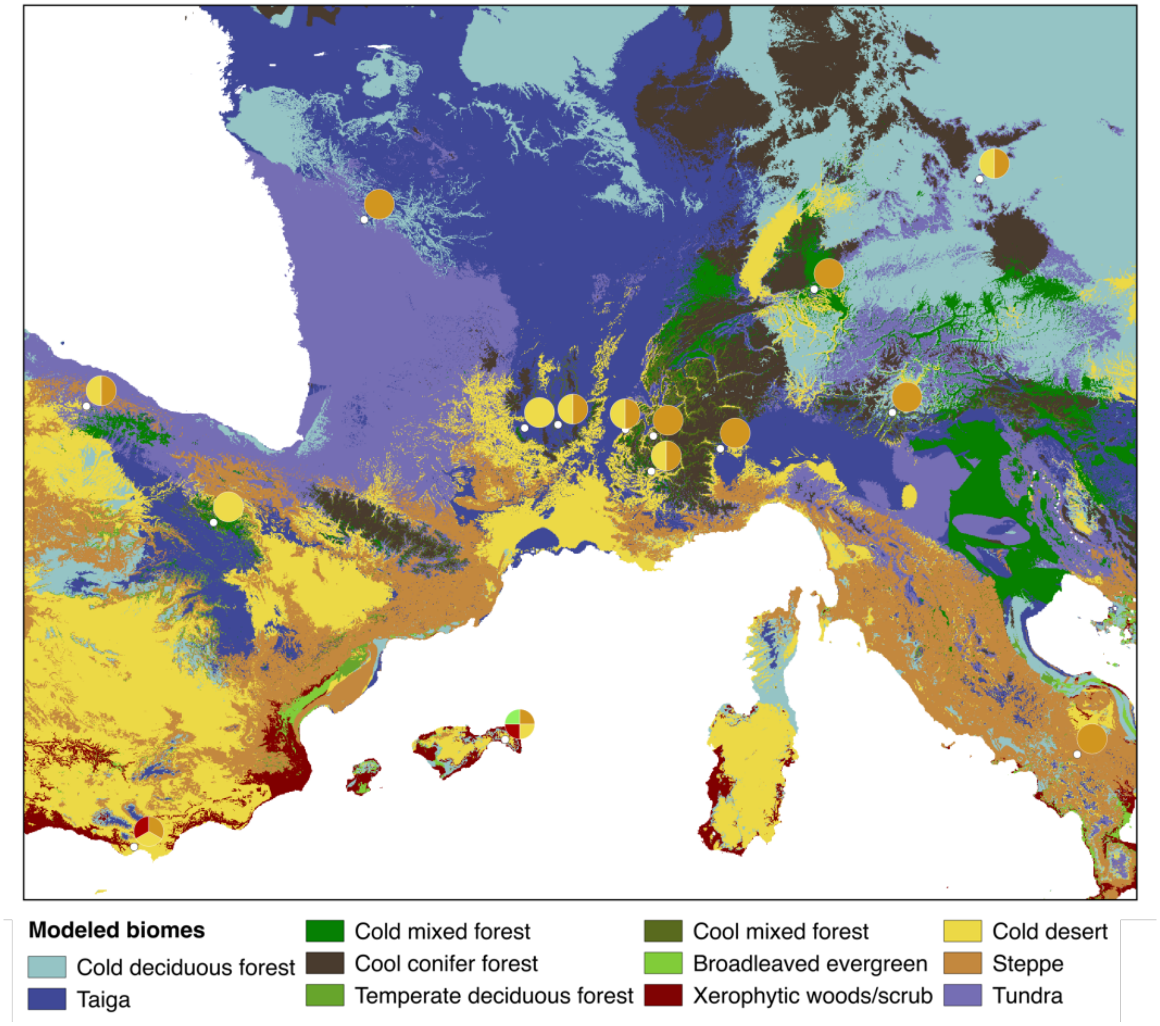
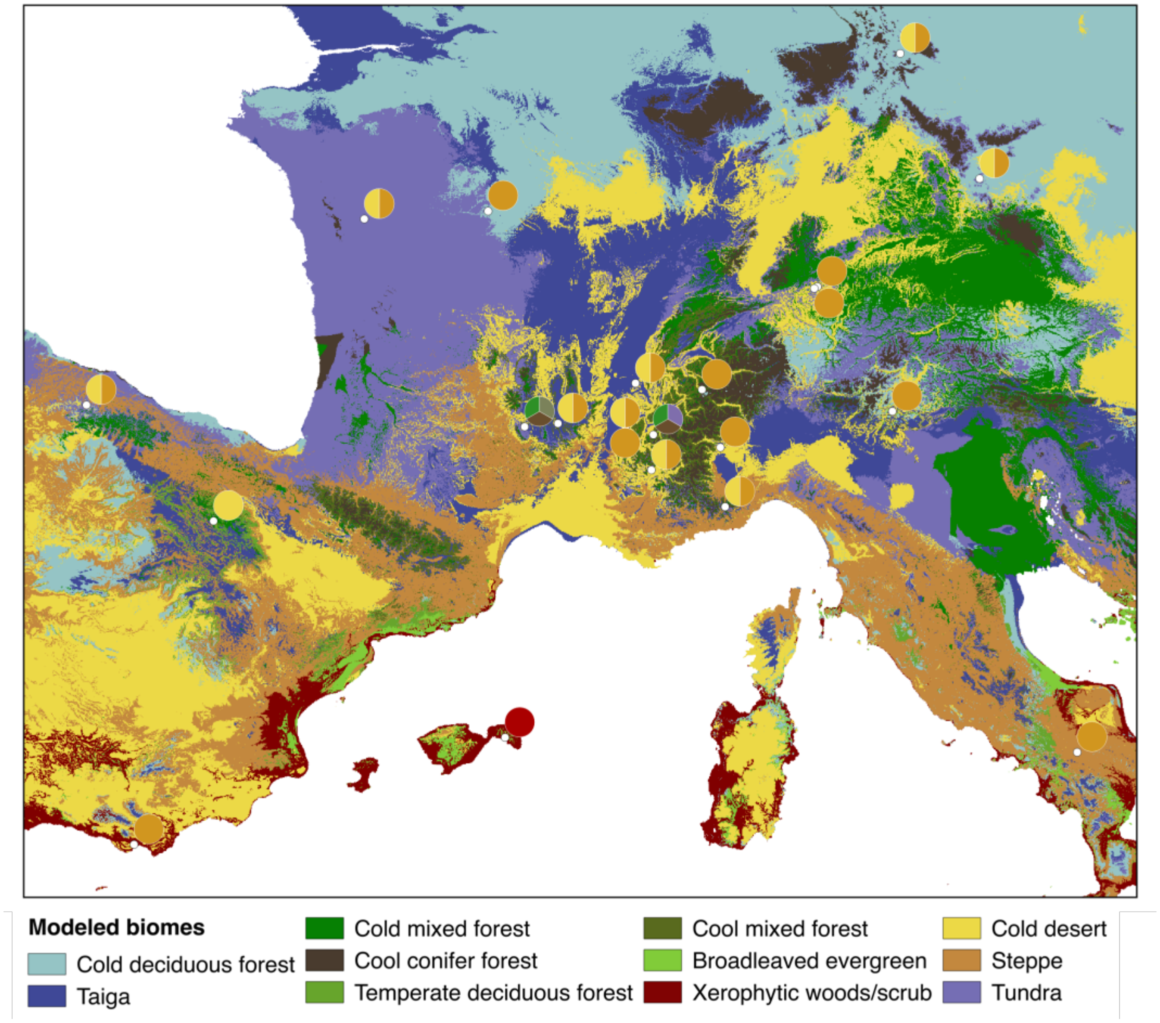
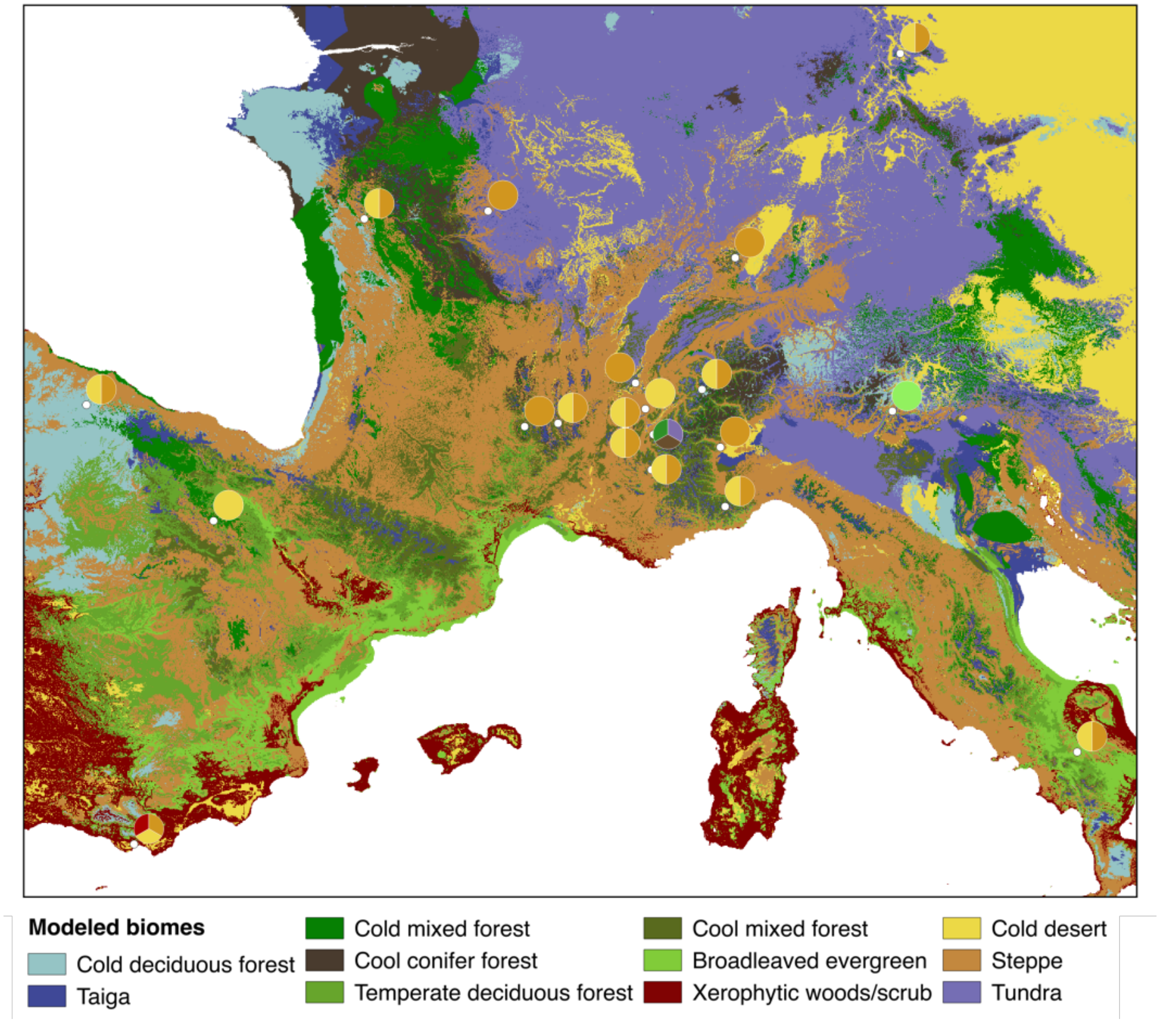


