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Energy regimes help tackle limitations with the prehistoric cultural-phases approach to learn about sustainable transitions: Archaeological evidence from northern Spain

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ABSTRACT: Human societies face challenges in transitioning towards low-carbon economies and sustainable management of land use and natural resources. Documenting and learning from past transitions helps policy-makers cope with such challenges. The agricultural revolution in Cantabrian Spain (*ca.* 7000 cal a BP) was one major adaptation of hunter-gatherers to a changing environment that started with the Last Glacial Maximum (*ca.* 24 000 cal a BP) and lasted until the Mid-Holocene (*ca.* 5300 cal a BP). Classic approaches to documenting prehistoric cultural timelines are based on manufacturing and technology, thus limited in their ability to describe the sustainability of past societies. Energy regimes, a functional societal approach independent from time, investigate and consider patterns of resource and energy use in various cohabiting and cooperating cultural phases. To examine past energy regimes, a database of archaeological remains was compiled to document four indicators: mobility, economy, overexploitation and societal complexity. Statistical analyses were conducted to elucidate trends, changes and continuity in subsistence strategies by hunter-gatherers and sedentary societies. Results show that energy regimes act as a complement to cultural phases, adding novel functional analyses of past societies to cultural stratigraphy units common in archaeology, shedding light on the sustainability of past societal transitions.

KEYWORDS: agricultural revolution; energy regimes; hunter-gatherers; northern Spain; subsistence strategies

Introduction

More than ever, our societies face drastic climate and landscape changes that result in the urgent need to render our energy systems more sustainable (IPCC, 2022). Greenhouse gas emissions, increasing global temperature, sea level rise and the depletion of biodiversity and primary resources are challenges that contemporary societies increasingly face. A transition toward low-carbon societies is required to cope with the negative impacts of ever-increasing greenhouse gas emissions. While the industrial era beginning *ca.* 200 years ago has been responsible for the emission of unprecedented quantities of greenhouse gases into the atmosphere, changes in climate and landscapes in Europe are well documented from as early as the Mid-Holocene, starting with the establishment of the first farming communities. This societal revolution had consequences including deforestation, cropland and pastureland expansion, intensification of land use, loss of wilderness and biodiversity, urbanisation, and the gradual specialisation of human land use (Ellis, 2015; Ellis & Ramankutty, 2008). Major changes in human societies can be described in terms of energy use by societies, with various parameters such as energy availability, flow, storage and conversion (Vlachogianni & Valavanidis, 2013). Energy is available in wood logs or petroleum, for instance, and can be stocked for later use and converted into thermal energy by combustion, which in turn can serve numerous activities (heating, metallurgy, chemistry, etc.). Hence, energy use largely changed over time (Sieferle, 2001; Burke, 2009; Fischer-Kowalski et al., 2014; Krausmann et al., 2016). Some key questions arising are: how were past human societies engaged in energy transitions? And what lessons can we learn from such transitions to help us move towards more sustainable energy regimes?

Alongside the natural sciences approaches to studying past environments, geoarchaeological studies offer a view on past human societies and how they interacted with their environments. Archaeologists most often use a classificatory phase-based approach to describe prehistoric cultures, including, among others, the Solutrean, Magdalenian, Epipalaeolithic and Mesolithic technocomplexes and the Neolithic period. These cultural phases were identified on the basis of archaeological index fossils (Leroi-Gourhan, 1964–1965; Mellars, 1989; Clark & Riel-Salvatore, 2006), starting in the second half of the 19th century, and are still predominant today, having become conventional (Clark et al., 2019). They mainly reflect technological knowledge and processing activities, and thus do not provide much information on

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societal adaptations to ever-changing environmental conditions (Neeley & Barton, 1994; Barton et al., 1996; Culley et al., 2013). Societal changes and adaptations often cross-cut or occur independently of cultural stratigraphic units (Clark et al., 2019; Culley et al., 2013). Dissatisfaction with the limitations of cultural and technological phases (Bordes, 1961) has led researchers to pursue novel ways to describe prehistoric societies (Clark & Barton, 2017). Recent attempts in Cantabrian Spain placed Palaeolithic research under the framework of human ecology to investigate forager mobility (Jones, 2016, 2013; Clark & Barton, 2017; Clark et al., 2019), successfully demonstrating the efficiency of expanding the prehistoric research approach beyond the paradigm of cultural phases (Clark et al., 2019).

