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The mobility of shepherds in the Upper Pyrenees: A spatial analysis of pathways and site-location differences from medieval times to the 20th century

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ABSTRACT

This paper investigates ancient pastoral mobility in a high mountain area of the Pyrenees. Firstly, modern transhumant routes were analysed using GIS tools in order to understand possible determinant factors (such as terrain slope and altitude, water courses and possible nodes) in the layout of a route used for seasonal livestock movements. The observations obtained were then used to model optimal paths which may have been used by ancient shepherds. Subsequently, an analysis was made of the spatial relationship between the simulated paths and the dispersion pattern of archaeological sites in two time periods: Late Antiquity-Medieval (3rd-14th centuries AD) and Modern-Contemporary (18th-20th centuries AD). The results show significant differences in the spatial distribution of the sites throughout both periods in terms of accessibility and proximity to possible pathways. This variability provides information concerning historical changes in the social structure of pastoral alpine landscapes over long periods of time.

1. Introduction

This paper focuses on ancient livestock routes across alpine and subalpine zones and how these seasonal movements lent structure to human settlements in high mountain landscapes in the past. Seasonal pastoralism is a socioeconomic activity in which shepherds move flocks between upland pastures in the summer and lowland pastures in the winter. The objective of this movement is to make use of seasonal variations in vegetation to feed flocks. These kinds of herder activities have been of great economic and social importance in different rural regions of Southern Europe. A great deal of variation can be found within this general strategy depending on the region. In the mid-20th century, this activity underwent a decline due to industrialisation, the withdrawal of primary activities and changes in the economy of rural zones. However, despite this downturn, the activity still exists in certain areas, particularly in Spain, France, Italy and Greece (Costello and Svensson, 2018).

Seasonal livestock movements have shaped the landscape of the rural areas in which transhumance took place. Place names, buildings such as huts and enclosures, bridges and water sources are the materialisation of this activity. These movements have constituted a significant element of the economy of the regions in question and have provided structure to the social and economic relationships between regions at different levels of altitude.These seasonal movements have been the object of study by ethnographers, anthropologists, geographers, historians and archaeologists since the beginning of the 20th century. Transhumance has been regarded as a social phenomenon which has connected different regions and societies since Late Prehistory. For instance, seasonal livestock movements have been proposed as an explanatory factor of cultural diffusion during the Bronze Age in the Iberian Peninsula (Jimeno, 2001). Other studies have considered that this activity could provide an explanation for the position of certain megalithic elements (Chapman, 1979; Galán and Ruiz-Galvéz, 2001).

Furthermore, over the last twenty years, archaeological research in the principal mountain chains of Europe has undergone significant development, particularly in the Pyrenees (Gassiot Ballbè, 2016; Orengo et al., 2014; Rendu et al., 2016) and the Alps (Della Casa, 2013; Walsh et al., 2014). Paleoenvironmental and archaeological research has shown that upland grazing areas in the Pyrenees have been exploited by pastoral groups since the fourth to third millenniums BC. (Galop, 2016; Gassiot Ballbè et al., 2014; Laborda et al., 2018). The spatial coincidence on a regional scale of prehistoric archaeological sites with modern transhumant settlements may suggest the dawn of a transhumant model

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of pastoralism at the end of the Neolithic. However, other studies reject this timeless interpretation. While "transhumance" is a modern term used to describe modern pastoral practices (Rendu, 2006), certain archaeological studies based on fieldwork data in different mountain areas reject the idea of continuity from early herder occupations of upland zones at the end of Prehistory to modern transhumant pastoralism. According to these studies, detailed examination of material remains reveals discontinuities and a succession of different pastoral practices over this large timescale (Carrer and Angelucci, 2017; Gassiot Ballbè et al., 2020; Le Couedic et al., 2016).

The aim of this paper is to investigate seasonal pastoralism movements in the past in upland zones and to explore their possible spatial relationships with the location of archaeological sites. To achieve these objectives, our research focused, first of all, on a well-documented historical transhumant pathway from the lowlands of the north of Spain to the Central Pyrenees. In this step, the goal was to understand the rationality of the route in an attempt to discover why the transhumant route runs where it does. This provided the basis for the next step, which consisted of modelling possible pastoral paths in the National Park of Aigüestortes and Estany de Sant Maurici (PNAESM) via the use of digital tools. This is an upland zone in which previous research carried out by our group has recorded nearly 380 archaeological sites related to livestock activity over different periods of time (Garcia Casas, 2018; Gassiot Ballbè, 2016). The second part of this study is devoted to exploring the spatial differences in the location of archaeological sites from two different time periods: Late Antiquity and Medieval (3rd-14th centuries AD) and the Modern-Contemporary period (18th-20th centuries AD). It takes up a previous analysis that, in similar terms, established significant differences between sites associated with livestock practices from the Late Neolithic and Contemporary periods (Gassiot Ballbè et al., 2020). The results contribute towards improving knowledge of the historical dynamics and mutations of seasonal pastoralism and can provide an insight into the social organisation of high-mountain Pyrenean territories in pre-modern times and their evolution towards the traditional agrarian and transhumant landscapes of the 20th century.

2. Regional settings

The research takes two scales of analysis into consideration (Fig. 1). The larger scale (Fig. 1b) is used to analyse the well-documented transhumant pathways extending from the Ebro Basin to the upland Pyrenean grasslands where the flocks graze in summertime. Fig. 1 b shows the path selected for this study from among all the transhumant routes ethnographically recorded in the area (Fig. 2). The area shown in the figure comprises the east of the province of Huesca in the region of Aragon and the province of Lleida in Catalonia. The starting point has been chosen as it is the confluence of three minor routes. The arrival point is situated in the Val d'Aran, near the French Border. The large area between these two points is characterised by a steep altitude gradient, passing from 200 to 300 m.a.s.l. in the Ebro basin to 3000 m.a.s.l. in the Upper Pyrenees. In the southwestern part of the path, the Ebro basin and Cinca Valley are characterised by a Continental-Mediterranean climate with low rainfall (300–350 mm/yr), high insolation and aridity. On the other hand, the Axial Pyrenees are mainly characterised by an Atlantic climate, with cold winters, mild summers and high rainfall throughout the year. Annual precipitation exceeds 1000 mm/yr, while average temperatures range from −4 °C to 2 °C in winter and 13 °C to 18 °C during summer.

The smaller and most important scale of analysis is the National Park of Aigüestortes i Estany de Sant Maurici (PNAESM) (Fig. 1a), where the archaeological sites selected for analysis are located. The PNAESM, which coincides with the upper part of the transhumant route, covers an area of almost 40,000 ha in the Pyrenean area of the province of Lleida at the eastern extreme of the granite batholith of Maladeta. Some of the peaks reach an altitude of 3000 m.a.s.l and the valley bottoms are, at their lowest points, over 1500 m.a.s.l. The relief shows traces of glacial action by the geological substratum and the alpine orogeny, with a landscape dotted with small lakes, cirques and U-shaped valleys delimited by peaks that are generally quite steep and rocky. The orientation of the valleys reveals significant variations, especially in terms of humidity and precipitation, a fact which, along with their

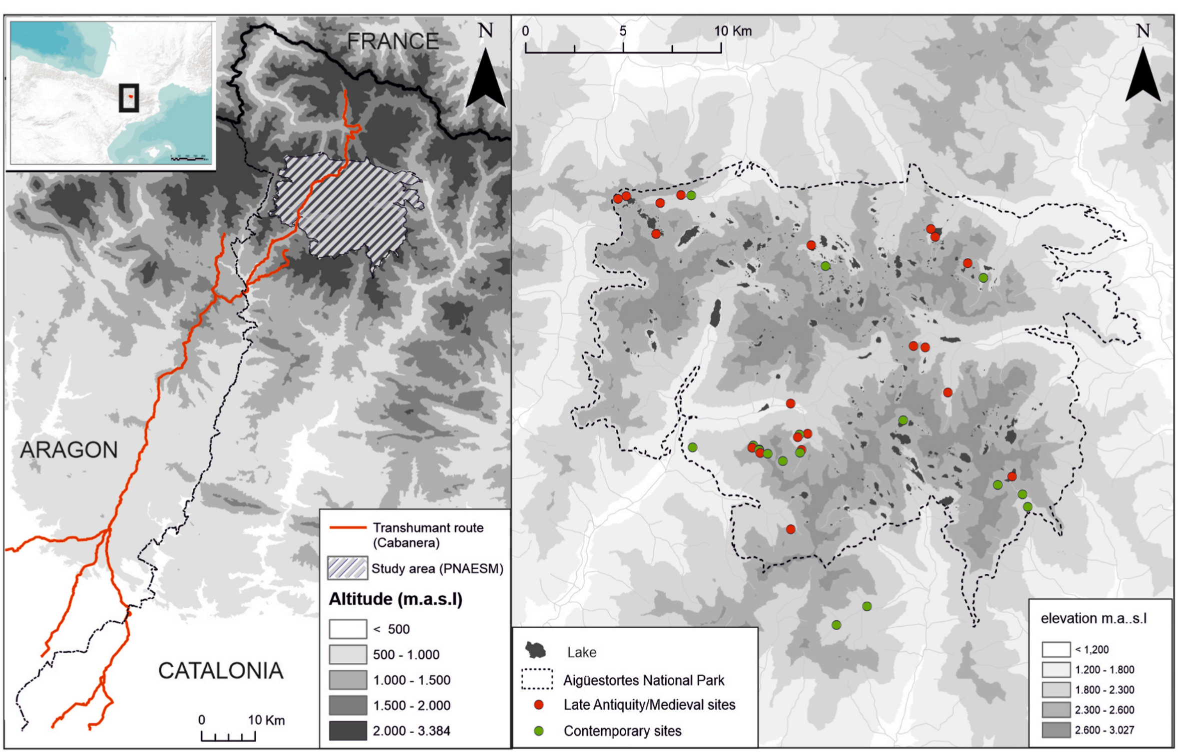

Fig. 1. a. (Left). The transhumant pathway analysed in a regional scale. Fig. 1 b (Right). Location of the study zone. The Aigüestortes and Estany de Sant Maurici National Park (PNAESM) and the archaeological sites analysed.