Upper Magdalenian A

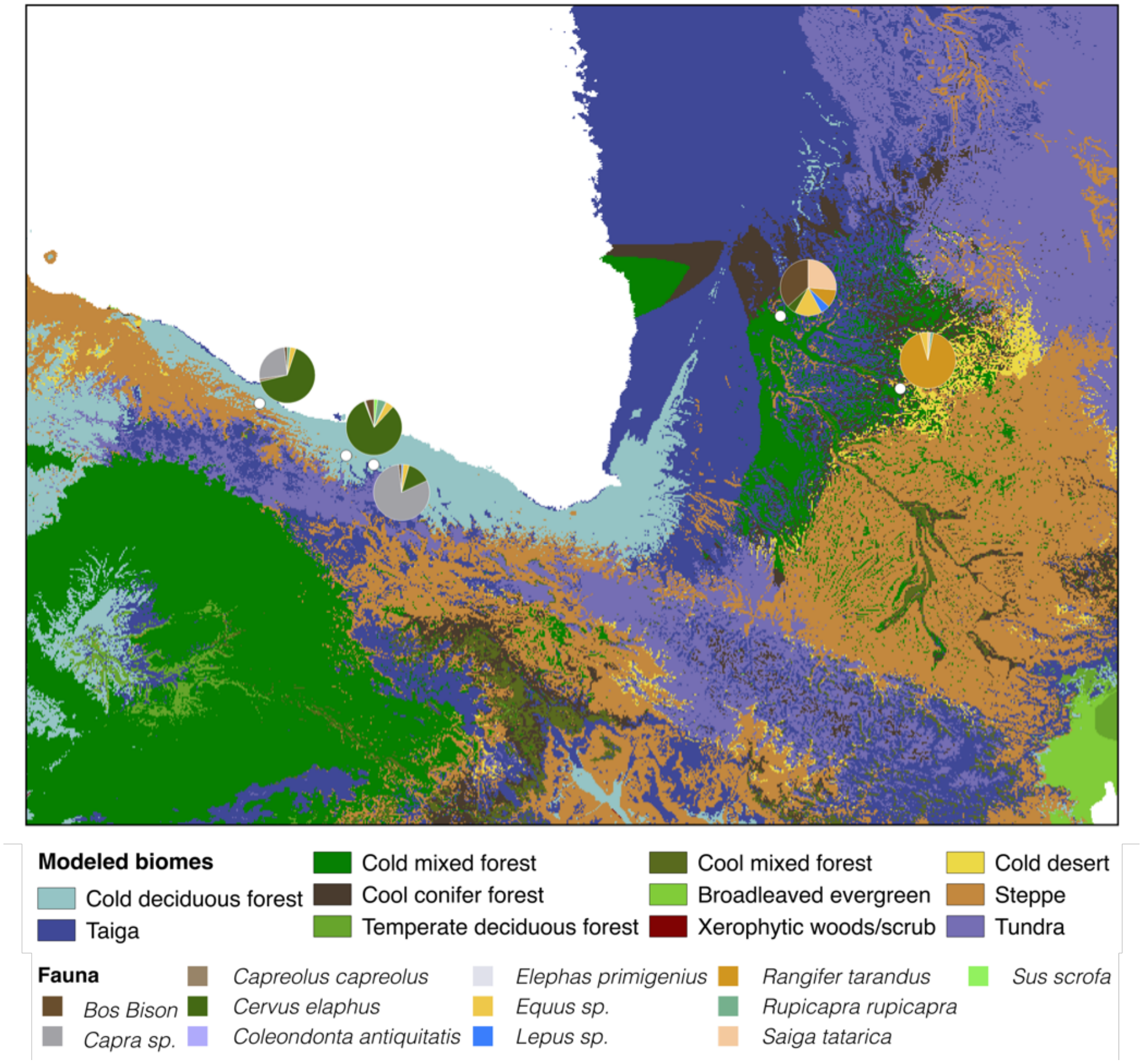


Upper Magdalenian B

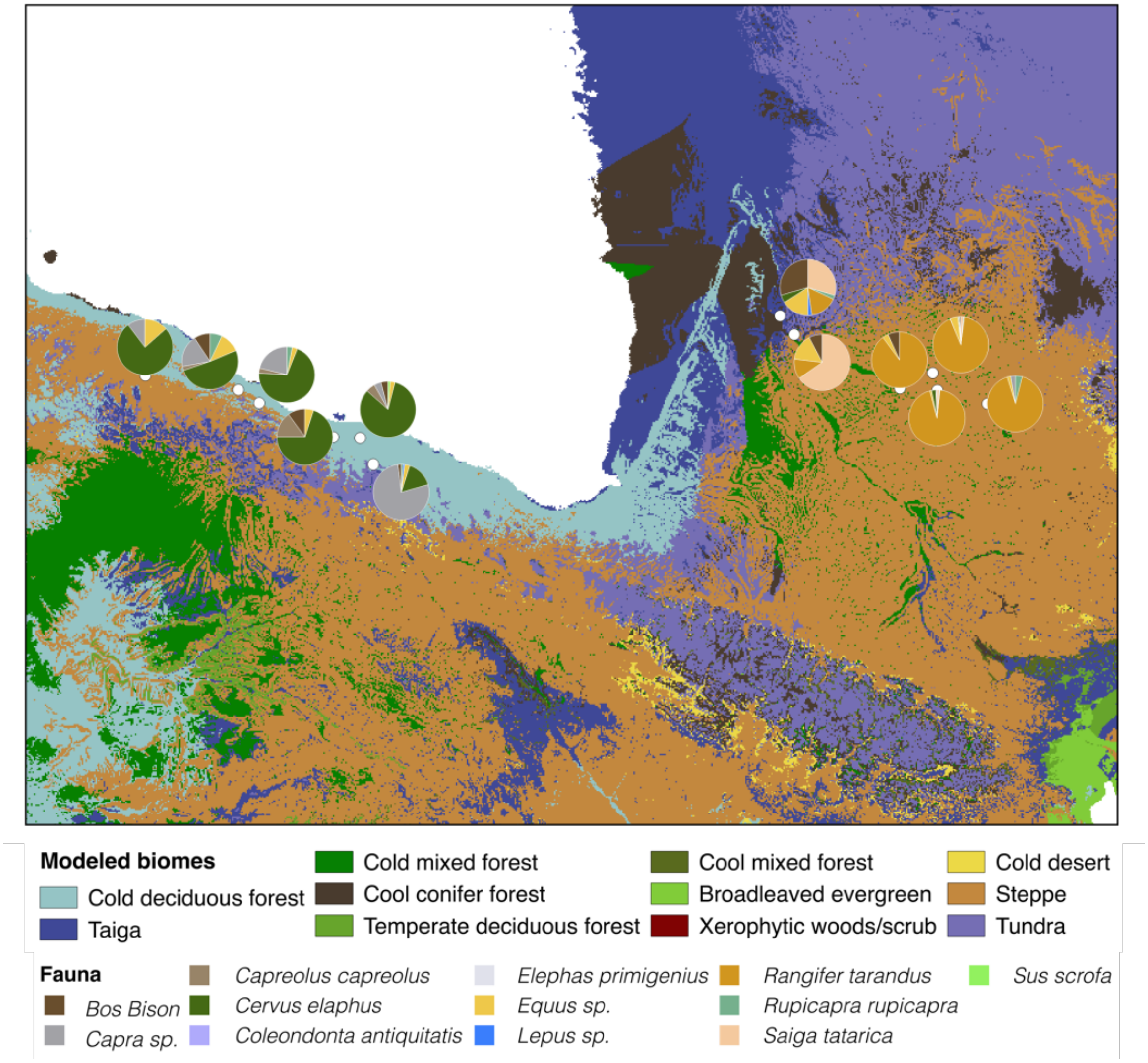


Faunal records

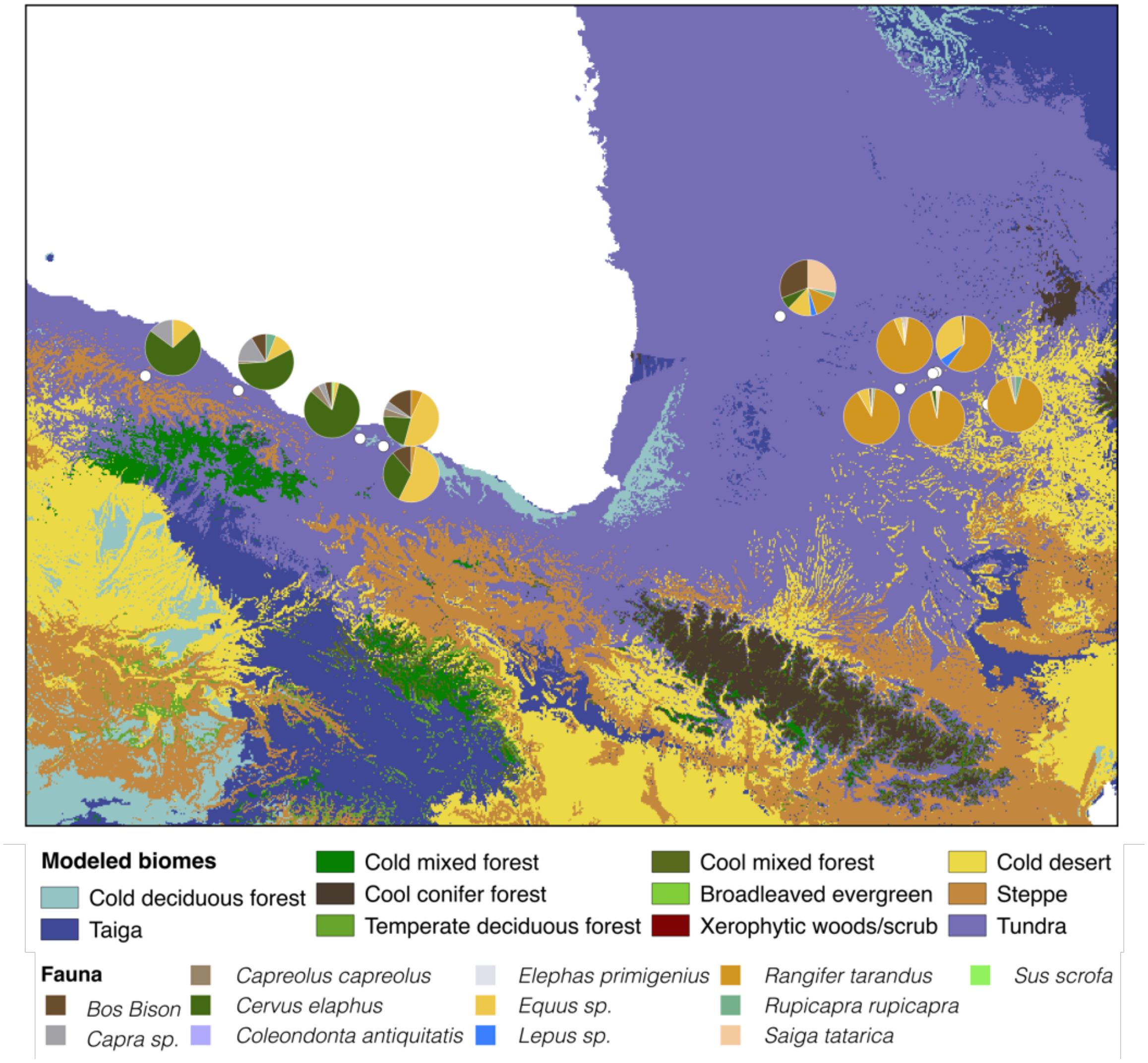
Lower Magdalenian A



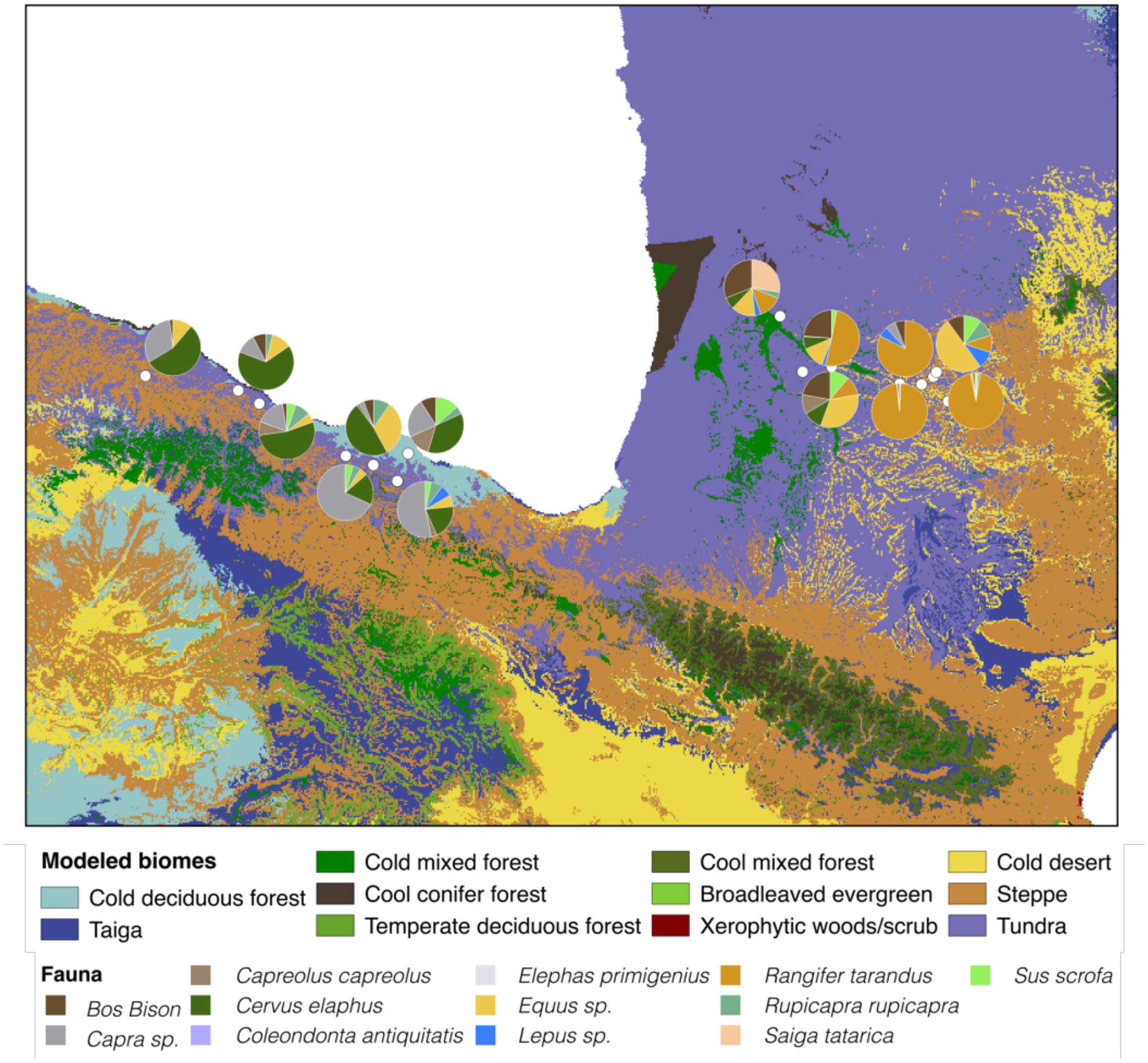
Lower Magdalenian B



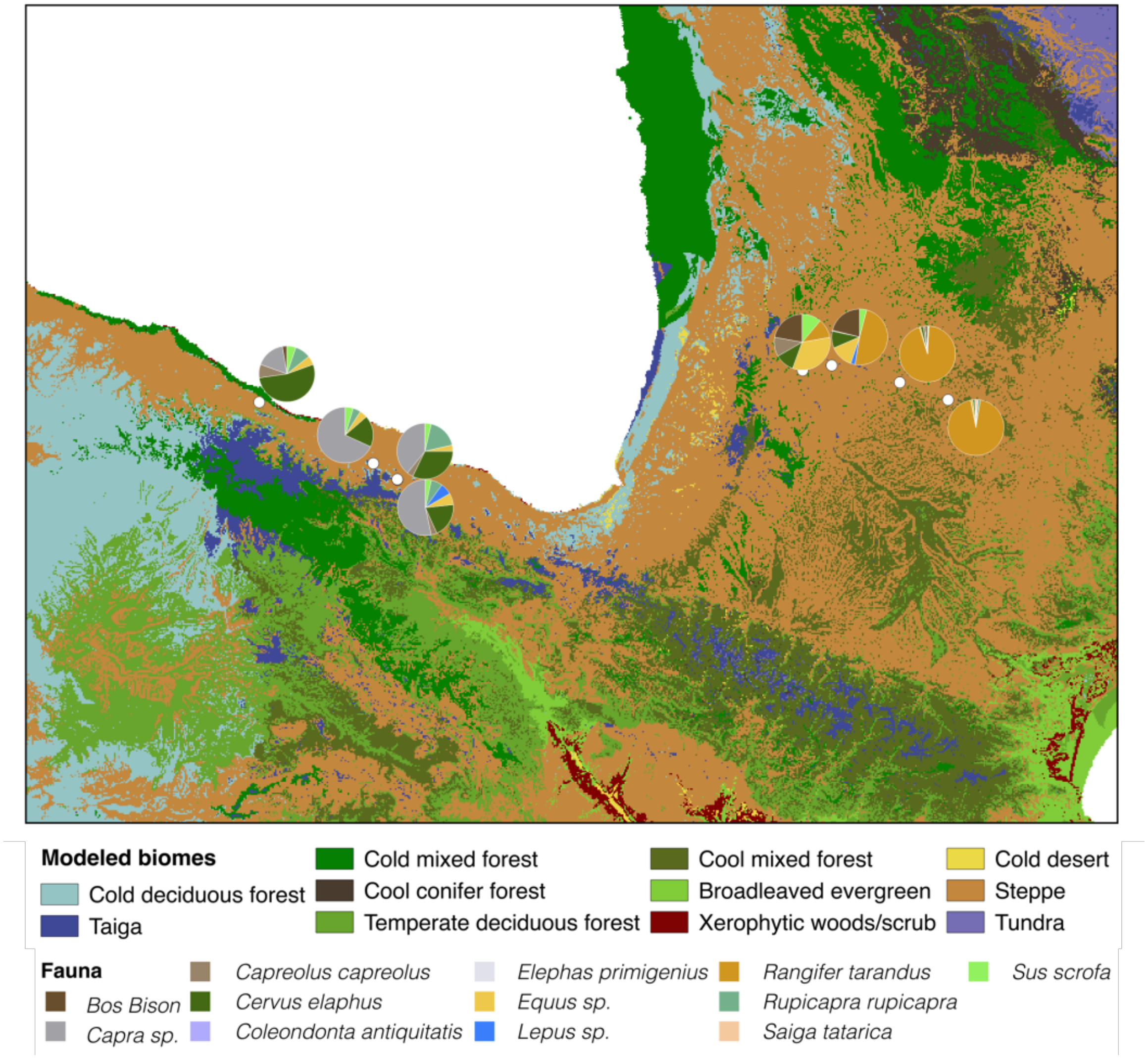
Middle Magdalenian



Upper Magdalenian A



Upper Magdalenian B



APPENDIX G

SOCIAL NETWORKS MODEL ODD

OVERVIEW

Purpose

This model has 2 purposes. The main one is to evaluate the impact of topography and resource distribution on the structure and extent of social networks created between groups of hunter-gatherers. The second is to test the assumption that social networks reconstructed from archaeological assemblages are good representations of the latent networks that produced them.

To reproduce hunter-gatherers' interaction, camps are set in a realistic world with a given topography, biome distribution, and resource level. Each camp needs to feed its 24 hunter-gatherers, out of which only 12 are modeled – 6 agents and 6 campers. Agents are used to create alliances with other camps, while campers are set to produce a set of 5 traits, that represents simplified artifacts found in the archaeological record. When alliances are formed between camps, campers can visit them, and learn the 'cultural traits' of other campers, which contributes to the widespread transmission of culture.

As this model aims to show the impact of geography on social networks, it mimics human movement on a realistic topographical surface. It shows how an agent chooses the route it perceives as being the easiest to reach a certain goal. Other least-cost path models explore similar issues, but they work on the implication that the whole world is perfectly known. They find the easiest route among all possibilities, which the agent then follows. This model differs from this approach because the agent does not have a perfect knowledge of the whole surface, but rather evaluates the best path locally, at each step, thus mimicking imperfect human behavior more accurately.

During the simulation, this model can produce one CSV file that records two types of outputs. One is the list of the 5 cultural traits of each camper, recorded each month after the first year. The geographical coordinates of each camper, as well as the camp from which they originated accompany this output. The other output is the record of all inter-camp alliances created, which includes the geographical coordinates of each camp, the number of times allied campers visited one another, and the last time a visit occurred.

Entities, state variables, and scales

The model is written in Netlogo, and uses the extensions GIS, profiler, and nw.