In this work, we focus on the major transition from foraging to sedentary economies in Cantabrian Spain, which still bears many knowledge gaps for archaeologists and geoarchaeologists (Arias, 2007; Lillios, 2019). In this region, the hunter-gatherer regime mainly includes Palaeolithic and Mesolithic societies, and is acknowledged to end with the transition to the Neolithic, marked by the establishment of the first farming communities *ca.* 7000 cal a BP (Fano et al., 2015). However, key aspects of foraging economies remained after the Neolithization process (Cubas et al., 2016), creating a mosaic pattern of synchronous Mesolithic and Neolithic sites and cultures, the nature, duration and dynamics of which remain poorly understood (Arias, 2007; Lillios, 2019).

We hereby hypothesise how the framework of energy regimes (ERs) is one possible solution to complement the paradigm of cultural phases. ERs describe human societies and their inter-relations with the environment, based on the resources and energy sources used by human societies (Vlachogianni & Valavanidis, 2013). ERs are independent of timescale sequences strictly linked to cultural entities, and hence provide a useful tool to classify and compare archaeological sites independent of the regions and time periods. These classifications and comparisons can be done on the basis of subsistence strategies, which are fundamental to a better understanding of the complex sustainability and dynamics of past societies (Feeney, 2019). Using ERs to complement cultural phases is a novel approach to investigating and better understanding the long-term evolution of past societies and how they overcame disruptions and transitional phases. There are currently four widely acknowledged ERs: hunter-gatherer, agrarian, industrial and low carbon (Burke, 2009; Fischer-Kowalski & Haberl, 2007; Goudsblom, 1992; Sieferle, 2001; Simmons, 2008; Valavanidis & Vlachogianni, 2013). In this work, we use the most recent terms of Standard Solar (for hunter-gatherers) and Agrarian Solar (for agrarian communities) regimes, which directly provide information on natural resources and energy sources. In a Standard Solar society, nomadic, migratory or semisedentary communities exclusively rely on solar energy, harnessing energy by eating either plants or animals (herbivores and carnivores) which in turn rely on solar energy (Valavanidis & Vlachogianni, 2013). Human activities are then determined by the availability of wild resources but also influence resource availability through, for instance, forest burning (Ellis, 2015). Agrarian Solar communities manipulate and concentrate the solar energy through agriculture, animal husbandry and landscape management (Valavanidis & Vlachogianni, 2013).

Our first step to applying the framework of ER to a concrete archaeological context consisted in a review of 95 articles and books on hunter-gatherer subsistence strategies linked to climate change, palaeoenvironmental processes and ecological theories, covering a period from the Last Glacial Maximum (LGM) *ca.* 24 000 cal a BP, until and including the first farming communities in Cantabrian Spain *ca.* 6300 cal a BP (Martinez et al., 2022). We thereby identified the following indicators of Standard and Agrarian Solar regimes: human mobilities, economies, overexploitation of resources and societal complexity. With this new work we propose to expand the potential of ERs by using actual archaeological data to add empirical evidence to the theoretical framework of ERs previously developed (Martinez et al., 2022). The goals of this paper are: 1) to identify a list of proxies for use as an indicator of ERs and related transitions; 2) to compile a database of archaeological material evidence that can be used as proxies of ERs; 3) to investigate the robustness of these proxies and indicators through relevant statistical analyses; and 4) to complement traditional cultural phases with the new, functional framework of ERs in order to help inform sustainability transitions in the use of resources and energy.

Geographic and temporal settings

Our research is based on the Cantabrian Spain region, which is delineated by an oceanic climate that, along with the northwest region of Galicia, clearly differentiates it from the rest of Spain with a Mediterranean climate (AEMET & IM, 2011). It is characterised by a dominating karstic limestone lithology (IGME & LNEG, 2015) and is spread across the NUTS-2 regions (Eurostat, 2020) of Asturias, Cantabria and the Basque Country (provinces of Biscay and Gipuzkoa) (Fig. 1). Our specific case study area is defined by interfluvia that act as climate and hydrographic barriers, but also as historical human and cultural frontiers. The western boundary is the river Navia in Asturias, which is the westernmost major waterway situated in the specific karstic limestone context mentioned above. The Bidasoa river in Gipuzkoa is the easternmost major river that discharges into the Atlantic Ocean, and hence marks the eastern boundary of the study area. The southern limit is marked by the ridge line of the Cantabrian range. The study area has a surface of *ca.* 20 000 km^2 which is fully placed within the Eurosiberian biogeographic region (Rivas-Martinez, 2007) and is characterised by a dissected landscape mosaic marked by inner valleys and high mountains changing across short distances (Mata Olmo & Sanz Herráiz, 2004). Indeed, the Euclidian distance between the coast of the Cantabrian Sea and the ridge line of the Cantabrian Mountain range is often less than 50 km (Straus, 2018).