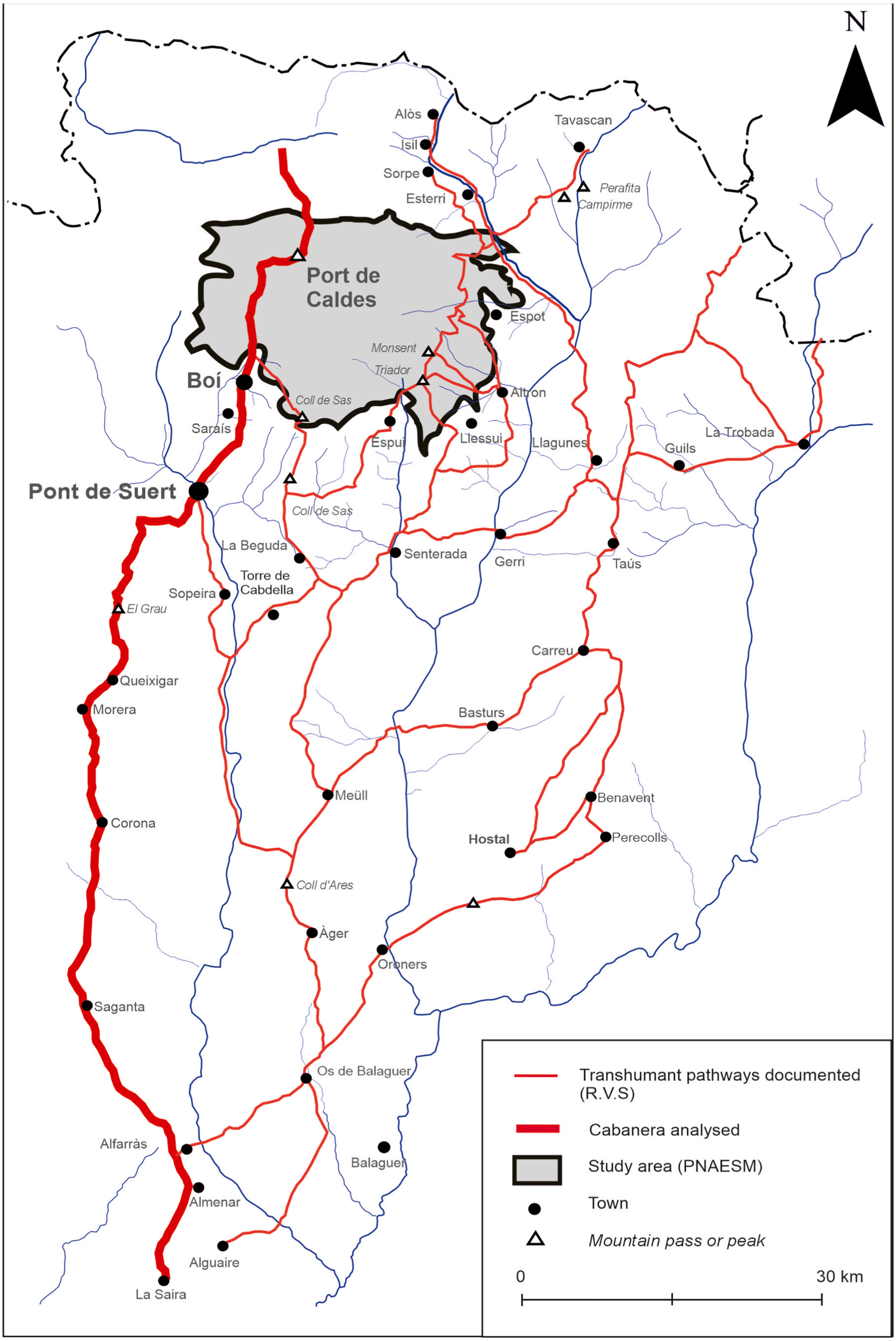

Fig. 2. Transhumant routes (cabaneres) at the beginning of XX century according the data collected by Ramon Violant i Simorra (R.V.S). Map adapted from data provided by Ignasi Ros. Some of toponyms are highlighted because they are mentioned again in the Fig. 8.

altitude, has a significant effect on ecosystems.

3. Materials and methods

3.1. The case study: archaeological data and previous research in the PNAESM

Since 2004, an archaeological research project has focused on the identification and mapping of archaeological remains in the PNAESM with extensive surface surveys employing a transect strategy to cover the majority of the accessible terrain (around 90% of the whole PNAESM area). The fieldwork recorded 378 archaeological sites (Gassiot Ballbè et al., 2016). Many of these are open-air structures built in dry-stone, mainly huts and enclosures interpreted as folds. Specifically, sites with one or more open-air structure comprise almost 65% of the total (Gassiot Ballbè, 2016). Furthermore, there are rock-shelters with traces of human occupation sometimes associated with open air structures and, to a lesser degree, ring-stones which could be tumuli and deposits of artefacts. Most of the archaeological sites are located between 2000 and 2400 m.a.s.l. In general terms, the spatial distribution of the sites is similar. Half of them are located less than 75 m away from a water source in grassland areas (Gassiot Ballbè et al., 2016). The combination of grass and water is a key factor in modern husbandry and it is probable that this was also the case in the past. The information on the surface was complemented by that from the excavations, which consisted of both small test pits and excavations of larger areas. Using radiocarbon dates of the samples collected, a large sequence from the last 10,000 years has been obtained.

Late Antiquity and the Middle Ages are, together with the last two centuries, the best represented periods in terms of archaeology. For the first sample, archaeological sites were selected with a chronology ranging from the 3rd to the 14th centuries AD. In this group, seven ensembles of between three and seven open-air structures were identified, with at least one of them a hut and two enclosures interpreted as folds. Another ten are large ensembles of more than eight structures. These kinds of settlements seem to be places where different groups of shepherds with several flocks would come together (Garcia Casas et al., 2022). This demonstrates a social organisation of pastoralism which is very different to that of modern transhumance (Garcia Casas and Gassiot Ballbè, 2022). The other three sites are rock-shelters with enclosures in the interior of which open area excavations or test pits have been carried out. The chronology of the occupations is inferred by AMS dating, with the exception of the three grouped settlements, in which the chronology is inferred by morphological similarities in the architecture and number of structures (Garcia Casas, 2018). Table 1 shows the radiocarbon dates of archaeological sites analysed (Garcia Casas et al., 2022; Garcia Casas and Gassiot Ballbè, 2022; Gassiot Ballbè, 2016). If there are more than one date in the same phase the table shows the maximum interval taking in account. All the radiocarbon samples are charcoal. The results have been calibrated to 95% probability with the IntCal20 curve using the OxCal program (Reimer et al., 2020).

For the contemporary period, 17 archaeological sites were selected, with radiocarbon dates being provided for only one case (SO-007A). The others were selected due to their morphological similarities with transhumant settlements of the early 20th century as described by ethnographers (Garcia Casas, 2013; Vilà i Vilà Valentí, 1950; Violant i Simorra, 2001) or as a result of modern materials related with the archaeological site being found on the surface. In this article, “contemporary” refers to a chronology estimated between the 18th and 20th centuries (Gassiot Ballbè and Garcia Casas, 2014).

The routes of the transhumant pathways were extracted from the official cartography of the autonomous government of Catalonia (Departament d’Acció Climàtica, Alimentació i Agenda Rural, 2012). This study pays particular attention to one such pathway (Fig. 1b). *Cabanera* is a Catalan word used to refer to a transhumant pathway and, for reasons of simplification, in this paper the selected path shall be referred to as the *cabanera*. This pathway was chosen due to the fact that it is the subject of a previous study (Nadal Subirà et al., 2010), the authors of which followed a transhumant flock at different times between 2004 and 2007, recording the route taken with GPS in order to create a shapefile. This provides a more precise route than the regional cartography. The route appears in the ethnographical studies by Violant i Simorra, written in the 1930s (2001: 77), and the geographer Vilà i Vilà Valentí (1950) (see Fig. 2).

In this paper, two terrain datasets with different resolutions are used. The first is the European Digital Elevation Model provided by the

Table 1
Archaeological sites from Late Antiquity and Medieval Age selected for the analysis. Where available the chronological interval is presented. For a better description of radiocarbon results see (Garcia Casas and Gassiot Ballbè, 2022; Garcia Casas et al., 2022) see SPM1 for more data about **radiocarbon** results. Other settlements have been dated for architectural typology as described in (Garcia Casas et al., 2022). Types: LS: Livestock settlement, GS: Grouped settlement. RO: Rockshelter associated to open-air structures.

Site (ID)	Name	Type	Archaeological intervention	Dated by	Interval	Phase	N. Dates
AA-024A	Gerber I	GS	Test pit	Radiocarbon	415–571 cal AD	1	
AA-026N	Gerber II	LS	Test pit	Radiocarbon	603–774	1	
AA-043	Conjunt del Mig	RO	Test pit	Radiocarbon	612–775 cal AD	1	
ESP-015	Portarro	RO	Open-area excavation	Radiocarbon	890–1020 cal AD 709–952 cal AD	3–4	1 for each phase
ESP-016	Pletiu de la Coveta	RO	Test pit	Radiocarbon	579–660 cal AD	1	
ESP-024	Pletiu de Subenuix	LS	Test pit	Radiocarbon	250–414 cal AD	1	
NA-026	Pletiu deth Pòrt de Caldes II	LS	Test pit	Radiocarbon	126–346 cal AD	1	
NA-076	Poblat della Passada deth Nebot	GS	Surface record	Typology	–	1	
NA-079	Conjunt del circ de Rius I	GS	Surface record	Typology	–		
NA-084	Despoblat del Tuc deth Lac Redon	GS	Test pit	Radiocarbon	213–361 cal AD	1	
NA-090	Despoblat del Lac Tort de dalt	GS	Test pit	Radiocarbon	255–423 cal AD 1301–1408 cal AD	1–2	1 for each phase
NA-091	Conjunt del Plan de Rius	LS	Test pit	Radiocarbon	1025–1160 cal AD	1	
SO-006	Conjunt de l’Estany Gran de Mainera	GS	Surface record	Typology	–		
VB-001A	Palanco de Llacs	GS	Test pit	Radiocarbon	1175–1273 cal AD	1	
VB-014	Cova del Sardo	RO	Open- area excavation	Radiocarbon	885–1032 cal AD	3	2
VB-017 sup	Despoblat i pletiu de la Cova (Conjunt superior)	GS	Open-area excavation	Radiocarbon	890–1020 cal AD 990–1154 cal AD 1225–1290 cal AD	1–2	3 for 2 phases
VB-019	Despoblat de Casesnoves	GS	Test pit	Radiocarbon	1215–1280 cal AD	1	
VB-085	Conjunt de la Pleta d’Erdo	GS	Test pit	Radiocarbon	545–642 cal AD	1	
VB-088A	Despoblat de Port de Rus	GS	Test pit	Radiocarbon	1277–1392 cal AD	1	
VB-098	Conjunt de les Cometes de Casesnoves IV	LS	Test pit	Radiocarbon	436–637 cal AD	1	

European Union's Copernicus Land Monitoring Service (European Union, Copernicus Land Monitoring Service, 2022) with a spatial resolution of 25 m. The second is taken from the website of the Institut Cartogràfic I Geològic de Catalunya (Institut Cartogràfic i Geològic de Catalunya, 2022). The geospatial information regarding hydrology was extracted from the official cartography of the government of the Autonomous Community of Catalonia (Departament de Medi Ambient y Agència Catalana de l'Aigua, 2015). All the GIS analysis was performed in ArcGIS 10.5. and the statistical analysis in R package.

3.2. Methodology

This research has two main goals: to identify the paths used by shepherds in the past and to examine the relationships between these paths and the archaeological sites. In order to achieve these objectives, the analysis was divided into two parts according to each goal. The first concerns the identification of seasonal pastoralism mobility and, particularly, the identification of shepherds' paths in mountain landscapes. The second part seeks to assess possible relationships between these paths and pastoral sites and whether these change over time.