The world is set at 324 x 222 patches at 1km resolution, and can accommodate DEMs of the Cantabrian and Dordogne regions, as well as a control flat landscape. It does not wrap around.

The global state variables are presented in Table 1, and the patch state variables are presented in Table 2. For all patches of any given slope, the model assumes that the 'inclined surface' – rather than the flat surface it covers – covers 1km^2 (see Figure 1).

This setting simplifies the computation of the least-cost path between sites, as explained below.

*Table 1. Global state variables. *Change during the simulation*

Variable name	Description
basemap	Takes on the imported elevation values – used with GIS extension
slopemap	Takes on the imported slope values – used with GIS extension
direction-map	Takes on the imported slope direction values – used with GIS extension
fauna	Takes on the imported resource values – used with GIS extension
biome-map	Takes on the imported biome values – used with GIS extension
rivers	Takes on the imported river vector – used with GIS extension
GIS-grid-cell-size	Set to 1, helps convert the GIS raster maps to their proper size
patch-size-km	Set to 1
hours*	Used to keep track of time
days*	Used to keep track of time
weeks*	Used to keep track of time
calendar*	Used to keep track of the calendar months
chosen-camp	Identifies the camp that will be follow for the monitor on resource level
agent-n*	Records which agent is going through the least-cost path code
vision-depth	Determines how far an agent can see. Set at 3km
km-per-hour	Used to calculate agents' speed
avg-km-per-day	Used to calculate agents' speed
network-sum	Sums the number of used alliances. For plots and calibration.
mean-link-cost	Averages of length of used alliances.
file-1	To create the outputs

*Table 2. Patch state variables. *Change during the simulation*

Variable name	Description
elevation	Elevation (m) above sea level. Imported as ASCII from DEM.
slope	Slope (degree) of the cell. Imported as ASCII.
direction	Between 1-360°. Represents the direction of the slope, with 360° set to North. Imported as ASCII.
resource*	Scale of 0-1. Determined by the precipitation and effective temperature at each patch. Imported as ASCII.
orig-res	Same as resource, but does not change. Keeps track of original resource level.
biome-patch	Integer scale from 0 to 11, that represent different vegetation biomes. Imported as ASCII.
water	True or false. Distinguishes between ocean and land patches.
river?	True or false. Rivers are imported as vectors. The model identifies all patches covered by them as river patches.
angle*	Used by territory patches to identify the angle towards the center
used?*	Determines if a patch has been walked on
occupied-by*	Records which agent is on the patch