In this work we investigate changes in subsistence strategies from the Solutrean *ca.* 24.0k cal a BP during the LGM (Straus, 2005), to the end of the Neolithic *ca.* 5.3k cal a BP during the Mid-Holocene. This time period encompasses the late Upper Palaeolithic (Solutrean & Magdalenian), Epipalaeolithic, Mesolithic and Neolithic cultures (Table 1). Successions of cold/dry events and warm/wet periods occurred during this unstable climatic sequence (Walker et al., 2012; Rasmussen et al., 2014; Tarroso et al., 2016). Late Pleistocene (Roberts, 2014) and Holocene (Walker et al., 2012) chronozones are used to refer to climatic evolution between the LGM and the Mid-Holocene. The Pleistocene/Holocene transition occurring at the end of the Younger Dryas *ca.* 11.7k cal a BP (Walker et al., 2012) abruptly marked the beginning of the Holocene interglacial, which resulted in abrupt shifts in human societies (Lillios, 2019; Roberts, 2014).

New trends of subsistence-oriented resource-use intensification began during the Solutrean, in response to population growth in the Cantabrian Spain glacial shelter during the LGM (Straus, 2005, 2018a). This trend continued through Magdalenian, Epipalaeolithic and Mesolithic phases, defined by an

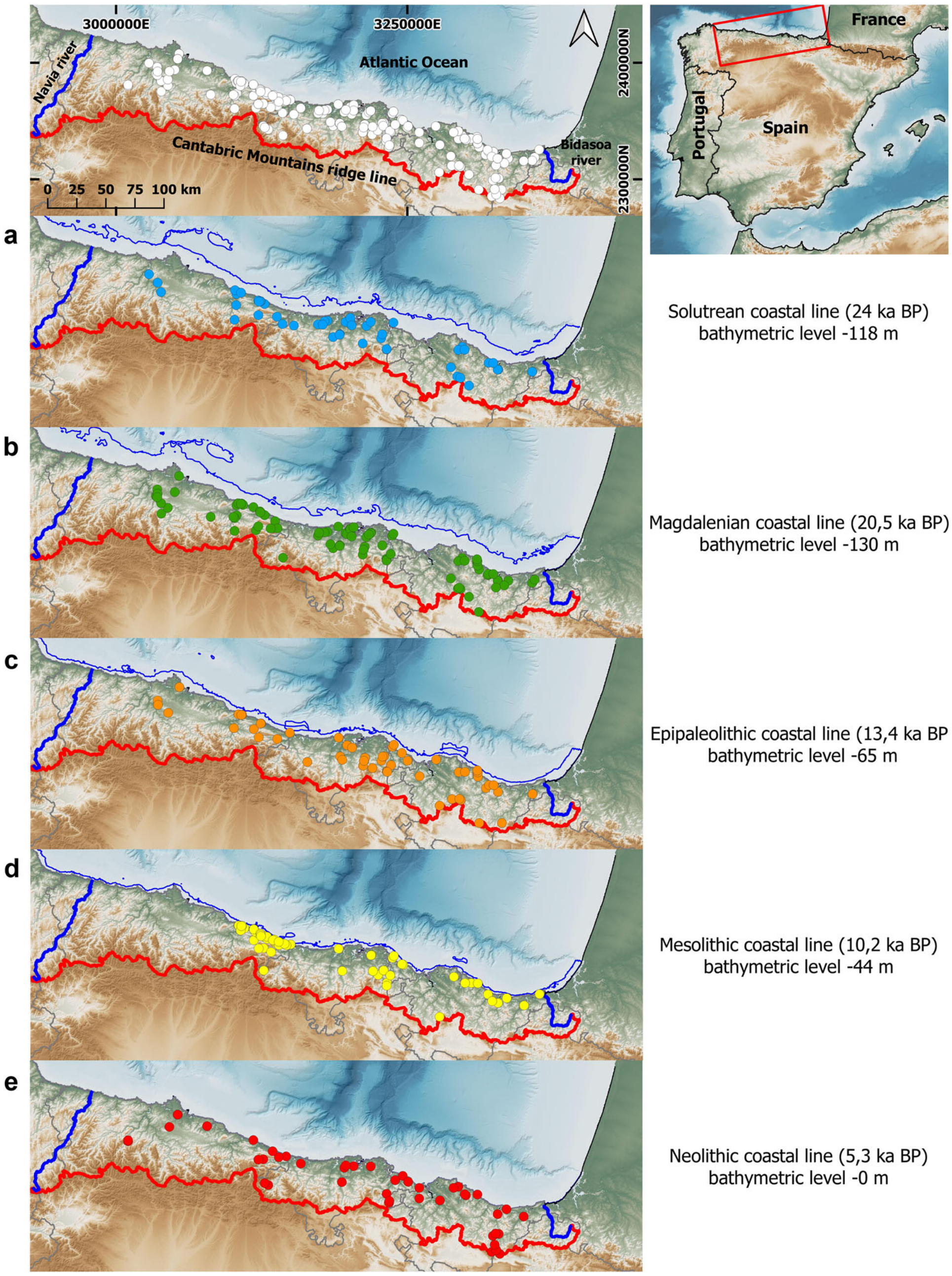

Figure 1. Map of the study area in Cantabrian Spain with archaeological sites and coastlines used in this work. On top, geographic position of the study area in southwest Europe. a) Solutrean sites; b) Magdalenian sites; c) Epipalaeolithic sites; d) Mesolithic sites; e) Neolithic sites. Edited with the open access Geographic Information System (GIS) software QGIS, version 3.16.14. [Color figure can be viewed at wileyonlinelibrary.com]

increasing and continuous exploitation of key natural resources (Alday & Soto, 2017; Straus, 2018). Although the Neolithic was marked by the expansion of sedentary economies, a continuity in previous subsistence strategies is well documented (Cubas et al., 2016; Fano et al., 2015). Hence, Neolithization was likely a long process characterised by the cohabitation of both Mesolithic and Neolithic communities for centuries (Arias, 2007; Lillios, 2019). To deal with such continuity we consider the Standard Solar regime as a gradual process, starting in the LGM (*ca.