Movement is one of the basic mechanisms used by humankind to explore, interact and manage the space around them (Ingold and Vergunst, 2008). Paths are the materialisation of this mobility in the landscape, weaving together the disparate elements of daily life (Snead et al., 2009:1). In addition to connecting people and places, paths also provide structure to the landscape around them. Thus, the identification of paths is an important issue when seeking to understand the way in which a given area is organised. The study of movements, trails and paths is a growing field within landscape archaeology (White and Surface-Evans, 2012; Polla and Verhagen, 2014), both as a theoretical paradigm to understand them as components influencing the formation of landscapes and for the development of new methodologies to enable the study of ancient movement, such as Remote Sensing and Geographical Information System-based modelling (Saintenoy et al., 2017). The application of these technologies to archaeological research has made a great contribution to the analysis of human mobility in the past. One of the topics addressed by the research has been the analysis of the routes of ancient paths, it can be mentioned (Gassiot Ballbè et al., 2020; Lanen et al., 2015; Herzog, 2017; Parcero-Oubiña et al., 2019) as examples.

For our case of study, the transhumant pathways, there are usually no stone causeway constructions which can be observed on pedestrian surveys or stratigraphically excavations as is the case of other ancient routes studied archaeologically (eg. Roman Roads or Inca paths) (Fonte et al., 2017; Mendez-Quiros Aranda and Saintenoy, 2021). Therefore, their traces in the landscape are more ephemeral and difficult to detect in archaeological surveys or excavations. Their markers are usually milestones, sources of water for livestock, territorial boundary markers or traces of rock modification to open up passable paths. An example of this is shown in Fig. 3 in which it is possible to appreciate work carried out on the rocks in order to facilitate movement. However, such marks are rare and are not sufficient to reconstruct the route of transhumant pathways. The study of transhumant pathways is frequently approached via the study of historical documentation (Fairen et al., 2006; Burri et al., 2015). However, such documentary sources have limitations, particularly in terms of chronology, as sources about transhumant pathways were most commonly written between the 15th and 18th centuries. For previous chronologies, mention of the routes of the pathways is rare, or completely non-existent before the year 1000. The assumption that these paths existed even before prehistoric times is problematic. Thus, historical documentation has chronological limitations. Moreover, trends in mountainous zones tend to be misleading on maps, with only certain paths (presumably the most important ones) being represented. For instance, in our study area, only two transhumant paths are documented crossing the area of the PNAESM in a north-south direction. However, if the distribution of settlements in the PNAESM (Fig. 1a) is examined, it can be observed that there was mobility through many more valleys.

Fig. 3. Traces of an ancient road in the PNAESM. (Right) carved cross in a mountain pass between two rocks with traces to be arranged as a passageway (Left). Photo: Grup d'Arqueologia de l'Alta Muntanya.

Seasonal mobility in terms of pastoralism can vary according to different types of practices. A great deal of research has been carried out on seasonal livestock movements in transhumant and nomadic shepherds (Chang and Tourtellotte, 1993; Cribb, 1991). To summarise briefly, in the case of the former, the routes are longer and more established, with the route taken being more or less the same every year, only changing due to unexpected circumstances, and with only one or a few specialised shepherds making the trip. In the latter case, the movements have more variability within an established framework and large families move with the flocks.

This paper explores other routes potentially used by flocks and shepherds to cross the PNAESM using the GIS-based modelling analysis called Least Cost Pathways (LCP). The modelling of human movement via GIS-based methods has been the subject of much research in the field of archaeology (e.g White and Surface Evans, 2012; Herzog, 2014; Polla and Verhagen, 2014; among others). Previous studies (Gietl et al., 2007) have shown that the resulting route can vary depending on the algorithm and GIS software package used. Furthermore, algorithms sometimes give priority to the shortest paths, even if they go through rough zones in which human movement would be dangerous without climbing equipment.

The starting point of this paper is that there are certain universal factors which affect human movement, and physical constraints that slow down, hinder or even completely prevent circulation. Slope is one of the main constraints modelled in GIS-based mobility analyses, but it is not the only one (e.g., it is impossible to walk in bodies of water such as lakes or great rivers). However, the importance of physiological factors is different depending on the subjects who are moving (Fonte et al., 2017) For instance, the gradient of slopes has a different effect on commercial routes used by chariots than on the movement of shepherds. In addition, there are differences in social and cultural values which affect subjective behaviour and decision-making when choosing a given route (Llobera, 2020). There are socio-political factors which cannot be neglected. Land ownership and usufruct regimes affect accessibility to certain pieces of land and spaces. Likewise, the safety of people or goods in movement is also a factor which can influence mobility. In both cases, the archaeological determination of these factors is extremely complex and requires a great deal of information which is generally difficult to obtain and is practically absent in our study area. In future, these factors should be incorporated into more complex studies of the mobility of people and herds. To achieve this, more specific research programmes will be required (such as the models developed by M. Le Couédic in the Pyrenean Ossau valley) (Le Couedic, 2010). Bearing this in mind, and for the reasons already pointed out in Gassiot Ballbè et al. (2020), the present study begins by considering orography as the main factor in the determination of optimal paths. Subsequently, other spatial constraints are added, such as water courses and the possible existence of nodes in the route.

A wide range of functions have been developed to mathematically express the influence of terrain gradient on human mobility in the past (see Verhagen, 2018 or Herzog, 2014 for reviews about different studies).Two of the main algorithms used in archaeological research regarding human mobility in the past were tested: the Tobler Function (Tobler, 1993; White, 2015) and the Llobera and Sluckin Function (2007). In addition, another function was tested which has been used with success in a previous study on Neolithic mobility in the PNAESM (Gassiot Ballbè et al., 2020). In this step, the anisotropic versions of these algorithms were used in order to make a comparison with a returning pathway. Consequently, it was necessary to take into account the positive and negative gradient slopes in both directions.

The first is algorithm is described in Sluckin and Llobera (2007),

$$M(sw) = 2.635 + 17.73sw + 42.37\ s^2w - 21.43s^3w + 14.93s^4w$$

where S is the gradient terrain obtained using the equation s = Tan ((“slope in degrees” * 3.1416)/180). Slope in degrees is obtained using the “Slope” command in Arcgis from a Digital Elevation Model.

The outcome of this function is expressed in energy consumed by a walker travelling in hilly terrain. For the purposes of the present study, it is better to obtain the travel cost in time units. Thus, the results were converting to time by dividing the outcome by 12800. This can be visualized as equivalent time intervals, based on the energy consumed at a standard walking distance of 5 km/h on flat terrain.

The second function tested is the Tobler’s algorithm (Tobler, 1993; White, 2015):

T = 0.001 / (6 * (Exp((-3.5) * (Abs((Tan((([S] * 3.1416) / 180))) + 0.05)))))

where

T = Time in minutes to walk 1 km.

S = Slope in percentage.

Finally, the third function employed is the Nunes algorithm expressed in the following formula (Gassiot Ballbè et al., 2020):

T = S*1,2532 + 9,1806.where

In the first part of the analysis, the proposals put forward by Güimil-Fariña and Parcero-Oubiña (2015) to analyse the reasoning behind the routes of historical paths are followed. Specifically, the research of these authors is devoted to understanding the rationality behind the route taken by a Roman road. In the present study, a similar procedure was performed. The route of the *cabanera* was compared with an LCP created with some of the most commonly used algorithms in archaeological research, taking only biomechanical considerations into account. This is a null hypothesis and no greater coincidence was expected. Rather, the goal was to compare the routes, to explore how a transhumant route deals with physical constraints such as slope, altitude or water courses and to attempt to create a GIS model in order to perform LCP analysis with results similar to real livestock routes. To perform the LCP paths, the ArcMap command called *Path Distance*, available in the ArcToolbox (White, 2015), was used, which calculates an accumulative cost surface from one point in an isotropic way, taking into account negative values (downhills). The workflow followed in this step provides the 25m DEM and a table of slope values and their associated costs as well as a raster with possible obstacles to pedestrian movement. These costs change depending on the algorithm used. Therefore, three different tables are provided for each function. The 25m DEM was used in order to facilitate the calculation over a large area and to reduce the bias in the DEM due to the surface of modern roads which did not exist in the past. The next step was to model the layout of different possible routes using the *Cost Path* tool.

The second part of the analysis consisted of performing LCP routes to cross the PNAESM taking into account the observations in the previous analysis. At this point, the 5m DEM was used for the following reasons: the area is smaller; the presence of modern roads is negligible; and in order to take into consideration smaller paths or passageways unnoticeable in a larger DEM. In this part, the main methodological goal was to modify the usual workflow of LCP analysis to adapt it to geophysical patterns of mountainous zones and to obtain an output route that deals with physical constraints in a similar way to the ethnographically studied route. In this part, the main issue in any LCP analysis was addressed: the definition of the departure and arrival points of the paths. In this step, places with historical or archaeological evidence of population in Late Antiquity or the Middle Ages were chosen (Gassiot Ballbè et al., 2020). Table 2 and Fig. 11 show the points selected to be connected as well as the type of evidence of human occupation and its chronology. The majority of the points coincide with present-day villages and the evidence is based on documentation regarding the foundation of local churches or, in town in the Val d’Aran, the discovery of archaeological materials suggestive of permanent populations. As an exception, the location of Ares on the mountain pass of La Bonaigua is worthy of mention. This was the main point of access to the Val d’Aran before the construction of the Vielha Tunnel in the 1950s. It can be noted that the chronological evidence of settlements outside the park does not match exactly with the chronology of the archaeological sites. In other words, some historical evidence of the foundation of churches is dated to the 9th and 11th centuries, clearly later than sites from Late Antiquity. However, it must be noted, on the one hand, as some historians (Adell and Riu Barrera, 1994) argue, that the foundation of medieval churches took place in villages with a long history (i.e., human settlement was prior to the first documentary evidence). On the other hand, there are locations in valleys which connect with other valleys where there is evidence of human occupation from the end of Prehistory (Cots, 2003).

Finally, the third part of the analysis was devoted to achieving the second objective of the research: to examine the relationship between the paths and the sites and to verify whether there are changes according to the chronology of the settlements. To achieve this, the distance from each settlement to the nearest LPC route was calculated. The development of GIS applications makes it possible to perform different calculations for distance (see Bevan, 2011; Herzog, 2014 or Verhagen, 2018; among others). Some studies consider distance according to geometric criteria using density analyses or Thyssen Polygons. This kind of application is problematic outside of flat zones. In steep terrain, such as that of this case study, there is no reason to measure human mobility in Euclidean terms without considering topography due to the fact that it is literally impossible to cross the area by walking in a straight line. For this reason, in the present study, distance is assimilated to a cost surface which produces a certain friction depending on given geographical criteria. As was the case in the first part of the analysis, slope is the basis of this friction. For this part of the analysis, isotropic algorithms were taken into consideration in order to calculate a friction surface expressed in travel time (e.g., Bevan, 2011; Kantner, 2012, as well as other cases discussed in Herzog, 2014). In this part of the analysis, it must be borne in mind that the roads or mobility axes tend to run along the bottom of the valleys while the archaeological sites are located on the slopes. In other words, in practically all cases, pastoral settlements are located at a higher altitude than the nearest possible axis of circulation. Therefore, the positive effect of using an anisotropic cost algorithm in terms of displacement cost is minimal. Considering positive and negative slope is

Table 2
Historical and archaeological evidences of human settlement surrounding the study zone. Points used to start and end the LCP crossing the Park. INVARQUE is the patrimonial inventory of Catalonia and is cited in Web and cartographical references (Departament de Cultura, 2022). The other references are also cited in “References) (Bolos i Hurtado, 2012; Ordeig, 1993; Cots, 2003).