last-user*	Records which was the last agent to walk on the patch
patch-counter*	Records how many ticks since being walked on
dist-to-goal*	Calculates the distance between itself and an agent's goal
direction-change*	Used to calculate if the patch is an easy one to walk on
elev-change*	Used to calculate if the patch is an easy one to walk on
new-elev*	Used to calculate if the patch is an easy one to walk on
new-slope*	Used to calculate if the patch is an easy one to walk on
energy*	Used to calculate if the patch is an easy one to walk on
cost*	Used to calculate if the patch is an easy one to walk on

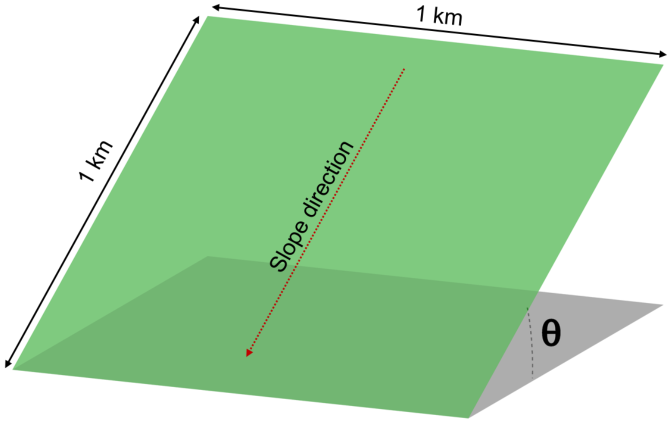


Figure 1. For all patches with slope θ, both sides of the inclined surface (green) are assumed to measure 1km.

To reflect the importance of rivers as preferred pathways, the model manually sets the slope of all river patches to 2°, and their elevation to 5m lower than their 8 neighboring patches. This increases the attractiveness of these river patches.

There are 3 types of turtle in this model: camps, agents, and campers.

Each simulation starts with 10 camps, which each hold 6 agents and 6 campers. The camps are set at random on the land. Two rules govern their placement:

- They cannot be on water
- They cannot be at altitude higher than 600m above sea level

Camps' state variables are presented in Table 3.

*Table 3. Camp state variables. *Change during the simulation*

Variable name	Description
biome	Records the biome on which the camp starts the simulation
territory-center	Records the center of the camp's territory (where it started)
territory-30-km	Records the set of all patches in the camp's territory (30km radius around its center)
n-campers*	Calculates the number of agents and campers at the camp at any time
food-source*	Calculates the resource level in a radius of 10km around the camp
food*	Indicates if food-source is sufficient to feed n-campers
leader*	Registers if an agent has been sent to visit another camp.
ally*	Registers the identity of an allied camp that can be visited by an agent and its camper
visitors?	True/false. Identifies if the camp is being visited by agents from other camps.
bet-central	Social network metric. Calculates the betweenness centrality of the camp.
clo-central	Social network metric. Calculates the closeness centrality of the camp.
cluster-coef	Social network metric. Calculates the clustering coefficient of the camp.

All agents and campers keep track of the camp from which they originated through the state variable *origins*. Each camper is linked to a specific agent – set using the state variable *my-leader* – whom it follows in circumstances detailed below. The state variables of these camp occupants are presented in Tables 4 and 5.