* 24k cal a BP) and also embracing its subsequent transition towards sedentary economies. The most recent limit of this study is set after significant human and biophysical changes occurred (Cubas et al., 2016; Fano et al., 2015) at the end of the Neolithic (*ca.* 5.3k cal a BP) (Blanco-González et al., 2018). The expansion in the use of domestic resources and sedentary economies corresponds to the Standard–Agrarian Solar regime transition.

Methodology

The structuring of the Standard Solar regime underpinned by archaeological data was organised on the basis of four characterising sets of indicators: mobilities, economies, overexploitation and societal complexity. These sets of indicators were previously identified from specific literature on hunter-gatherer societies in Cantabrian Spain considered up to and including the early farming and pastoral communities (Martinez et al., 2022). Various proxies have been used to document each indicator (Table 2).

All proxies are measured over time. Proxies of mobility include aspects related to: 1) the type of mobility (residential/logistical continuum) calculated from the statistical variance of the distribution of archaeological site elevations; and 2) the reduction of mobility linked to the appearance of ceramics. Economic proxies refer to: 1) the foraging economy based on

Table 1. Chronological framework including the date from 24.0k cal a BP to 5.3k cal a BP, geological times, climatic phases, cultural phases, and energy regimes. Upper Palaeolithic and Mesolithic dates are by Straus (2005, 2009). There were expressed in ^{14}C BP, so we calibrated them using the tool Calib (http://calib.org/calib/calib.html). Neolithic dates are from Fano et al. (2015) and the Chalcolithic date is by Blanco-González et al. (2018). Late Pleistocene chronozone dates are by Roberts (2014), and Holocene chronozone dates by Walker et al. (2012).