Cost factor	Ascribed cost
Slope-based pedestrian cost (Llobera and Sluckin, 2007)	MSw = 2.635 + 17.73 Sw+42.37 Sw2 − 21.43 Sw3+14.93 Sw4
Extra cost to avert river beds (depending on the sector)	3X
Extra cost to avert mountain ridges (wit a buffer of 10 m) (Carrer and Angelucci, 2017)	4x
Extra cost to avert slopes above 60%	3X
Extra cost to block crossing slopes above 100%	10X
Extra cost to block crossing lakes	10X

useful in calculations aimed at obtaining LCPs as the specific route may vary depending on whether negative slope is considered in the outward and return. However, this step is not intended to determine a specific route from an LCP crossing the study area to the archaeological site. The aim is to obtain a magnitude of the distance in terms of human mobility between the two entities (LCP and settlement). In this step, the 5m DEM was used in order to obtain a more detailed result.

Since the aim was to obtain plausible magnitudes and not exact results, the obstacles were simplified by only considering lakes as a barrier to movement. The procedure followed consisted of: 1) Calculating the slope in percentage from a DEM distributed by the ICGC with a pixel width of 5m (Institut Cartogràfic i Geològic de Catalunya, 2022); 2) Producing a friction surface with each one of the 3 algorithms (Llobera, Nunes and Tobler) 3) Performing a cost surface using the Cost Distance command. The procedure generated three continuous maps of displacement in minutes from the LCPs obtained to the rest of the analysed area (the surface area of the PNAESM) (Fig. 12). Next, the value of the pixel corresponding to each settlement was extracted in the three maps (results shown in Table 5). Finally, a statistical test was performed in order to check whether the distance of the archaeological sites to the nearest LCP depends on their chronology.

4. Results

4.1. Modelling transhumant movements

The study assumes that proximity to the optimal route is an important factor in the location of an archaeological site. This premise was verified by comparing the amount of terrain accessible from a route in time intervals with the number of sites at the same distance. Specifically, a cost terrain surface was performed from a section of the *cabanera* route crossing the PNAESM to the surrounding areas which was surveyed during archaeological fieldwork, the results of which can be observed in Fig. 4a and 4b and Table 3. In the first test, we used the Llobera and Sluckin algorithm. As a result, 33% of the archaeological sites are located less than 15 min away from the transhumant route despite the fact that this threshold only includes 11% of the terrain evaluated. On the contrary, only 5 out of 91 sites (5%) are located more than 150 min' walk from the transhumant route in contrast to 33.5% of the terrain (Fig. 5). Therefore, these observations suggest a preference for locating the archaeological sites close to the transhumant route.

The second test was used to verify whether altitude is a variable which can explain the variability of the spatial distribution. In other words, to check whether there are differences in the altitudinal distribution of the sites depending on their chronology. To perform the test, the absence of normality in the elevation values was verified with the Shapiro-Wilk test (P-value 0.142). Therefore, the non-parametric Kruskal Wallis test was used to check the distribution of altitude sites according their chronology as independent value. The outcome (P-value 0.915) confirms no significant differences between the two samples. Thus, there are no differences in the altitudinal distribution of Medieval and Contemporary sites.

To perform the first LCP model, it was considered necessary to add an extra cost for the lakes and water masses to avoid the LCP passing through them. For this reason, an extra cost of x10 to cross lakes or water masses was added. The results of LCP01 are shown in Fig. 6, in which it is possible to observe differences depending on the cost function performed. The outcome of the LCP performed with the Tobler cost function (LCP01TO) is quite different to the route of the *cabanera*, coinciding at its beginning with a slight variation going to the east before coinciding again. However, the most important divergence occurs when arriving at Alta Ribagorça. It does not go to Pont de Suert and continue to the north, following the course of the Noguera Ribagorçana river avoiding the Boí Valley. Arriving close to Espitau de Vielha, the route of LCP01TO turns to the east and reaches the PNAESM via the Canau de Rius mountain pass. Next, it crosses the Valarties Valley and arrives in the town of Arties. The route does not match again with the *cabanera* until the final stretch in the Val d'Aran. It should be noted that both routes cross the PNAESM, albeit via different valleys. The LCP performed with the Nunes algorithm is even more different, matching with LCP01TO along the course of the Noguera Ribagorçana river and following the same route. However, it only coincides with the *cabanera* in the previously mentioned final stretch. The third function, the Nunes algorithm (see Gassiot Ballbè et al., 2020), shows a great coincidence with the first one in the upper zone. However, in the lowlands it has a different layout.

On the other hand, the LCP created with the Llobera algorithm (LCP01LLO) shows a greater degree of coincidence, particularly in the Pyrenees, the mountain zone on which the analysis is focused. Despite some differences ascending through Aragon, the LCP01LLO model crosses the Noguera Ribagorçana in the town of Pont de Suert, follows a similar path through the Boí Valley and crosses the PNAESM area through similar valleys. There are two differences which are of particular interest in terms of this study. The first divergence occurs after crossing the Caldes mountain pass with the route going straight up a near vertical zone (highlighted in Fig. 6). From personal experience and observations during fieldwork in the area, passing through this route is difficult and dangerous without climbing equipment. The second difference is a detour of the Cabanera arriving at Vall d'Aran and the Garona watershed. There is no apparent geophysical reason for taking this detour.

In order to understand the first divergence mentioned, attention was focused on one of the methodological goals of this paper: the need to adapt the cost functions to the features of high mountain zones and to explore the effects of features of mountain topography on the routes of transhumant pathways, the most important of which is, in our modelling, the slope gradient. In the last LCP model, at least one unrealistic stretch in the output route was shown. It can categorically be stated that slopes of more than 125% are always dangerous for human movement without special equipment. As far as the movement of shepherds with their flocks is concerned, the following aspects can be stated: a)

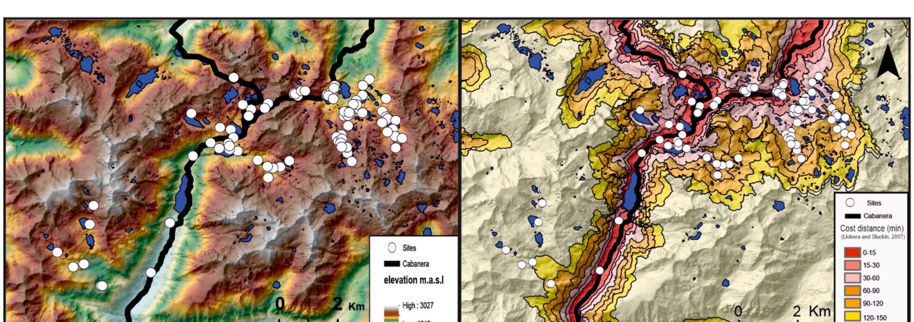

Fig. 4. a (Left). Map of the PNAESM zone selected for the test, transhumant pathway (Cabanera) and nearby archaeological sites. Fig. 4 b (Right). The same map with the cost distance in minutes reclassified on intervals.

Table 3
First test results. Amount of land and number of archaeological sites at each cost distance interval.

NORMALITY TESTS	LLobera		Tobler		Nunes	
	W	p-value	W	p-value	W	p-value
Distance to nowadays transhumant route	0.87954	0.0008346*	0.87473	0.000628*	0.88795	0.001386*
Distance to LCP	0.95687	0.1605	0.96001	0.2022	0.95356	0.1257
SIGNIFICANCE TESTS	LLobera		Tobler		Nunes	
	T	p-value	T	p-value	T	p-value
Distance to LCP (T Test)	−2.7655	0.009405*	−2.6741	0.01171*	−2.8369	0.007957*
	Chi-square		Chi-square		Chi-square	
Distance to nowadays transhumant route (KW-Test).	0.00092879	0.9757	0.014861	0.903	0.0083591	0.9272

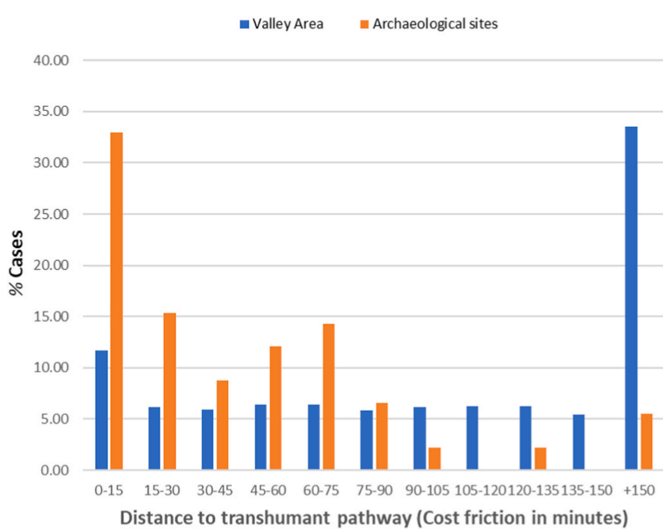

Fig. 5. Graphic comparing the number of sites and the amount of terrain surrounding the transhumant pathway.

Shepherds do not usually use climbing equipment in their movements; b) There is a threshold at which movement becomes dangerous and should be avoided. The main question is: where is this threshold? The perception of a "steep slope" can be subjective and imprecise, especially in terms of performing GIS analysis. To respond to this question, the slope of the *cabanera* was examined via the analysis of its altitudinal profile (the results are shown in Fig. 8). More than half of the terrain crossed by the *cabanera* has slopes of less than 15%. Indeed, slopes steeper than 60% are extremely rare, accounting for less than 5% of the pixels in the layout. It should be pointed out that the pixels are imprecise due to their size (625 m^2). Extreme values in the graphic can be related with these pixel inaccuracies. To improve the analysis, the methodology proposed by Güimil-Fariña and Parcero-Oubiña was followed, adapting it to our study case. An extra cost of x3 was assigned to slopes steeper than 60% (in an attempt to avoid them and only use them if absolutely necessary) and x10 to slopes of more than 100% (to definitively avoid passing through terrain with this gradient). According to the first test results, the analysis was performed with the Llobera cost function (see Fig. 9).

The results (LCP02) are not sufficiently satisfactory to understand the route of the *cabanera*. The outcome shows a divergence even higher than that of LCP01LLO in comparison with the original route of the *cabanera*. Altitude could be another possible factor in understanding why the *cabanera* runs where it does. Fig. 7 shows that the maximum altitude is 2564 m.a.s.l. Thus, in the next test an extra cost factor of x4 was added for land above 2350 m, providing exactly the same outcome (LCP03) as LCP02. Therefore, altitude can be discarded as a movement factor to model in our case study.

At this point, another possible constraint for mobility in the study area was examined. Common sense suggests that it is not possible to walk through lakes and large rivers. However, if the route of the *cabanera* is examined, it crosses some large rivers and streams. It is necessary to bear in mind that what is being modelled is the movement of shepherds with their flocks numbering hundreds of livestock. Even crossing a river (in this case Noguera Ribagorçana) with small boats seems impractical. It is known that there were bridges to cross the river, but the great majority were built in the 19th or 20th centuries. However, on the route there is a village (Pont de Suert) the name of which suggests the presence of a bridge from at least Medieval times. Indeed, toponymical and historical studies (Coromines, 1970) suggest the existence of the town and the bridge from at least the 1000 AD. Therefore, in subsequent models the existence of a bridge in this village was taken into consideration.