*Table 4. Agent state variables. *Change during the simulation*

Variable name	Description
origins	Records the identity of the camp from which the agent comes
goal*	The identity of the next camp that will be evaluated by the agent
on-my-way*	Used to time the agent's travel
reached-goal?*	Used to time the agent's travel
agent-dist-to-goal*	Distance between the agent and its goal (as the crow flies)
patch-vision*	Set of patches visible by the agent facing a certain direction
good-patches*	The visible patches that are the easiest to walk on
winner-patch*	The best patch to move to
dist*	The energy needed by the agent to move to the *winner-patch*
going-through*	Identifies the patch that is between the agent and the *winner-patch* (if applicable)
starting-day*	Records the tick at which the agent started walking
dist-traveled*	Records the number of patches walked on since the agent started walking
agent-speed*	Divides the *dist-traveled* by the time walking to estimate the walking speed
just-visited*	Identifies the camp that was just evaluated by the agent (for troubleshooting)
leader?*	True/false. Tells the agent to go visit another camp
visiting*	Identifies the camp being visited by the agent
agent-counter*	Keeps track of how long the agent has been visiting another camp (only used for "Random" setting)

*Table 5. Camper state variables. *Change during the simulation*

Variable name	Description
origins	Records the identity of the camp from which the camper comes
my-leader	Records the identity of the agent to which the camper is linked
prestigious?	True/false. Indicates if the camper is a prestigious artist (only used for "Prestige" setting)
visiting*	Identifies the camp being visited by the camper
art*	List of 5 number, representing cultural traits
previous-art*	List of 5 number, representing cultural traits. Used to calculate cultural transmission

Links are used between agents and camps to help agents identify a goal to visit. They are also created between camps to represent alliances. There are two types of inter-camp links used, ally-links and network-links. Both record the distance traveled between their two nodes (given by agents). However, network-links also record how many times campers from one of their nodes visits the other node.

Simulations are set to stop automatically after 60,000 ticks or if all campers are dead. Each tick represents 10 minutes of walking time. The length of days can vary from 6-12h of walking time. Weeks are set at 7 days, and months at 4 weeks. The model keeps track of which month it is on, as settlement pattern can be monthly or seasonal.

Process overview and scheduling

At the beginning of the simulation, each camper is given a set of 5 numbers, stored in the variable *art*. These represent cultural traits of modeled "artifacts."

At every tick, the model checks if it has reached its end (60,000 ticks) or if all campers are dead. If one of those is correct, the model stops.

If the model keeps going, it updates the plots and the timing variables (number of days, weeks, and months passed). It then updates the counter of patches that have been walked on in the past few ticks.

The model asks camps to setup their foraging or collecting settlement pattern. Foragers move only if it is a new month, and collectors move twice a year. They then calculate how many mouths they need to feed, and choose how the alliances will be formed (based on the "Alliances" parameter setting).

The setting of the parameter "Alliances" influences the impact of resources on the rest of the model. When it is set on "Social," each camp has a 3/10,000 chance to send an agent out at each tick. Sent agents bring with them their camper. At each tick, the visited camp has a 3/10,000 chance to send its visitors back to their origins. If it set on "Resources," the camp uses allies to cope with insufficient food level. This is calculated every week. Each camp evaluates the level of resources within its territory, defined as the land patches located within 30km of the camp. Each camp calculates also the number of agents and campers it is currently hosting, and evaluates if the territory holds enough resources to feed its current population for the next two weeks. If the level of resources is too low, the camp sets its *food* variable to "low." If the camp has visitors from another camp, it sends them away. It then looks for help. If the camp has potential allies, it asks the closest of those if it could accommodate some visitors for a while. If the ally can, one agent and its camper are sent there to stay until the resource level of that visited camp becomes too low to sustain its population and visitors, at which points, the visitors return to their original camp. To move to and from visited camps, the agents and campers simply jump to it rather than move on the landscape. Camps send out agents and campers on visit every week until they can feed their remaining population.

When a camp with low food does not yet have allies, it sends agents to find new ones. At the beginning of each tick, all walking agents check to see if they have reached their goal and finished their search for allies. If they have, they jump back to their camp of origin. If they haven't they keep walking. Agents take the topography into consideration and walk along the easiest possible path to reach their goal. This is modeled as walking from temporary target to temporary target. If they stumble upon an unevaluated camp on their way, they make that camp their new goal. When they reach their goal, they evaluate if it is a good potential ally, by asking if the goal is located in a biome that differs from the agent's origin, and if it has enough resources to feed its campers for the next two weeks in addition to a family of four. If the goal is not a good ally, the agent chooses another camp to visit. This goes on until the agent has evaluated all other camps once. If the agent has still not found a good ally, it jumps back to its origin, and starts a new search. When an agent finds a good potential ally, the model creates a link between the agent's original camp and its newly found ally, and returns to its camp. The inter-camp link records the distance traveled by the agent since it left its origin.

Every day, each camp calculates how much resources it needs to feed its occupants, and gathers the necessary amount from its territory. This is modeled as asking a certain number of patches to set their resource level to 0. If there are not enough resources around, one of the occupants dies.

Every day, all campers produce "art" – modeled as a set of 5 numbers – and transmit cultural information. There are three possible cultural transmission processes: Autodidact, Conformism, and Prestige, which are based on the work of Eerkens and Lipo (2005), and are selected at the beginning of the simulation. The Autodidact method implies that campers learn from themselves: every day, they simply copy their own set of cultural traits. When selected, conformism leads campers to copy the mean of each of the 5 traits of all other campers located in the same camp. The prestige method requires the model to give a certain prestige to a random 20% of the campers at the beginning of the simulation. The identity of those prestigious individuals does not change during the run. Campers copy the cultural traits of the prestigious individuals when one is nearby. Prestigious individuals copy their own traits. All transmissions add a certain amount of copying error. The transmission rate can be changed from 0-100% of the time. When campers do not conform or copy a prestigious individual, they copy their own traits.

When the user decides to create outputs, the model creates a CSV file at the beginning of the simulation, to which it writes new information each month, after the first year. The information includes the cultural traits of all campers, as well as the identity and the number of uses of inter-camp links used for visits.

DESIGN CONCEPT

Basic principles

This model tries to simplify the impact of geography and environmental resources on the formation of social alliances between hunter-gatherers, and in turn, its impact on the transmission of cultural traits. Moreover, it aims to go beyond the GIS approach to least-cost path that requires perfect knowledge of the whole environment to choose the best path between two points. It relies on the work by Naismith (1892, in Aitken 1977) and Langmuir (1984) on walking time expenditure in rugged environments. Their walking time values are integrated in the *calculate-energy* procedure.

Emergence

Due to the random position of the camps, the structure of the created networks changes at every simulation. Moreover, the transmission of cultural traits leads to the creation a different palimpsest of cultural objects for each simulation. For mobility, natural switchbacks occur as a result of the agent's aim to get closer to the main goal while choosing a relatively easy route.

Adaptation

Camps improve their fitness by finding allies that can help out in times of need. The walking agents can create switchbacks and change direction completely when they find that the easiest route is leading away from the goal. Agents try to maximize their speed, which requires minimizing the slope they walk on. It thus allows them to conserve energy and find allies faster to help their camp feed their occupants.

Objectives

When the parameter "Alliances" is set on "Resources," the camp's objective is to feed its occupants, and it will send agents in search for allies when resources are running low. When the parameter is set on "Social," the camp sends agents to visit other camps without a specific objective.

The agent's decision is influenced by the speed at which it can cross a patch, and by that patch's distance to the main goal. These two values can sometimes provide different results, with distance taking precedence over speed when the agent is allowed to use large switchbacks.

The objective of this model is to evaluate how topography affects mobility, and how this in turn affects the structure of social networks. Therefore, it is important to model agent's mobility as realistically as possible. The model also aims to evaluate how social networks can be interpreted from archaeological palimpsests, which is why I model transmission of cultural traits between campers. As we cannot know how traits were transmitted in prehistory, I model different methods – autodidact, conformism, and prestige – which are simplified versions of what is observed in real life.

Learning

Patches change their resource values when the camp feeds its campers, every day. During the following ticks, at a rate defined by the parameter "replenishment rate," the patches regain their original resource level.

Patches update their *new-slope*, *new-elev,* and *energy* values when they are considered as a possible path by an agent. They also change their *used* status and they start a 10 ticks counter when they get walked on. This is to insure that the same agent does not walk on that patch over and over again

The agent changes its temporary target when it reaches it. It also changes its general goal when it reaches it.

Campers change their art variable every day. If they are not learning traits from others, they copy their own traits, with a certain amount of copying error (up to 3% of the value).

The ally links record the distance traveled between its two nodes, which is given to them by the agent that created the alliance. This value can change if another agent finds a faster route.

The network links count the number of times visit occur between their two nodes.

Prediction

Patches have the memory of their original resource level. Therefore, depleted patches can regain their resources easily by querying that memory.

Camps do not predict the consequences of their action.

Walking agents try to predict the cost of walking on certain land patches. Each agent looks at patches in a cone of vision that covers up to three rows of patches. This implies that they can predict what the topography will be like further along the way and make their path decisions according to this information. I chose the depth of the cone to be at least three times the size of the patch so that the agent can see at ~ 3km ahead. This is realistic on a flat terrain, and prevents the agent from seeing too far ahead, as the path choice needs to remain local.

Campers keep a short-term log of their cultural traits, which is used for computation of the new traits, adding a certain amount of error.

Sensing

By checking if they have enough resources to feed their occupants for the next 2 weeks, camps sense the state of their resources and can look for help before they start running out. This is explicitly modeled and is errorless.

The walking agents sense the cost of walking on surrounding patches, which help them determine the easiest path to their goal. This is also explicitly modeled and errorless.

At the beginning of every day, certain campers sense the cultural traits of all or selected campers found at the same camp. This process is explicit and errorless. However, if they choose to copy some of those values – based on the cultural transmission parameter setting and the rate of learning – they copy them with a certain amount of error.

Interaction

Camps create alliances between one another. Different types of link represent those. An ally link shows that at least one of the camps can help the other if needed. A network link shows that one agent and one camper from at least one camp has visited the other camp.

The walking agents interact indirectly with the patches when they evaluate the patches' distance and energy values. The patches that are considered potential temporary targets ask the patch on which the agent stands to communicate its energy value so that the walking speed includes both patches (and the patch between the two, when applicable).