Dates k cal a BP	Geological time	Chronozones	Cultural phases	Energy regimes
24.0–20.5	Late Pleistocene	Last Glacial Maximum	Solutrean	Standard Solar, Immediate Return
20.5–17.5			Magdalenian	
17.5–15.6		Oldest Dryas		
15.6–14.7				
14.7–13.4		Bølling–Allerød		
13.4–12.9			Epipalaeolithic	Standard Solar, Transition Immediate–Delayed Return
12.9–11.7		Younger Dryas		
11.7–10.2	Holocene	Early Holocene		
10.2–8.2			Mesolithic	Standard Solar, Delayed Return
8.2–7.0		Mid-Holocene		
7.0–5.3			Neolithic	Transition Standard–Agrarian Solar
After 5.3			Chalcolithic	Agrarian Solar

Table 2. List of proxies adopted for each indicator of an energy regime.

Proxies	Indicators
Variance of site elevation	Logistical/residential continuum
First appearance of ceramics	Reduction of mobility
Marine mollusc MNI	Foraging economy
Ungulate MNI	
Domestic plants and fauna	Sedentary economy
Marine mollusc size	Overexploitation
Marine mollusc age	
Young ungulate proportion	
Burials	Societal complexity
Megalithic structures	

Abbreviation: MNI, minimum number of individuals.

the number of wild marine molluscs and ungulates in the archaeological context; and 2) sedentary economies indicated by the presence of domestic plants and fauna. Trends in the size and age of marine molluscs along with the proportion of young ungulate remains were selected as proxies of overexploitation. Finally, burials and megalithic structures were chosen as proxies of societal complexity. These proxies provide a direct image of the actual archaeological records. However, they are directly dependent on the archaeological records, which representativeness might be unequal in regards to cultural phases, geographic locations and taphonomic biases.

All proxy information was gathered and incorporated into a unique database comprising 336 entries (see Appendix 1), using version 6.3 of the open access software Libre Office (https://www.libreoffice.org/). These proxies were identified from previous works that had employed a similar methodology to explore mobility patterns (Jones, 2016), foraging economies (Marín-Arroyo, 2013) and resource overexploitation (Gutiérrez-Zugasti, 2011). The first occurrences of ceramics, domestic taxa, burials and megalithic structures were chosen as they anchor important societal changes in time. Source materials and data for each indicator were selected from most recent syntheses. Previous sources cited in these syntheses (e.g. initial articles, archaeological reports) were also explored in order to check the quality of the data and to incorporate additional data that were ‘lost’ when being reused by successive works. Among the source materials, all sites and data were considered and none disregarded, except for data that presented acknowledged misinterpretation and dating issues. More detail regarding the selection of each proxy is presented in the following sections.

Each entry in the database corresponds to a piece of archaeological evidence, and encompasses: 1) geographical information (administrative region, site, latitude, longitude, elevation); 2) archaeological description (nature and details of the archaeological remains, stratigraphic level and context, associated findings, culture); 3) historical dating information (dated materials and methods, lab code, radiocarbon dating, standard deviation, calibrated date); 4) information about proxies (see Table 2); and 5) sources of the information (scientific articles and books, archaeological reports, all references to source materials are in Appendix 1). Geographic information systems (open access software QGIS version 3.16.14, using the ETRS-extended/LAEA Europe system of coordinates) were then used to map the archaeological sites and coastlines for each cultural phase mentioned in this study (Fig. 1). These coastlines were drawn using the methodology elaborated by Fraile Jurado and Mejías-García (2022) involving the identification of sea level positions from Zazo (2015) and Silva et al. (2017) syntheses of sea level changes over time. To do so, bathymetric data were extracted from a digital terrain model provided by the European Marine Observation and Data Network (EMODNET, 2020). The result is a surface that represents the total of emerged time of the Iberian continental shelf for the time covered in this work. All radiocarbon dates were calibrated into calendar dates using the tool Calib (http://calib.org/calib/calib.html). More precise methodological details of the research work to investigate each of the four indicators of ERs, including the analytical procedures, statistical tests, and other analyses performed, are described in the following subsections. Statistical analyses were executed in the open access software R version 4.1.3 and are described in the results section.