The beds of the main rivers (the Segre and its affluents Noguera Ribagorçana and Noguera Pallaresa) were added as a constraint. Partially following the methodology of another case study (Güimil-Fariña and Parcero-Oubiña, 2015), an extra cost of x3 was added to a buffer area of 5 pixels (25 m) around the courses of the rivers, with the exception of Pont de Suert, where the cost was not altered. A relatively low degree of difficulty was attributed due to the fact that the existence of fords or other bridges that have now disappeared cannot be discarded. Finally, it was taken into account that the route of the *cabanera* crosses the main rivers at different points. Therefore, they cannot be modelled as insurmountable obstacles. In this case the extra cost is not high, meaning that the movement along rivers is not completely hindered. Finally, a further constraint (ridges) was added to the new model (LCP04). Mountain paths usually avoid ridges, due to their exposure to high winds and lightning. To create the ridges in the model, another study in ancient mountain pastoralism (Carrer and Angelucci, 2017) was followed. A hydrographic analysis was performed using an inverse DEM to execute the *Flow Direction* and *Flow Accumulation* commands. Then, the ridges were extracted creating a buffer of 10 m around them and an extra cost of 3x was added. As with the case of the rivers, the goal was to avoid LCP routes crossing this type of terrain, albeit without creating impassable barriers (if necessary, a shepherd and his/her flocks can cross a ridge or a river).

The outcome (LCP04, Fig. 10) now shows a remarkable similarity with the route of the *cabanera*. The pathway avoids crossing zones with steep slopes although there is still a divergence when the routes descend from the PNAESM to the Val d'Aran and cross the Garona river at another point. Here, the *cabanera* makes a detour, apparently with no relation to geophysical constraints. This may have been caused due to the existence of a bridge or ford, rights of access or other sociohistorical reasons. At this point, it is considered that the LCP04 model is useful for modelling ancient shepherds' paths between different villages crossing the archaeological zone of study (the PNAESM).

4.2. *Making the least Cost Paths*

At this point of the analysis, a method was defined to obtain LCP routes with a route similar to well-documented ethnohistorical transhumant routes passing through mountain zones. To summarise, the method employs the Llobera anisotropic algorithm giving an extra cost

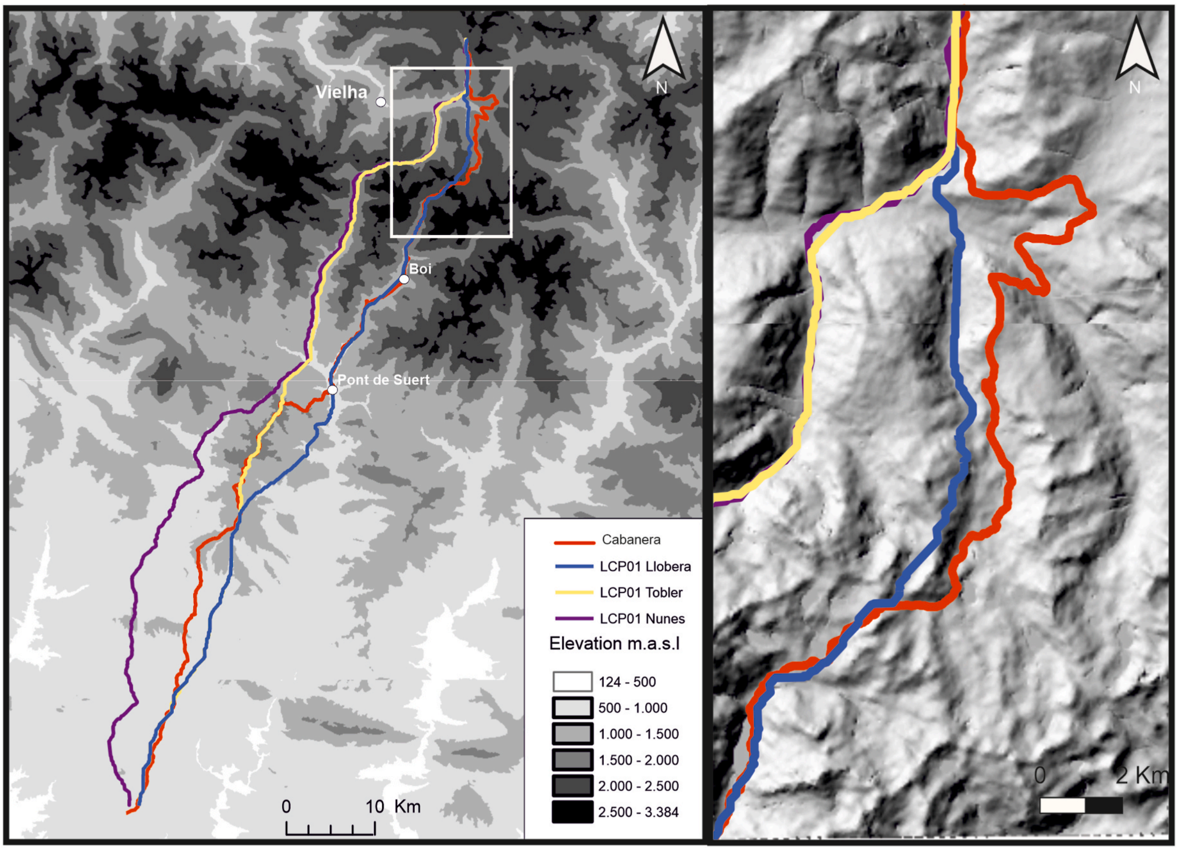

Fig. 6. Comparison of the Transhumant Route layout, and the LCP's obtained using Tobler, LLobera and Nunes algorithms.

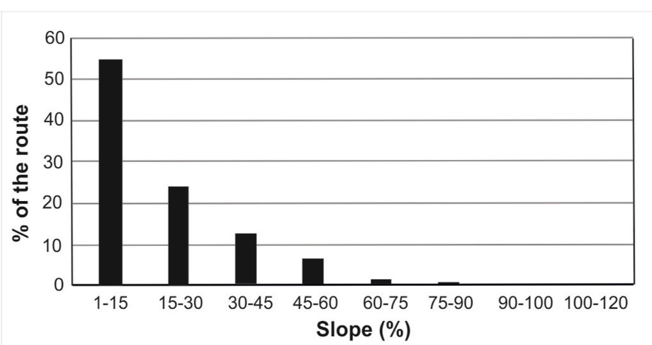

Fig. 7. Histogram of the slope transhumant route.

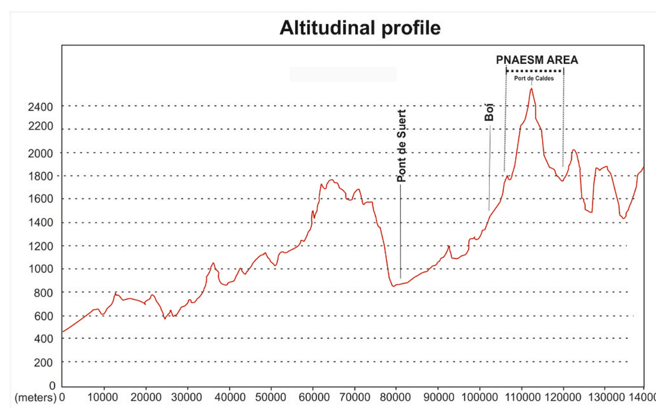

Fig. 8. Topographical section of the transhumant route selected for the study shown in Fig. 1b and Fig. 2. The 2564 m threshold is highlighted.

of x3 to rivers, x10 to lakes, x4 to ridges x3 to the slopes above 60% and x10 to the slopes above 100% (Table 4). The next step was to plot the LCPs between the aforementioned points surrounding the PNAESM. The goal was to produce a hypothetical mobility map of shepherds in the past based on current data regarding transhumant routes which could be of assistance in evaluating the location of archaeological sites (the results can be observed in Fig. 11). As can be seen, the routes of the three transhumant paths (*cabaneras*) inside the PNAESM show a high degree of coincidence with the LCP routes obtained. On the other hand, it should be noted that the LCP also coincides with present-day pedestrian pathways. It should also be noted that the LCPs performed are similar to those modelled in previous studies (Gassiot Ballbè et al., 2020; Garcia Casas, 2018).

4.3. Site locations, pathways and mobility

Having addressed the question of how to model ancient pastoral mobility in a mountain zone, the second part of this study is devoted to exploring spatial differences in the distance from the archaeological sites to the LCP outcomes. In this part of the analysis the methodology employed for modelling geographical relationships is different as the spatial phenomena to explore them are not the same. First of all, the goal was to understand the geographical factors which can influence the layout of a transhumant path. Then, another spatial (and social) phenomenon was addressed: the distance from a possible livestock pathway to the locations of certain archaeological sites. The goal was not to address how much time it takes to move from one place to another.

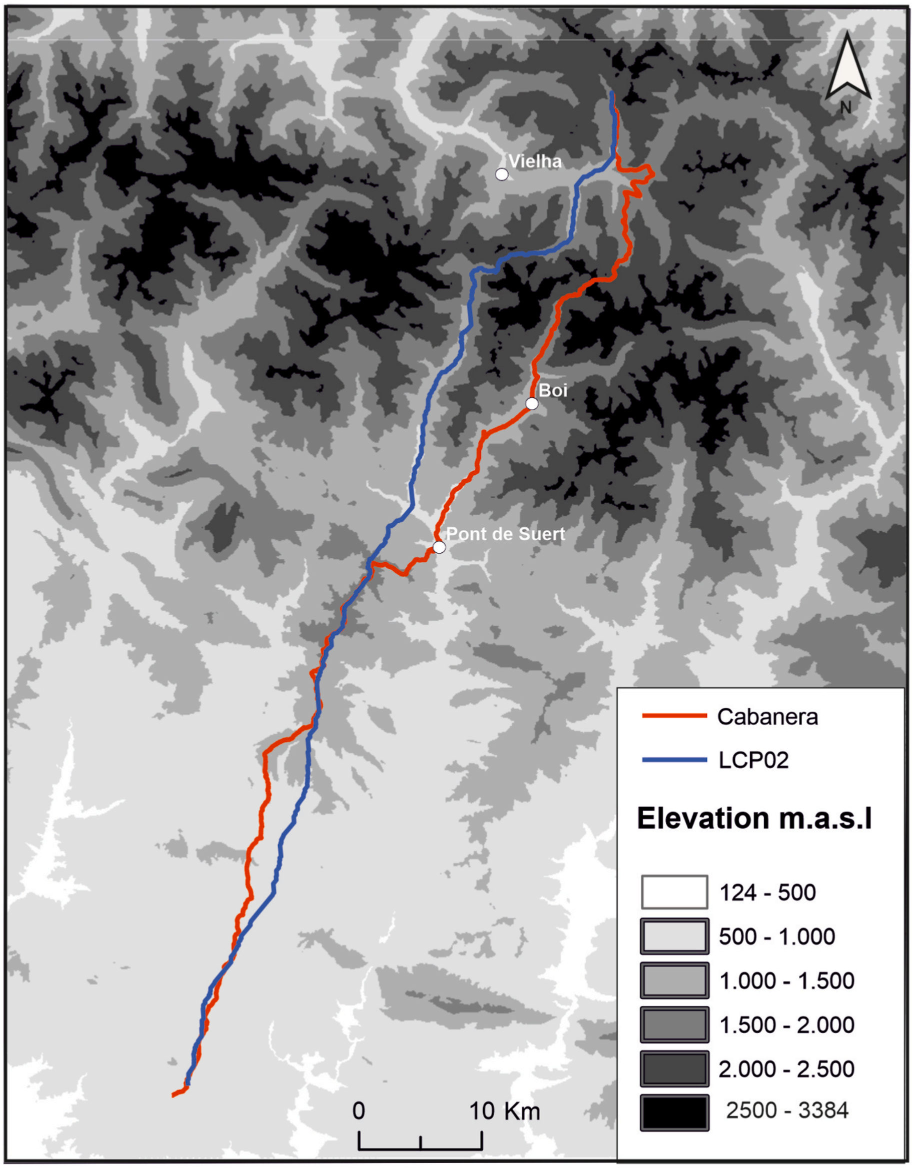

Fig. 9. LCP02 and the layout of transhumant route (cabanera).