Agents also interact with camps when they evaluate their alliance potential.

When they are found in the same camp, campers interact with one another by sharing cultural traits.

Stochasticity

Camp placement is set at random at the beginning of each simulation, which allows evaluating the different impact of biome fragmentation and resource distribution on social networks.

The walking agents incorporate a bit of stochasticity in their movement. When two or more patches are the easiest to walk on, the agent selects one of the two randomly. This is set to mimic imperfect human behavior, and to provide different possible paths between two points.

Campers' first set of cultural traits is set from a random-normal distribution, with the number of their camp as the mean and a standard deviation of 5. This allows the creation of rough style clusters assigned to each camp, but with ever varying traits. Moreover, as the camp placement affects the alliances formed, the interactions between campers differ from one simulation to the next, thus producing different palimpsests of cultural traits.

Collectives

There are three collectives:

- Camps
- Agents
- Campers

Observation

The interface has a few monitors and plots that present the temporal change in certain variables. The monitors at the top show how many days and weeks have passed, as well as a rough average of all agents' walking speed. These can be used for troubleshooting. For example, *walking speed* can be used to test the good functioning of the model as

Naismith's model suggests that walking speed on relatively flat environment should range around 4-5km/h. The speed should not go above 6km/h nor below 2km/h.

The 6 plots located below the main window relate to the formation of social networks. *Network links* keeps track of how many inter-camp visits are done in a simulation. *Ally distance* shows the average distance between camps that are being visited. *One camp's resource* shows the weekly resource level of one camp chosen at random. It can be used to narrow down the best value for patches' replenishment rate and the occupants' food requirement. *Closeness, cluster coefficient,* and *betweenness* show the evolution of simple social network metrics.

In addition, to the side of the main window, I have added a legend that explains the color of the agent – as it changes throughout their search for allies – and camps (only relevant when alliances are resource-driven).

DETAILS

Initialization

The world is set on a 324 x 222 grid matrix that can represent the landscape of the Dordogne or Cantabria during the 5 subdivisions of the Magdalenian, or a flat surface used as a control. The world does not wrap around. The patch size of the viewer is 2.3, with font size 10. The tick counter label is set at "10 minutes."

The elevation, slope, direction, and biome values of each patch are automatically updated from ASCII files, based on the user selection. Patches that are located underneath a river vector are transformed into river patches, with slope 2° and elevation 5m lower than their 8 surrounding land patches. Rivers and coastal patches are given the maximum resource value (100) to represent the productivity of marine and riverine environments. All resource values are divided by 100 to be on a scale of 0-1.

If the region is set to "No GIS", the elevation of all patches is set to 50, the slope to 1, and the direction to a random value between 1 and 360. Resource is set at a random value between 0 and 0.6, which is set to mimic the levels found in the realistic environments (mean around 0.3). The world is then divided into 4 quadrants with their separate biome – modeled as values 1 to 4.

Ten camps are randomly positioned on the landscape. They can only go on land patches that are below 600m asl, based on a survey of the literature that showed that Magdalenian sites were never found higher than this value. Each camp identifies the identity of the patches within a 30km radius as its territory. It then produces 6 agents, who in turn produce 6 campers. All agents and campers record the identity of their camp of origin. The agents are assigned a camp other than their origin to evaluate first. The campers are assigned a list of 5 cultural traits. The numbers are taken from a random-normal distribution with the number of their camp as the mean and a standard deviation of 5. Negative cultural traits are automatically set to 0.

Input data

For each parameter combinations, 6 external data are uploaded in the model – elevation, river, slope, direction of slope, resource level, and biome. The elevation comes from a DEM set at 1km resolution. As the model can represent 2 real regions during 5 periods, it actually requires a set of 10 DEM maps, out of which the proper one is uploaded at setup.

The DEMs used to construct the world are composites created with the USGS GMTED2010 7.5 Arc Second map and the bathymetry elevation GEBCO 30 Arc Second map. For each temporal subdivision of the Magdalenian, the sea level was adjusted to the values presented in Table 2, and based on the work of Peltier and Fairbanks (2006).

Table 2. Sea-level anomalies (in m) estimated from Peltier and Fairbanks (2006).

	Lower A	**Lower B**	**Middle**	**Upper A**	**Upper B**
Sea-level anomaly (m)	-113	-110	-109	-96	-78

The slope and direction maps were produced from those composite DEMs in the GRASS Geographical Information System. GRASS calculates direction clockwise with North at 90°; however, NetLogo requires North to be 360°. Therefore, I used the following GRASS *r.mapcalc* statement to convert the values for each grid cell:

$$\text{if}(x = 0, 0, \text{if}(x < 90, 90 - x, 360 + 90 - x))$$

where x represents the direction of the original map. These maps change by region, but not by time period, as the model uses the elevation map to distinguish land from water. The river vector of each region was created in GRASS, using the *r.stream.extract* tool of the hydrology module, with minimum flow accumulation set to 1200. It was then exported as a shapefile. It does not change over time.

The biome and resource maps come from environmental reconstructions of climate and vegetation based on modeled climate data from TraCE-21ka, and an ecological MaxEnt model calibrated using modern vegetation and climate relationships. They vary by region and time period.

All input maps are in the ASCII format.

Submodels

This model has 4 main submodels. One of them relates to the resources available to the camps and the consequences of resource depletion, one relates to agents' mobility, one relates to the formation and use of alliances, and one to campers' transmission of cultural traits.

Resources:

The resources and camps' settlement pattern are affected by time. Therefore, they rely on the global variables *day*, *month*, and *calendar.* While *month* calculates how many months have passed since the beginning of the simulation, *calendar* rotates through the 12 months of a regular calendar (e.g., January, February, …). This allows forager and collector camps to time their residential mobility. At the beginning of each tick, these time variables are updated.

If the model just started (tick 1), it tells camps to forage or collect based on the chosen parameter setting. If the simulation is further advanced, the model asks foragers to forager every month, and collectors to collect every 6 months.

The distinction between foragers and collectors is based on ethnographic research on hunter-gatherer settlement topologies (Kelly 1995, 2013; Binford 1980). Collectors move their camp seasonally and use logistical forays to take advantage of the resources available in their entire territory, whereas foragers move camps regularly to patches of abundant resources.

Camps of both settlement patterns have a circular territory with a 30km radius, based on estimates of minimal band territory size (from Whallon 2006). While the size of the whole territory is the same for both settlement patterns, their resources gathering strategies differ, as explained below.

Due to the relatively low effective temperature documented for these regions during the Magdalenian (~ 12) and their highly variable climate, I assume that the economic defendability of those territories was too low to lead to territoriality and defense of resources (as per Dyson-Hudson and Smith 1978, see also Marean 2016), which is supported by the lack of signs of violence in the Magdalenian (Lahr et al. 2016). Therefore, modeled camps can have overlapping territories, and they do not defend their resources.

As shown in Figure 2, collectors move their camps only twice a year, once to the highest point of their territory, and once to the lowest point. This represents the Magdalenian inferred seasonal preference for higher altitude in the summer and lower altitude in the winter (Marín Arroyo 2009; Straus 1981, 1986, 1992). Every day, however, collector camps gather resources from the whole territory, which represents the usage of small logistical forays far from the camp (Binford 1980; Conkey 1980; Rensink 1995; Straus 1986).

Forager camps start the simulations 10km from the edge of their territory, and move clockwise every month. The movement represents a shift of 30° angle from the center of the territory, which allows the camp to cover the whole territory over a year. Forager camps collect resources only from the patches located within a 10km radius.

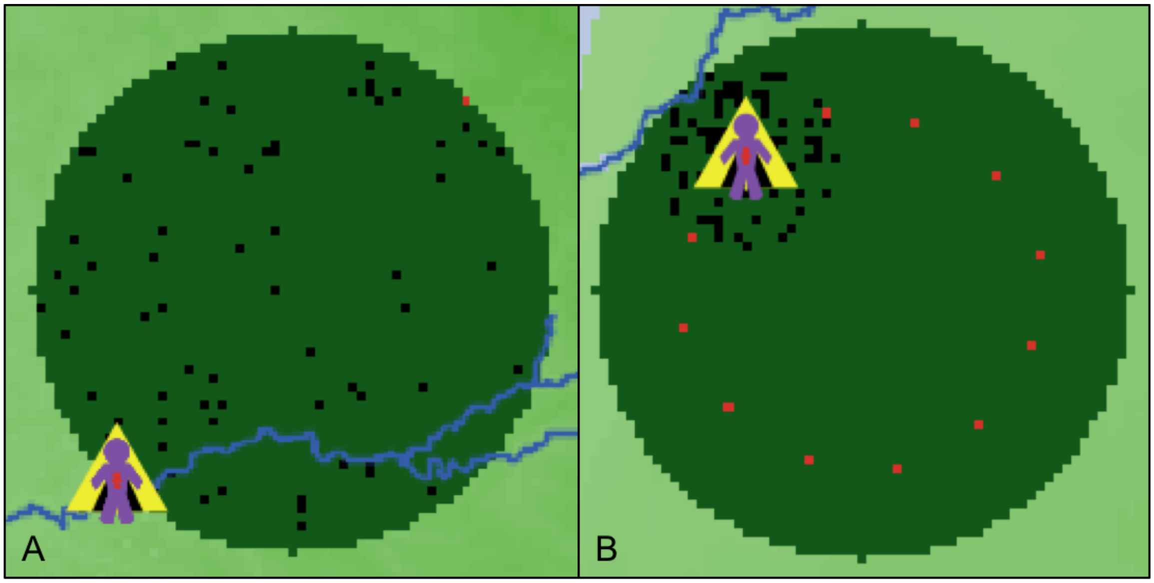


Figure 2. Territory and movement of camps for both settlement patterns. A. Collector (logistical mobility), B. Forager (residential mobility). The black patches represent where the resources are gathered while the red patches show where the camp will move to during the year.