Mobility proxies

It is widely acknowledged that hunter-gatherers with different strategies move across the landscape differently (Fisher, 2002; Grove, 2010). Hence, the mobility of hunter-gatherers is often used to track subsistence strategies in archaeological records (Henry, 1994; Villaverde et al., 1996; Holt, 2003; Conard et al., 2012; Jones, 2013, 2016). The logistical/residential continuum is one way to explore hunter-gatherer mobility (Binford, 1980; Kelly, 1995). At one end of this continuum, residential societies frequently move their base camp to exploit predictable resource patches. This type of mobility is more frequent in highly seasonal environments, where the same resources are available year after year (Binford, 1980; Cowan, 1999; Aldenderfer, 2008; Morgan, 2008; Jones, 2016). At the other end of the continuum, logistical societies have less mobile base camps from which small groups go on expeditions to gather specialised resources. This type of mobility is believed to have been adopted mainly in environments with less predictable resources (Binford, 1980; Cowan, 1999; Aldenderfer, 2008; Morgan, 2008; Jones, 2016).

Statistical variance of archaeological site elevations is employed to analyse hunter-gatherer mobility. A high variance of site elevation often indicates an environment with predictable patches of resources along a wide range of elevations, while a low variance value suggests that resources are less predictably scattered across more concentrated elevations (Jones, 2013, 2016). Previous research suggests that a high variance in site elevation is often linked to residential mobility, while a low variance indicates logistical mobility (Henry, 1994; Aldenderfer, 2008; Morgan, 2008; Jones, 2007, 2013, 2016). Hence, logistical societies are more territorial than residential ones, know their environment better and how to exploit the resources within it. One limitation of this methodology is a potential research gap for highland Upper Palaeolithic sites, as there are very few sites at high altitude (see 'Investigating human mobility through time' in Results, below). However, this scarcity of sites is mostly explained by the wide extent of glaciers at altitude from the Solutrean to the Epipalaeolithic, when deglaciation was occurring concurrently with an increase of sites at altitude (Straus, 2005, 2015).

To investigate the mobility of hunter-gatherers in our study area, 309 records of site occupation were gathered for Solutrean (50 records), Magdalenian (90), Epipalaeolithic (55), Mesolithic (63) and Neolithic (51) phases. These records come from: 1) the Radiocarbon Palaeolithic Europe Database V28 (Vermeersch, 2021); 2) the radiocarbon dataset gathered by Clark et al. (2019) as supplementary material; 3) our own dataset presented above; and 4) a synthesis of scientific publications (Fano et al., 2015; Cubas et al., 2016), especially regarding the transition to the Neolithic. These occurrences of occupation per cultural phase were incorporated into a GIS geodatabase. Elevation data were then extracted from version 1.1 of the digital elevation model of the Iberian Peninsula (spatial resolution 25 m, vertical accuracy 7 m), retrieved from the Land Monitoring Service of the Copernicus Programme (EU-DEM, 2016).

Prerequisite analyses (tests of Shapiro–Wilk, Levene and Bartlett) are necessary in order to determine the most appropriate statistical test regarding the nature of the data (Table 3). Then three tests were applied to test the site elevation variance between cultural phases: 1) Welch's ANOVA; 2) Kruskal–Wallis; and 3) ANOVA. Statistical metrics obtained on the variance of site elevations are described in 'Investigating human mobility through time' (Results). Finally, the *post hoc* tests of Games–Howell (relevant after Welch's ANOVA), Nemenyi (relevant after Kruskal–Wallis) and Tukey (relevant after ANOVA) were applied to identify divergent cultural patterns.

The decrease in mobility of Neolithic societies is substantiated by the appearances of ceramics (Kelly, 1991; Beck, 2009). Although there is evidence of hunter-gatherers carrying storage vessels such as the Ertebølle culture in Northern Europe (Povlsen, 2013), they are found in contexts of semisedentarism (Rice, 1999) or by contact with groups of agropastoralists (Beck, 2009). The first records of ceramics in the study area (21 records) were gathered from the literature (Arias et al., 2000; Cubas & Fano, 2011; Ontañón-Peredo

Table 3. Results of statistical tests performed on site elevation data. The data are not normally distributed and the variances are heterogeneous, hence the test of Levene became more relevant than Bartlett for the homogeneity of variance, while the test of Welch's ANOVA was the most relevant for comparing site elevations between cultural phases.