Rather, the purpose was to obtain a plausible magnitude regarding the distance from a spatial entity (the LCP) to two samples of archaeological sites with different chronologies in terms of human mobility.

Table 5 shows the distance in minutes from the LCP pathways to the archaeological sites. Firstly, attention was paid to the distance to the LCP routes. The time differences depending on the algorithm used are, in general, quite significant if the sites are located at a short distance from the LCP (less than 20 min). At higher time thresholds the distance can increase by more than 20 min depending on the algorithm. If the results are examined, it can be seen that these differences do not follow a linear pattern either for short or long distances. They can be attributed to how the algorithms deal with different thresholds of slope. It is interesting to note that the Llobera algorithm provides, in all cases, higher distance values than the other algorithms. In general, the Tobler algorithm provides lower values, although, in some cases, the results of the Nunes algorithm are similar. However, if the means are taken into account, the results are clearer, showing considerable differences depending on chronology. In this regard, it is useful for the purposes of this research, which focuses on modelling and obtains possible magnitudes rather than reconstructing the exact time that a shepherd took in the past. The next step was to check if the differences in the frequencies depending on chronology were statistically significant. To achieve this, first of all, the Shapiro-Wilk test was performed (VanPool and Leonard, 2011) on each of the three series of frequencies according to the algorithm. The outcomes (shown in Table 5) demonstrate that the frequencies in each of the three series (distance according to the Llobera, Nunes and Tobler algorithms) are distributed normally. Therefore, the T-test was used to perform the analysis with the results showing a high degree of significance (see Table 6) in the outcomes provided by the three algorithms. The distances in time provided by each algorithm are different, although in all three cases there are significant statistically differences depending on the period. Therefore, it can be stated that differences in the distance to an LCP route are related to the chronology of the archaeological site.

However, if the distance from each settlement to present-day transhumant routes (*cabaneras*) is taken into consideration, there are no significant differences (see Table 6). The distribution was not normal and therefore the Kruskal-Wallis Test was used. The values for distance in minutes to the archaeological sites are high even in the medieval or contemporary settlements, with the exception of two cases in each chronology (SO-007 for the Contemporary period and NA-026 for the Late Antiquity/Medieval period). This could be explained by the layouts of present-day transhumant routes which only cross some areas of the

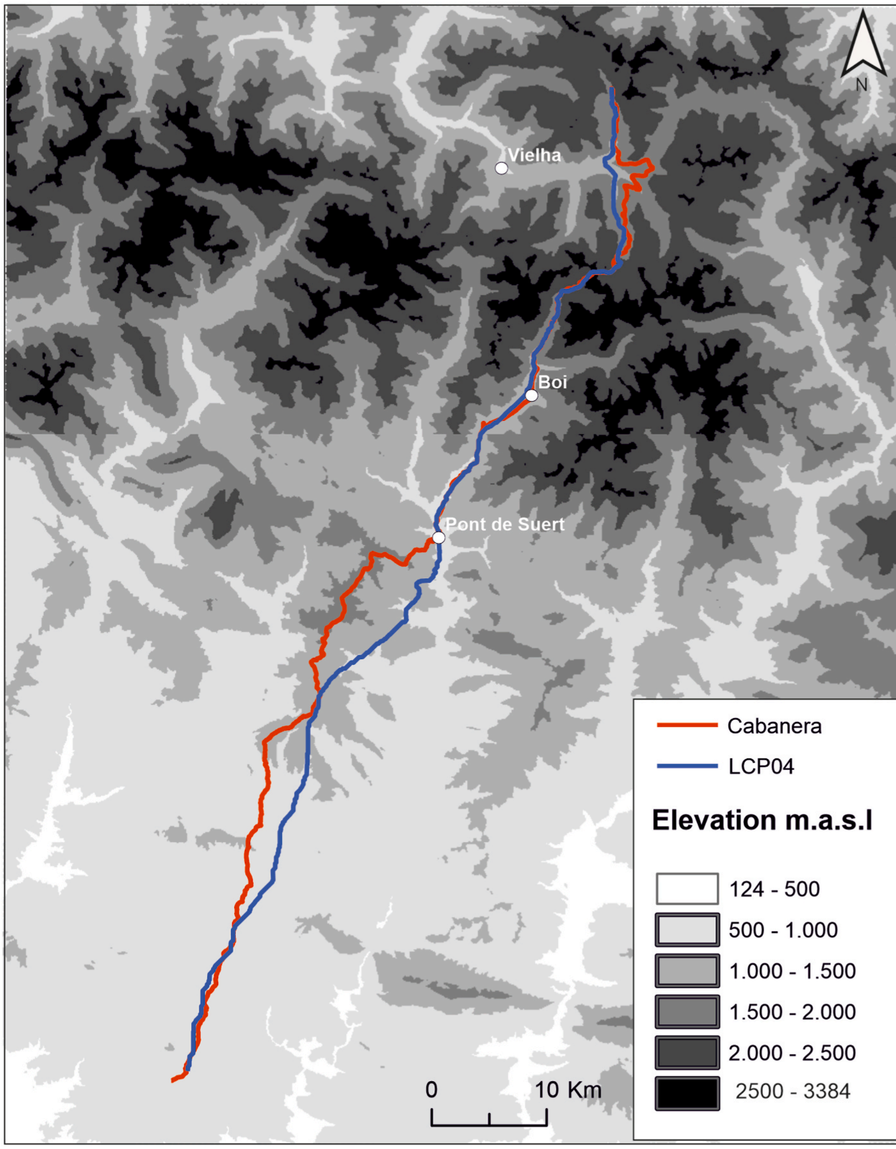

Fig. 10. LCP04 and the layout of transhumant route (cabanera).

PNAESM. For this reason, LCP analysis proved useful in studying ancient mobility. Even if the reconstruction of the routes is not the goal, GIS models make it possible to approach possible axes of circulation. Moreover, the differences in distance to the archaeological sites provide information concerning historical changes in landscape use.

5. Discussion

The research presented here has been successful in understanding mobility linked to the seasonal movements of livestock between the plains of the Ebro Valley and the Central Pyrenees and how this provided structure to the territory in the high mountain landscapes of the Pyrenees in the past. It has also made it possible to verify the existence of a historical change in the organisation of the territory and settlement patterns in relation to the possible routes crossing the PNAESM that arose between the end of the Late Middle Ages and the last two centuries before the present. Below, these achievements will be discussed following the order in which they were presented.

The analysis of a present-day transhumance route has enabled an understanding of the topographical and geophysical factors that influence the route of a current transhumance pathway linking the Ebro Valley with the PNAESM in the Central Pyrenees. In brief, the maximum slope thresholds of this route have been determined, along with the role of rivers, water masses and ridges as factors affecting the mobility of livestock and the role played by a village as a node. However, more than its explanatory factor, in our opinion, the main achievement of this part of the research has been to obtain a methodology to obtain viable LCPs as regular circulation routes. As pointed out in the introduction, the direct application of some of the procedures and algorithms for obtaining LCPs in archaeology risk obtaining routes that are unfeasible for human circulation. In many cases, the outputs prioritise crossing extremely steep slopes rather than travelling long distances to get around them, and, although in some cases it is physically possible to avoid them, these are routes with a high risk of falling without climbing equipment. Thus, they are unlikely to constitute frequently used communication routes.

The analysis raised has made it possible, via the observation of a known route, to obtain quantifiable and reproducible factors in GIS operations. The resulting LCP returns a path very similar to the transhumant route used as an ethnographic reference. The same factors were then applied to LCP analyses of mobility between permanent settlements and other points of settlement surrounding the PNAESM, obtaining

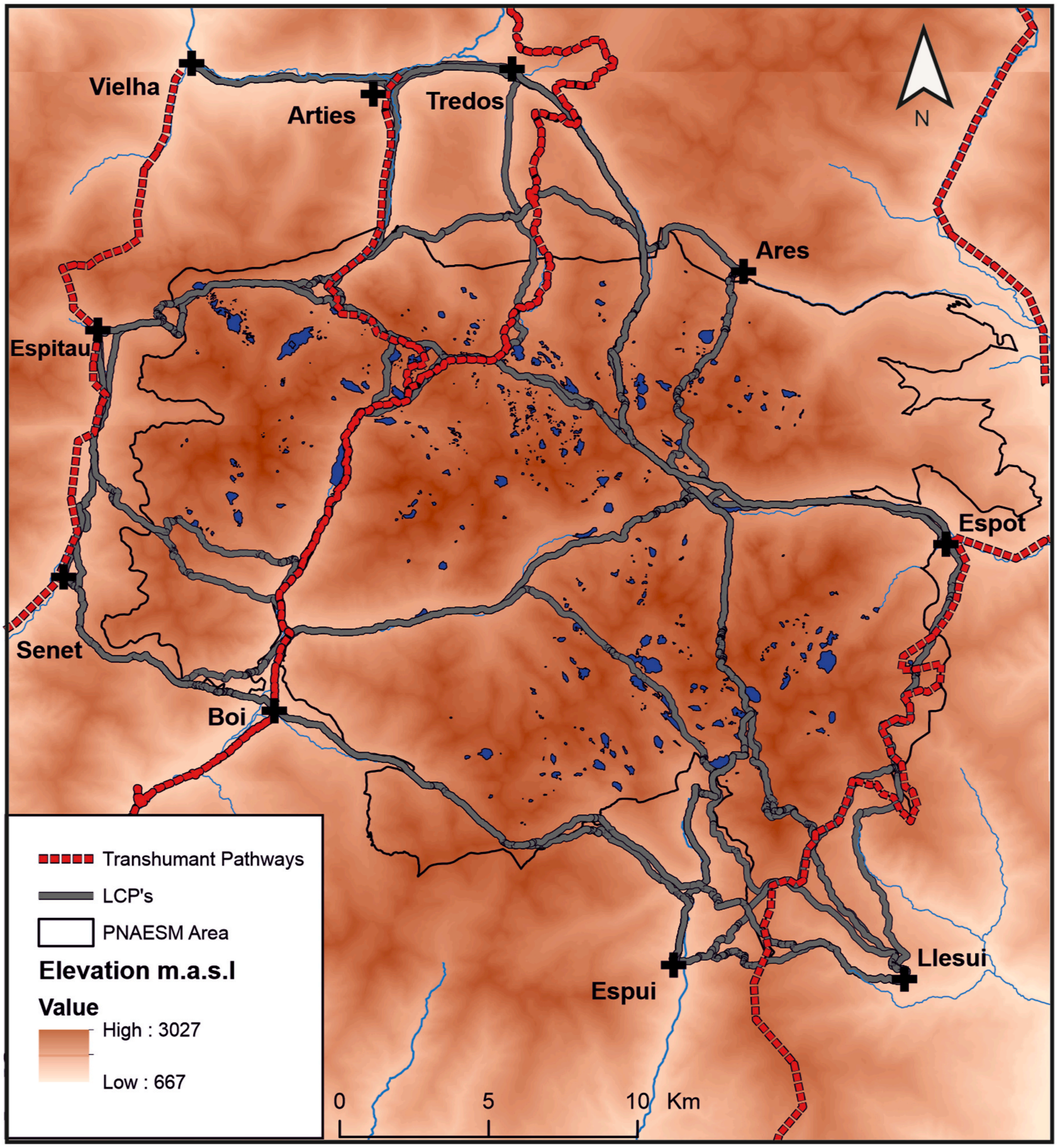

Fig. 11. LCP's between the selected points surrounding the PNAESM and transhumant pathways. Permanent settlements and other evidences of permanent occupation attested in the region where PNAESM is located (see Table 2).