To calculate the amount of resources necessary to feed their occupants daily, camps count the number of agents and campers present at the site at a given time. An average hunter-gatherer population usually turns around 24 occupants (c.f., Birdsell 1968; Lee and DeVore 1968; Wobst 1974); however, as this model does not need to simulate the action of all those occupants, their presence is inferred only by the total amount of required resources. As only 6 agents and 6 campers are modeled, campers eat 3 times as much as agents. Therefore, every day, each camp calculates the amount of resources needed by its occupants using:

$$R = r(A + 3C)$$

where *A* and C stand respectively for the count of agents and campers located at the camp, and *r* represents the amount of resource needed by each occupant (value set at the beginning of the simulation). Calibration tests have shown that social networks emerge only for *r* values between 0.1 and 0.3.

Each camp then gathers *R* resources from patches located within its defined foraging territory. While this action does not change the state of the camp or its occupants, it depletes the resources of nearby patches. The number of patches to deplete is based on the territory's remaining resource level, using:

$$x = R \Big/ \frac{1}{n} \sum_{i=1}^{n} P_i$$

where P stands for the patches with available resources and x for the number of those patches required to satisfy R. This simply divides R by the average resource level of all pristine patches within the foraging radius. When it is calculated, x number of patches, selected randomly within the foraging radius, change their resource value to 0.

If most patches are already depleted and the remaining resources are not enough to feed all occupants, one camper dies. If all campers are dead and the resources are still insufficient, one agent dies. The camp dies when all its occupants are dead, and the simulation stops when no camper is left. This model does not focus on demography; therefore, for the sake of simplicity, agents and campers do not reproduce and their number can only decrease over time.

To reproduce the resilience of natural environments, every day, a certain percentage of depleted patches are chosen at random to replenish their resources. This percentage is set at the beginning of the simulation using the parameter "replenishment-rate," and remains constant during. Calibration tests have shown that the impact of replenishment values on social networks decreases above 10.

Every week, all camps evaluate if the resources available in their territory is enough to feed their occupants for the next two weeks. For both settlement patterns, the camps consider only the immediate 10km radius territory, which allows camps of both types to suffer resource shortages. While collectors gather resources from their whole territory, asking them to evaluate the resource level of their immediate surrounding is a simple way to model the seasonal resource shortages that deplete entire parts of real collectors' territory. The camps that do not have enough resources ask for help from their allies or send agents to find new ones.

Agent mobility:

This is one of the most important parts of the model, as it is what distinguishes it most from other models that aimed to simulate prehistoric cultural transmission (e.g., Axelrod 1997; Eerkens and Lipo 2008; Mesoudi and O'Brien 2008; Perreault and Brantigham 2011; White 2012).

This submodel is used to represent realistic walking patterns in a modeled landscape. Its general characteristics are based on GIS least-cost path scripts, which use the elevation, slope, and direction of raster cells to calculate an easy-to-travel path between two points. While GIS least-cost path tools efficiently identify the easiest way to move between two points, I could not use them for my agent-based simulation for two reasons:

1. With GIS tools, all grid cells in the computational region are used in the calculation, which is time consuming. In this model, a total of 60 agents can travel at the same time, which would require the creation of 60 simultaneous but independent least-cost-paths, slowing down the runs considerably.

2. GIS tools take the whole landscape into consideration to identify the best path between two points. This is not how humans move on the landscape, where they have a limited knowledge of their surroundings. Humans make walking decisions with the information available to them wherever they are, which means that they can choose a route that seems easy locally, but that might lead them to a cul-de-sac or a very steep slope later.

As I wanted to represent realistic human movement between sites, I wrote an agent-informed version of the GIS least-cost path tool for this model. In this script, the path is defined through decisions made by the agent based on information provided by the surrounding patches.

An agent always has a general goal towards which it is walking as well as a temporary target that helps monitoring its progress. When it leaves its camp to find allies, the agent's general goal is one of the other 9 camps, set at random. At the beginning of each tick, the agent evaluates if it has reached its temporary target. The agent can look for another temporary target only when it has reached the one it has for the moment. The temporary target is selected as follow.

1. The agent turns towards the general goal. It evaluates the cost of moving through all patches visible in a cone of vision of 180° and a depth of 3km. These patches are labelled 'considerable'.

    a. Water patches are ignored, as well as patches the agent has already walked on in the past 10 ticks (to avoid agents getting stuck in a loop).

    b. If there are no considerable patches nearby, the agent extends its search to all patches within a radius of 3km – mimicking the possibilities of looking back temporarily.

    c. If the agent cannot find any considerable patch nearby, it dies. This does not happen often, but avoids the creation of unrealistically long paths when an agent might get stuck in a cul-de-sac.

2. Every considerable patch calculates its distance from the agent's goal (as the crow flies).

3. The agent reduces the range of considerable patches by keeping only the ones that bring it towards its general goal, allowing for a few switchbacks to reduce the cost of traveling in a straight line in mountainous environments. The agent reduces the considerable patches to the ones closer to the goal than d in:

$$d = D_A + (D_A * S)$$

   where D_A stands for the distance of the agent to the goal, and S to the switchback value selected at the beginning of the simulation.

4. Every remaining considerable patch then calculates how costly it would be for the agent to move through it, using:

$$C = |\Delta_E * D_P * 2A|$$

where Δ_E stands for the elevation change between the patch and the agent's location, D_P represents the patch's distance to the goal, and A is the angle at which the agent would attack the slope of the patch. A is calculated using:

$$A = |t - f|$$

where t represents the agent's angle of approach, and f represents the direction of the patch's slope. To transform those values into 0-360°:

$$\text{if } A \geq 180,\ A = |\,A - 270\,|$$

$$\text{if } A < 180,\ A = |\,A - 90\,|$$

Figure 5 helps illustrate this concept. In this figure, the white arrows and their associated number in the middle window show the direction of the slope, whereas t is the direction the agent would travel towards to reach each patch. As A represents how much of the slope the agent will suffer, patches with low A are preferred. The patches with lowest cost are selected as potential temporary targets. For example, in Figure 3, the patch south of the agent would be the temporary target.

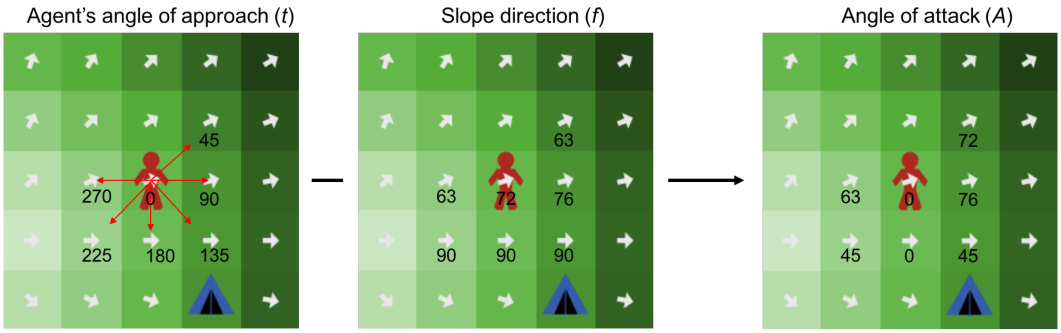


Figure 3. The conversion of slope and angle of approach to new angle of attack.

5. Each potential temporary target patches calculates the slope of the path, as well as the distance the agent would need to travel to reach it, using trigonometry.

In Figure 4, the green square represents a grid cell with slope θ and elevation E. The red dotted arrow represents the hypothetical path followed by an agent, with angle of attack A. Here, the distance covered by the path corresponds to the hypotenuse of a right-angle triangle with adjacent = patch-size (1km) and opposite unknown (dark green triangle in Figure 4). The hypotenuse is calculated with:

$$hyp = \frac{adj}{\cos A}$$

The length of the opposite side can thus be calculated using the Pythagorean theorem:

$$opp = \sqrt{hyp^2 - adj^2}$$

which allows calculating the new elevation change (Δ_e), as we can use *opp* as the hypotenuse of a new triangle with slope held constant (grey triangle in Figure 4).

$$\Delta_e = \sin\theta * opp$$

If the agent is going down, this value is multiplied by -1. Finally, Δ_e is used as the opposite side of a right-angle triangle with hypotenuse = actual distance traveled (red triangle in Figure 4). We use this triangle to calculate the new-slope (s):

$$s = \left|\sin^{-1}\frac{\Delta_e}{hyp}\right|$$

These equations provide the distance traveled (*hyp*) when using the patch diagonally, the real elevation gained or lost (Δ_e), and the slope (s) on which the agent walks. The patches use these values to calculate how fast the agent can travel on such a surface.