Shapiro–Wilk (normality of the data)	Levene (homogeneity of variance)	Bartlett (homogeneity of variance)	Welch's ANOVA (statistical test)	Kruskal–Wallis (statistical test)	ANOVA (statistical test)
No condition	Condition: data not normally distributed	Condition: data normally distributed	Condition: data not normally distributed, heterogeneous variance	Condition: data not normally distributed, homogeneous variance	Condition: data normally distributed, homogeneous variance
W = 0.80484 *p*-value = 2.2e^{-16}	F = 2.6287 *p*-value = 0.03448	K^2 = 20.852 *p*-value = 0.0003388	F = 1.7032 *p*-value = 0.1527	χ^2 = 10.263 *p*-value = 0.03623	F = 2.412 *p*-value = 0.049
Data not normally distributed	Variance heterogeneous	Variance heterogeneous	No significant difference	Significant difference	Significant difference

et al., 2013; Cubas et al., 2016) and are presented as a histogram together with the first published records of domesticated species (plant and fauna), burials and megalithic structures (Fig. 2).

Economy proxies

Hunter-gatherer economies in Cantabrian Spain from the LGM onward have been widely explored, and two main subsistence strategies identified: 1) a situational specialisation; and 2) an overall diversification (Straus & Clark, 1986; Straus, 1991, 2005, 2009, 2018). The situational specification is marked, on one hand, by the intensification of red deer (*Cervus elaphus*) hunting in coastal and valley lowlands, and by the intensification of ibex (*Capra pyrennaica*) hunting in rocky mountains on the other (Straus, 2005, 2009). The overall diversification is marked by the broadening of marine mollusc gathering and fishing (Straus, 2005, 2009). These subsistence strategies intensified over time until and including the Neolithic period, after the emergence of agriculture and pastoralism (Arias, 2007; Straus, 2009; Cubas et al., 2016; Lillios, 2019).

The minimum numbers of individuals (MNIs) of marine molluscs and ungulates in archaeological contexts were gathered from a large number of sources (see Appendix 1) in order to highlight changes in hunter-gatherer economies. MNIs from the eight most represented ungulate species in archaeological contexts were also gathered, including: aurochs (*Bos primigenius*/*Bison* sp.), horse (*Equus* sp.), red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), ibex (*Capra pyrenaica*), chamois (*Rupicapra rupcapra*), wild boar (*Sus scrofa*) and reindeer (*Rangifer tarandus*). Marine molluscs in archaeological contexts are represented by a large number of gastropod and bivalve species. The main bivalve species documented include: mussel (*Mytilus galloprovincialis*), flat oyster (*Ostrea edulis*), palourde clam (*Ruditapes decussatus*), razor shell (*Solen marginatus*) and furrow shell (*Scrobicularia plana*). The main gastropods are: limpet (*Patella vulgata*, *Patella intermedia* and *Patella ulyssiponensis*), periwinkle (*Littorina littorea*) and top snail (*Osilinus lineatus*). In his synthesis on the parameters possibly impacting the amount, size and age of marine molluscs in archaeological contexts through time (effects of exposure, zonation, environment and predation due to changing sea level and climate), Gutiérrez-Zugasti (2011) highlighted that if environmental factors cannot be ruled out, it is not known how these changes affected mollusc populations, and hence that these species remained a relevant proxy for human economy. Records of ungulates and marine molluscs for each cultural period were compiled in our database. The mean MNIs per stratigraphic level for each culture were then calculated in order to identify economic trends over time.

Data from the first records of domestic taxa (plant and fauna) in archaeological contexts (37 records) were used to identify the transitional phase towards sedentary economies. These data were gathered from a large number of sources (see Appendix 1).

Overexploitation proxies

Previous research results have established that the overexploitation of resources by human populations is evidenced by an increase in the killing of young ungulates, mainly for hunting (Fano, 2004; Straus, 2009) and by a reduction in the size and age of marine molluscs (Straus, 2005, 2009, Gutiérrez-Zugasti, 2011) over time. To investigate episodes of resource overexploitation, the MNIs of young and adult