possible paths to cross the study area where the archaeological sites analysed are located. These are potential paths that could have been used in the past and for which no documentation has been preserved, a normal fact given that until recent times the mention of the specific livestock routes is anecdotal and extremely imprecise. It is understood that these possible routes are suitable for livestock movements similar to those recorded today or in recent centuries. In our research a present-day transhumant route was used as a basis to infer possible pathways in the past. This approach implicitly assumes that the subjects who are moving and subjective human behaviour have not changed significantly. It can be argued that pastoral movement can change depending on the different size of flocks, the animal species concerned, if there are pregnant animals in the flock, etc. These factors can affect the ability to cross areas of rough terrain and therefore affect the decision-making process when choosing one route or another. These arguments are true and must be taken into account. However, as has been argued above, the methodology is non-reconstructive: the aim is not to reconstruct the exact route, but to understand factors which provide information about pastoral movements in mountain zones, leading to the creation of plausible possible pathways. On the other hand, other studies on LCPs in archaeology (Kantner, 2012) suggest that comparing the resulting routes with the distribution of archaeological sites along them can suggest that the possible pathway was indeed used. As explained above, the first group of sites in the Medieval era fulfil this condition.

Furthermore, it could be of interest to compare the outcome of the network of pathways in this research with a previous study in the same area focused on the accessibility of Neolithic archaeological sites to grazing areas and possible roads (Gassiot Ballbè et al., 2020). In that paper, LCP pathways were performed using the Nunes algorithm adding extra cost only to water masses such as lakes. Despite the differences in methodology, the degree of divergence in the routes obtained is low. In general, the routes cross the same valleys and mountain pass with only

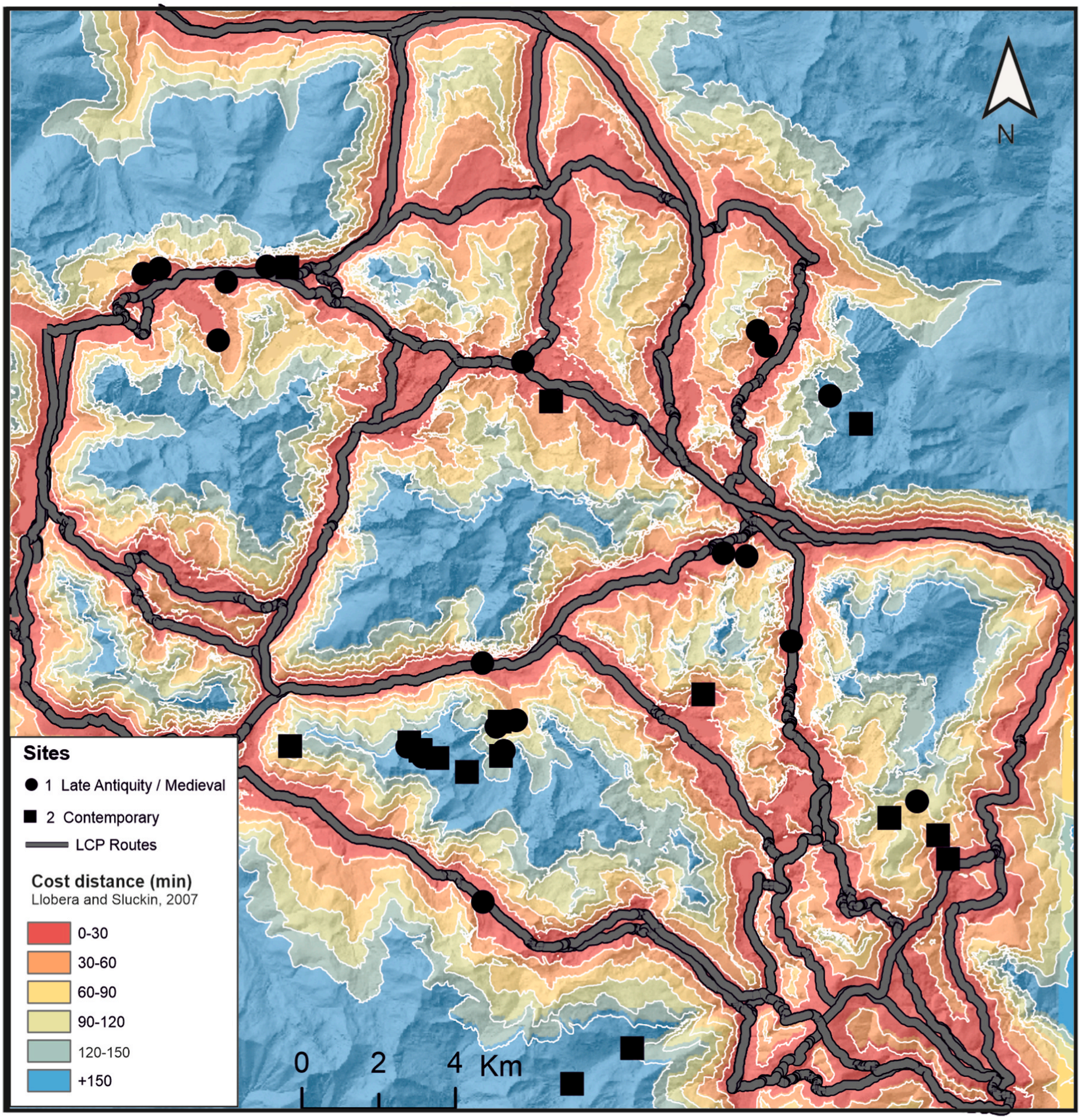

Fig. 12. National Park of Aigüestortes and Estany de Sant Maurici (PNAESM). Map with LCP routes and cost distance to archaeological sites.

two exceptions. Furthermore, it can be suggested that using a well-documented route as the basis of the analysis makes the performances strong.

The third part of the research was devoted to analysing the spatial relationships between possible communication routes and two groups of archaeological settlements from different time periods. The results indicate a historical change in the position of seasonal summer pastoral settlements between the Middle Ages and the 18th-20th centuries. These interpretations complement our knowledge of the archaeological record of the PNAESM and the evolution of seasonal pastoralism from its prehistoric origins to the present day. The beginning of seasonal pastoralism in the Central Pyrenees seems to be situated at the end of the Neolithic (Gassiot Ballbè et al., 2017). However, over the next two millennia, rather than a progressive evolution, discontinuities can be observed in the social practices.

Another remarkable change took place in Late Antiquity. The number of known archaeological sites increased enormously compared to the previous period and paleoenvironmental indicators indicate a general clearing of the forest to create pastureland. Both types of archaeological indicators suggest a significant increase in livestock activity in the study area (Gassiot Ballbè and Pèlachs Mañosa, 2017). The morphology of the settlements also changed. A new type of settlement appeared with several huts and enclosures in the same location. In other publications (Garcia Casas and Gassiot Ballbè, 2022), these have been called "grouped settlements". They seem to be settlements in which different groups of shepherds with several flocks came together in the same place to spend at least part of the summer. Such settlements suggest a way of organising animal husbandry which was quite different to that of the transhumant shepherds of the previous centuries. In other publications, two sub-groups of these settlement types have been mentioned according to their chronology, along with certain differences in the internal morphology of the architectural structures (Garcia Casas and Gassiot Ballbè, 2022). The first group (AA-024, AA-026, AA-043, ESP-024, NA-084, VB-085, VB-098, NA-026, ESP-015) is dated from the Late Roman Empire to the Late Antiquity (approximately between the 2nd and 5th centuries) (Gassiot Ballbè, 2016). There are also differences in spatial positioning as the first group is concentrated in the northern part of the PNAESM in the Val d'Aran and the locations are clearly close to an

Table 4
Cost factors used to make the LCP' the different locations with population evidence surrounding the study zone. MSw = energetic **expenditure** (Kj/m), Sw = terrain gradient. Based on (Parcero-Oubiña et al., 2019).

Location	Type	First insight	Notes	References
Ares	Toponymy, mountain pass			
Arties	Archaeological. Roman stela and Roman necropolis	III - IV Century d. C		Cots 2003, INVARQUE
Espitau de Vielha	Documentary. Chapel, crossroad	1180		Bolós i Hurtado 2012
Espot	Documentary. Church and fortification	819		Ordeig (1993)
Espui	Documentary. Church and fortification	819		Bolos i Hurtado 2012; Ordeig (1993)
Llessui	Documentary. Church and settlement	852		Bolos i Hurtado 2012
Senet	Archaeological. Insights of Roman Villa.	III-IV Century d. C		INVARQUE
Suert	Archaeological, different evidences.	From Bronze Age	Evidences of different type and chronology (megalithic structures, necropolis, houses …)	INVARQUE, Cots, 2003
Vall de Boí	Documentary. Different churches and medieval towns	1064	Vall de Boí includes the medieval towns and	Bolós and Hurtado, 2012, Ordeig (1993)
Vielha	Documentary and archaeological. Medieval town	Medieval. Unclear.		INVARQUE

Table 5
Distance in minutes from each archaeological site to the nearest LCP and nearest *cabanera* (transhumant route). The table shows the results using each one of the three algorythms LLO (Llobera), TO (Tobler) and N (Nunes). MED: Medieval sites. CONT: Contemporary sites.