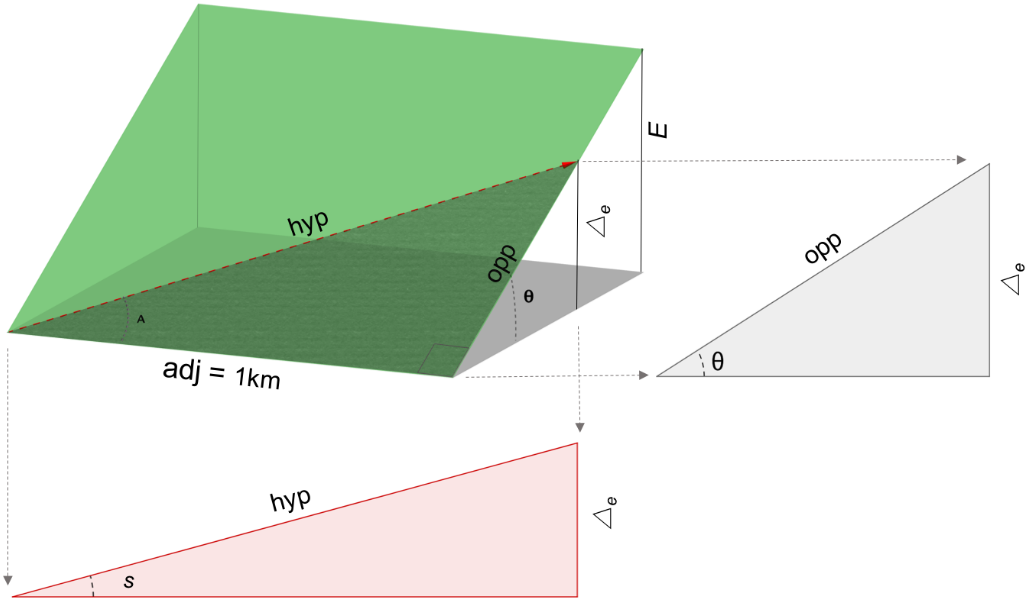


Figure 4. Calculating the distance and slope of the agent's travel.

6. The distance that can be traveled on rugged surface comes from the *r.walk* tool in GRASS GIS and based on Naismith's rule (Aitken 1977) and Langmuir (1984). It suggests that an agent can walk 5km/h on flat terrain and up to 6km/h on a gentle downward slope (between 5-12°), but that the speed decreases to 2km/h when going up or down on a steep slope (> 12°). While these speed values are probably lower than what is found in hunter-gatherer populations, both modern and prehistoric, documented reduced mobility during this period (Holt 2008) suggests that the speed of movement might not have been too far from these estimates. Each potential temporary target thus uses its calculated slope and elevation gain/lost values to calculate its *energy* level (Table 3), which represents how fast the agent can travel on its surface.

Table 3. How fast the agent can reach the center of a patch, based on its elevation change and slope.

Direction	Slope	Walking speed (km/h)	*energy*
Up	**0°-5°**	4	4000/6
	5°-12°	3	3000/6
	≥ 12°	2	2000/6
Down	**0°-5°**	5	5000/6
	5°-12°	6	6000/6
	≥ 12°	2	2000/6

As the agent moves from the center of one patch to the center of another, the energy values are calculated for both patches involved are averaged. If one of the potential temporary target patch is separated from the agent by another patch, the energy value of that middle patch is added to the averaged values of both ends. This represents the realistic cost of moving longer distances. The agent chooses the patch with the highest energy value, which represents the patch that can be traveled to the fastest.

Agents move from one temporary target to the next, while moving in the general direction of their goal. At every tick (representing 10 minutes), they accumulate the energy level of their temporary target. While that value remains lower than the distance between the agent and the target (as the crow-flies), the agent stays where it is. As soon as the accumulated energy goes beyond the distance between the two, the agent moves to the temporary target and chooses a new one.

Agents record the length of their trip by adding up the number of patches they travel on. Along the way, they might encounter a camp other than their goal. If they have already evaluated the potential of that camp on this trip, they ignore it. However, if this is a new unevaluated camp, they make it their new general goal. The distance between all pairs of camps are identified by all agents. The value is recorded as part of an invisible link between the two camps. When an agent reaches a camp, it updates that value only if it has found a quicker path than a previous agent. This condition insures that the quickest least-cost path between two sites will be the one considered, and will not be changed for distances calculated by agents who have visited other camps since they left their origins.

Patches register which agents walk on them through two variables. *Patch-counter* is set at 10 as soon as one agent walks on a patch. The variable *last-user* records the identity of the agent that walks there. Every tick, patches with a patch-counter that is above 0 subtract 1 from its value. When its counter gets to 0, the patch changes its *last-user* value by taking the ID of a camp at random. This simple procedure prevents runtime errors.

Alliances:

This submodel relates to how alliances are formed and used. When the setting “Alliances” is set on “Resources,” camps evaluate every week if they have enough resources available to feed their occupants for the next two weeks – used to represent hunter-gatherers’ adaptation to fluctuating resources.

The camps with depleted territories ask for help. If they already have allies – represented as ally links – the camp asks its closest ally if its resources are still sufficient for itself and a family of four. If the ally does not have enough resources anymore, the camp destroys its alliance and asks another of its allies. This continues until the camp finds an ally that can help or until no ally remains. In the latter case, the camp sends agents to find new allies. If one ally has enough resources, the camp sends an agent and its camper to live there to relieve the pressure on the camp. This is inspired by Wiessner’s (1982) account on !Kung families who cope with low resources by visiting the relatives with whom they have *hxaro*. All visitors remain in an allied camp until its resources become too low to sustain its occupants and visitors. They then return to their original camp. The visiting mobility is quick and simply involves hopping from one camp to the next, as least-cost path mobility is only important to define the distance between the two camps.

Agents who are sent out to find allies move through the landscape and evaluate camps until they find a suitable ally. Every time they reach a camp, they evaluate if it is in the appropriate environment and if it has enough resources to feed its occupants as well as an additional family of 4 for the next two weeks. Alliances can only be formed between two camps located in different biomes, as ethnography shows that alliances formed to safeguard against resource fluctuations are usually made between groups living in different environments because those environments would respond differently to climate change (Kelly 1995, 2013; Whallon 2006; Wiessner 1982).

If an evaluated camp is not suitable (same biome or not enough food), the agent removes that camp from its list of possibilities and moves to another one. The agent continues walking until all camps have been visited. It then returns to its origins, and the search cycle starts over.

When alliances are socially driven, the resource level does not affect mobility. Camps send agents out at least once a year, but not as often as every week – modeled as a 3/10,000 chance to send an agent out at each tick. When an agent is sent out, it moves to its goal. As soon as it reaches the goal, it creates an automatic alliance between it and its original camp. The agent is then joined by its camper, who simply hops to the agent. The length of the visit is also set at random, with 3/10,000 probability of return at every tick – value set for the same reasons as explained above. This random movement is set to represent the alliances created between groups of hunter-gatherers for reasons unrelated to the environment – e.g., social aggregation, mate exchange, or simple social calls (Conkey 1980; Gamble 1998).

In both settings, the model records the spatial length of each alliance and the number of times each is used (see section 4.3). These values are stored as part of the network links created between camps.

<u>Cultural transmission:</u>

This submodel relates to the transmission of cultural information between campers. All campers start the simulation with a list of 5 values, representing style variants, taken from a random-normal distribution with their camp number as the mean, and a standard deviation of 5. Negative values are always set to 0. Using the camp number as the mean of a normal curve creates natural clusters at each camp, which represent cultural 'styles' that are primarily transmitted within minimal bands before being exposed to external influences (Axelrod 1997; Buisson et al. 1996; Wiessner 1983; Wobst 1974). The three distinctive learning methods – based on the work of Eerkens and Lipo (2005, 2008) affect how the list is updated every day.

Autodidact implies that cultural traits are not passed on between individuals. Instead, all campers learn for themselves by copying their own traits. When the transmission method is set on *Conformism*, campers copy the average of all other campers found at the camp. Each trait in the list is replaced by the mean of the campers' similar trait. In other words, the first trait of a camper is replaced by the mean of the other campers' first traits. *Prestige* transmission requires attributing 'prestige' to a certain number of campers – here set arbitrarily as 20% of the campers. Campers copy the list of a prestigious individual only when they are in the same camp. In all transmissions, 3% reproduction error is added to the new values to account for human error (Eerkens and Lipo 2005, 2008). This is represented by Eerkens and Lipo (2005)'s equation:

$$Y(t+1) = Y(t) + Y(t) * c * N(0,1)$$

where $Y(t)$ is the value copied, c is the error rate (3% divided by 2), and $N(0,1)$ is a random variable chosen from a normal curve with mean 0 and standard deviation 1.

The percentage of campers transmitting cultural information via prestige and conformism methods is set by a parameter value. If the value is set at 10%, roughly 10% of the campers learn from others every day; the other 90% use the autodidact method.

APPENDIX H

METHODS FLOWCHART – AGENT-BASED MODEL

[CONSULT ATTACHED FILES]

APPENDIX I

METHODS FLOWCHART – SOCIAL NETWORK RECONSTRUCTION

[CONSULT ATTACHED FILES]

APPENDIX J

MAGDALENIAN PORTABLE ART CHARACTERISTICS

[CONSULT ATTACHED FILES]

APPENDIX K

SOCIAL NETWORK METRICS – ARCHAEOLOGICAL ASSEMBLAGES

Cantabria

	Graph density	Degree centrality	Cluster coefficient	Shortest path	Pearson *r*	Covariance	Longest alliance	Strongest alliance
Lower Magdalenian	0.01	2.80	0.73	1.33	-0.02	-0.09	140.58	140.58
Middle Magdalenian	0.02	2.33	0.60	1.30	-0.23	-0.73	188.27	182.53
Upper Magdalenian	0.01	2.00	0.38	1.92	-0.30	-6.71	204.06	48.76

Dordogne

	Graph density	Degree centrality	Cluster coefficient	Shortest path	Pearson *r*	Covariance	Longest alliance	Strongest alliance
Middle Magdalenian	0.01	1.50	1.00	1.00	0.97	0.55	10.52	10.52
Upper Magdalenian	0.03	8.13	0.77	1.48	0.33	1.06	145.18	86.92

Inter-regional

	Graph density	Degree centrality	Cluster coefficient	Shortest path	Pearson *r*	Covariance	Longest alliance	Strongest alliance
Middle Magdalenian	0.02	4.80	0.86	1.14	0.13	4.25	636.49	493.39
Upper Magdalenian	0.02	10.86	0.68	1.59	0.03	1.41	683.07	445.62

APPENDIX L

POSTER – SUMMARY OF RESEARCH

[CONSULT ATTACHED FILES]