Cost distance (min)	Total area (ha)	% Cases	Archaeological sites	% Cases
0–15	774.34	11.66	30	32.97
15–30	410.75	6.18	14	15.38
30–45	394.27	5.94	8	8.79
45–60	425.46	6.41	11	12.09
60–75	425.19	6.40	13	14.29
75–90	387.59	5.84	6	6.59
90–105	407.81	6.14	2	2.20
105–120	414.73	6.24	0	0.00
120–135	414.89	6.25	2	2.20
135–150	361.39	5.44	0	0.00

LCP route. Less than 20 min away, the second group (NA-091, NA-076, NA-090, SO-006, VB-001A, VB-014, VB-017sup, VB-019, VB-088) presents chronologies in the Middle Ages (between the 11th and 14th centuries). Their locations are more variable as they are spread over several areas of the PNAESM, some of them in the valleys of Llacs and Casesnoves. However, not all of the archaeological sites dating from Late Antiquity or the Medieval period correspond to this type of settlement. Settlements can also be found which consist of one or two huts with one or two enclosures (VB-098 and NA-026) or rock shelters (ESP-016 and VB-014). A description of the settlements can be found in the supplementary material. All of the Late Antique and Medieval settlement types seem to be located less than an hour from an LCP to cross the park, with only five exceptions (those located in the aforementioned valleys of Llacs and Casesnoves and one settlement in the Valley of Cabanes, which is located far away from the rest). In these three valleys there are no potential circulation routes. In this regard, its location pattern is similar to the Neolithic settlements mentioned above, close to optimal routes that could have been the road network for livestock circulation in this sector of the Pyrenees (Gassiot Ballbè et al., 2020).

At the end of the Middle Ages another major change took place in the forms of occupation of the territory and the social organisation of pastoralism. The grouped settlements were abandoned, with the archaeological sites formed over the following centuries presenting a different morphology and internal organisation of space. Modern and, especially, contemporary settlements are much more similar to the ethnographic image of traditional transhumance (Garcia Casas and Gassiot Ballbè, 2016). A previous study has suggested a significant discontinuity of pastoral practices from the end of the Middle Ages and the first centuries of the Modern Era (15th-17th centuries) (Garcia Casas and Gasiot Ballbè, 2022). This has been observed in changes to the morphology of pastoral structures. In the present research, the discontinuity in space in the same chronology was observed. Both studies provide information regarding significant changes in the Pyrenean Landscape. The majority of the sample of the contemporary settlements analysed is located more than an hour away from the optimal routes to cross the PNAESM, an interpretation that suggests a significant change in the social organisation of movement and the role of communication routes.

How can this be explained in historical terms? A difference was observed in the distance to the archaeological sites from routes crossing the PNAESM, showing a change in the social organisation of the landscape. What were the general historical mutations in the Pyrenean societies which led to this change? At this point, with the current state of research on this issue, it is difficult to provide definitive explanations. It would be necessary to collect more archaeological data and cross them with documentary sources. However, a hypothesis can be suggested based on our historical knowledge of socio-historical changes in the Modern Era in rural zones of north-western Catalonia (Ros, 2016). Between the 16th and 17th centuries, written documentation shows numerous conflicts over grazing rights between local communities and feudal lords in the Pallars region (Bringue, 1996). The outcomes of these conflicts were quite different depending on the village and the valley, but in cases such as the Valls d'Aneu (in the north-east of the study area), the communal councils gained the power to regulate all elements related to seasonal livestock farming (Padilla Lapuente, 1999). In addition to the ownership of many grazing areas converted into communal territory, they gained the right to regulate the maximum number of cattle that could graze, the timing of herds moving in and out, the entry of foreign cattle and the areas where they could graze. The municipal councils also controlled the payments and paid the corresponding taxes. Disputes over grazing rights also took place between municipalities. Numerous court rulings between the 15th and 17th centuries defined the territories in which a community could send livestock to graze, be it its own livestock or foreign livestock to which this right was leased. This division of the territory would give rise to the *pletas,* a traditional term to refer a mountain area with a refuge for the shepherds and grasslands to feed the flocks (Violant i Simorra, 2001).

These delimitations may have had an effect on the location of the livestock settlements where huts or shelters for shepherds and enclosures were built. The decision-making was different in comparison with earlier times. It is known that in the Middle Ages the mountain grasslands were owned by feudal lords and, especially, abbeys, as was the case with Lavaix and Ovarra (Bolós and Hurtado, 2012). However, very little is known about the specific forms of pastoralism, who the herders were and the technical work processes they employed. The documentation reflects ownership and grazing rights, but not who carried out the seasonal herding or their ways of life (Garcia Casas et al., 2022).

Table 6
Outcomes of the statistical analysis of the results showed in Table 4. (Distance in minutes depending if the site is medieval o contemporary).

Code	Chronology	LCP_LLO	LCP_N	LCP_TO	CAB_LLO	CAB_N	CAB_T0
NA-091	MED	4.7	4.4	3.4	70.9	58.4	47.2
NA-076	MED	8.9	7.5	7.3	174.2	139.9	117.6
NA-084	MED	20.4	17.9	14.5	173.0	124.7	127.3
NA-079	MED	5.9	5.4	4.4	112.9	94.6	75.8
AA-026N	MED	43.4	33.5	30.9	362.0	279.8	311.0
NA-090	MED	32.3	26.6	27.6	180.4	130.7	138.0
AA-024A	MED	30.7	21.7	21.6	356.9	287.5	303.8
NA-026	MED	0.3	0.3	0.2	0.7	0.5	0.4
AA-043	MED	162.6	116.6	126.2	392.1	325.8	274.5
ESP-015	MED	11.5	10.1	8.0	314.6	265.9	224.6
ESP-024	MED	43.9	37.3	30.9	283.3	238.1	205.1
ESP-016	MED	1.7	1.5	1.2	302.5	260.8	209.5
VB-014	MED	4.2	3.4	3.1	171.2	143.9	133.5
VB-001A	MED	59.9	53.8	41.2	235.1	199.6	171.2
VB-017 sup	MED	87.2	75.8	59.5	260.8	219.3	189.3
VB-019	MED	151.9	113.6	114.4	225.8	178.1	188.8
VB-085	MED	123.9	103.1	87.4	299.9	249.5	218.3
VB-098	MED	172.9	132.7	127.8	246.9	197.3	201.9
SO-006	MED	86.5	75.7	58.3	90.3	77.0	58.8
VB-088A	MED	2.1	2.0	1.5	271.6	234.3	185.5
NA-102	CONT	4.2	3.6	2.8	54.1	44.9	35.4
NA-054	CONT	31.3	24.0	22.2	64.5	52.3	44.8
AA-060	CONT	186.7	149.7	142.9	350.8	291.4	246.4
TC-009	CONT	26.4	18.8	25.2	354.8	280.1	344.3
VB-017inf	CONT	75.0	65.9	50.9	248.0	209.3	180.9
VB-018sup	CONT	144.9	108.1	109.9	218.8	172.3	184.0
VB-110	CONT	116.9	88.4	84.4	128.2	91.8	112.4
VB-111	CONT	166.4	125.9	123.5	240.5	190.5	197.6
VB-112	CONT	166.1	126.4	123.2	240.2	191.0	197.3
VB-086	CONT	124.9	105.4	87.7	302.5	252.6	217.7
VB-096	CONT	197.0	146.3	151.0	281.1	223.3	225.0
VB-004	CONT	167.0	144.6	113.3	336.8	269.7	243.0
SO-005	CONT	89.1	76.3	60.1	92.7	78.9	59.9
SO–008B	CONT	39.0	34.5	26.2	42.2	36.1	27.1
SO-007A	CONT	7.2	6.8	4.8	12.8	11.4	7.9
TDG-01	CONT	151.5	124.5	99.5	374.5	297.2	272.0
TDG-02	CONT	194.5	164.1	130.8	418.4	337.4	302.7

Moreover, in high mountain areas, the boundaries of each property are vague and imprecise. It is possible that the feudal lords who owned the mountain areas and their rights of use exercised little control over where shepherds settled in the high-altitude pastures. On the contrary, written documentation of disputes between local communities in the following centuries shows that the high mountain areas were completely divided up in modern times. Thus, in modern and contemporary times, in the decision-making process to build a new settlement, the priority would be to settle on the clearly-defined plots of land on which a community had grazing rights and not near roads. Another reason suggested by a previous study (Gassiot Ballbè et al., 2020) could be the great availability of grass to feed animals near the site. This may be an explanatory hypothesis that should be corroborated in future studies.

However, beyond the specific historical causes, this research has demonstrated the existence of differences in the position of settlements according to chronology. These interpretations add to other research that warns that many of the elements of mountain landscapes attributed by “common sense” to the Middle Ages have a modern origin. In this case, the spatial layout adds to these observations. Other research, both in the same area and in other mountain areas, has already warned of the danger of making direct analogies between modern transhumance and the different forms of pastoralism that have been practised in the long sequence of time since the end of Prehistory (Garcia Casas, 2013; Garcia Casas and Gassiot Ballbè, 2022). Furthermore, the results of this study make it possible to affirm that the location of archaeological sites relating to mountain livestock rearing does not depend merely on the biophysical elements of the landscape (such as altitudinal level, slope, water sources, etc.) or on environmental determinisms. The decision-making process regarding where to establish a pastoral settlement was also influenced by social factors that changed over time. In this regard, after comparing our results with other studies in the same area (Gassiot Ballbè et al., 2020) and in other high mountain zones of Europe (Carrer, 2013), it can be stated that there are no statistical differences regarding the location of the archaeological sites over time. It can be suggested that shepherds’ criteria for choosing a settlement location according to altitude or slope remain the same in different chronologies. Therefore, explanations must be sought in sociohistorical reasons and, more specifically, in changes in territorial organisation for the differences in the geographic location of the archaeological sites. It would be interesting to test this hypothesis in other high mountain areas where archaeological studies of livestock settlements have been carried out over large time scales.

6. Conclusion

The study of past societies through the spatial dispersion of archaeological remains has been revealed as a successful trend which has contributed new data and interpretative models. These studies have been applied in different environments as well as in prehistoric and historic periods. Our research has focused on mobility related to seasonal pastoralism, analysing pastoral pathways as an archaeological element which can provide an insight into the location of different sites. It is also interesting to note the differences between medieval sites and transhumant settlements. The mountain landscape, in modern and contemporary times, was, and still is, divided into plots and their corresponding grazing rights. On the contrary, the location of medieval sites near to axes of mobility demonstrates a different organisation of upland territories.

These results complement other archaeological research in the PNAESM which rejects a supposed continuity between prehistoric, ancient and medieval livestock and traditional transhumance documented by ethnographers in the early 20th century. Additionally, combined with other archaeological and paleoenvironmental studies, they help to gain an understanding of the long history of human occupation of high-mountain Pyrenean landscapes with its different phases and discontinuities. In the present study, LCP analysis was employed. In future, it could be interesting to evaluate the applicability of other methods, such as focal mobility networks (Llobera et al., 2011) or corridors of movement (Pinto and Keitt, 2009), to this kind of studies. As a final remark, we believe that the methodology employed here may also be of interest if applied in other zones. Firstly, as a methodological tool in zones with rough topography to analyse mobility, to obtain plausible potential routes and to explore the relationship with archaeological sites. And finally, not only in other upland zones but also in mid-mountain areas and plains where there is evidence of ancient transhumance, the results can improve our knowledge of the origins and development of seasonal pastoralism as well as the complementarity between different altitudinal ranges and the role of these activities in the formation of present-day rural landscapes.

Author contributions

David Garcia Casas: Conceptualization, Methodology, Data curation, Writing- Original draft preparation, Writing – review & editing, Visualization. **Ermengol Gassiot Ballbè**: Direction of archaeological research at PNAESM, field work and sites recording. Supervision, Resources, Writing – review & editing, Visualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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