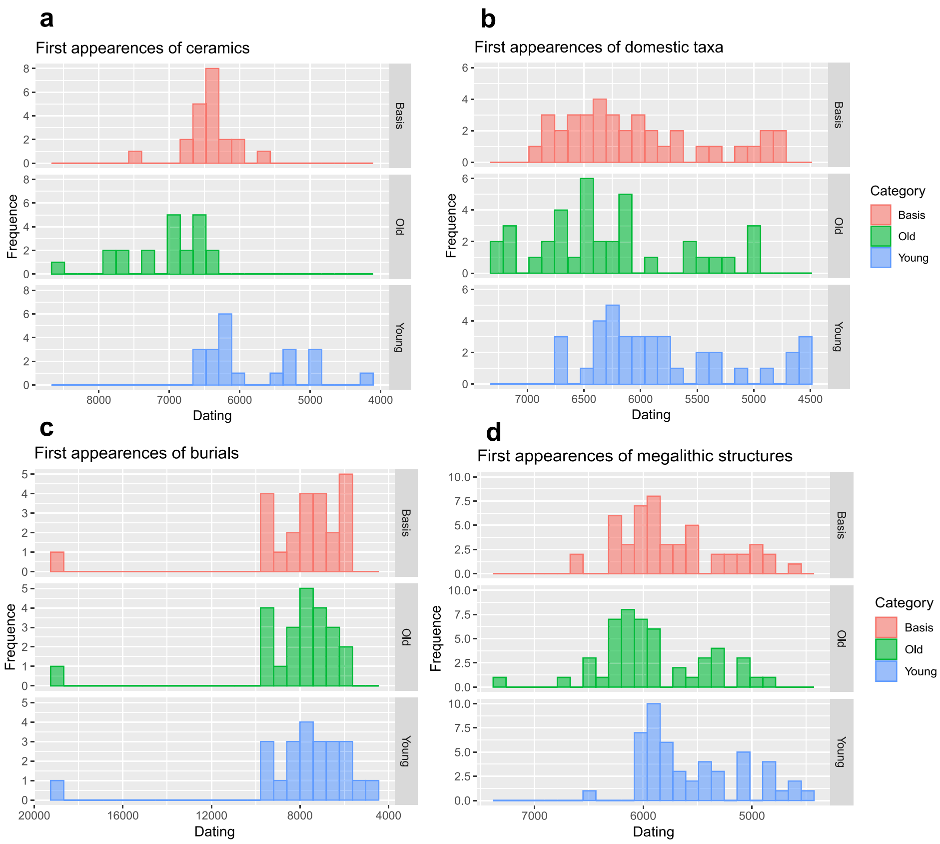

Figure 2. Histograms of a) first appearances of ceramics, b) domesticated species (plant and fauna), c) burials and d) megalithic structures. In all parts are shown the basic dating, an old hypothesis (by adding the standard deviation to the dating) and a young hypothesis (by subtracting the standard deviation from the dating). The age is expressed in cal a BP. [Color figure can be viewed at wileyonlinelibrary.com]

ungulates from the eight most represented species in archaeological contexts (see 'Economy proxies', above) were gathered from the literature (see Appendix 1). Then the proportion of young ungulates was calculated for each cultural phase to explore trends through time. In our database we compiled 58 records of young and adult ungulate MNIs for Solutrean (23 records), Magdalenian (21), Epipalaeolithic (8), Mesolithic (4) and Neolithic (2) cultures. More data exist for the Neolithic (Mariezkurrena, 1990), but they are expressed in 'number of rest' (the total number of bones), which cannot be compared with MNI data (the minimum number of animals that can be counted from the bones). Hence, these data were not incorporated into our database.

The sizes and ages of one marine mollusc, *Patella vulgata*, were gathered from the work of Gutiérrez-Zugasti (2011). *Patella vulgata* was chosen because: 1) it is the most abundant marine mollusc in an archaeological context; and 2) it is also present along the whole cultural continuum due to its adaptiveness to changing climatic conditions (Gutiérrez-Zugasti, 2011). Some 53 records of size of *Patella vulgata* are documented for the Solutrean (14 records), Magdalenian (19), Epipalaeolithic (6), Mesolithic (11) and Neolithic (3) cultures, and 24 records of the age of *Patella vulgata* for Solutrean (4 records), Magdalenian (4), Epipalaeolithic (4), Mesilithic (9) and Neolithic (3) cultures. These size and age data actually mean data extracted from published datasets (Gutiérrez-Zugasti, 2011). Therefore, the numbers of individuals from which each mean has been calculated were also retrieved in order to determine the weighted mean of size and age data for each cultural phase.

Prerequisite analyses (tests of Shapiro–Wilk, Levene and Bartlett) are necessary to determine the most appropriate statistical test regarding the nature of the data (Table 4). Then three tests were applied to statistically test the differences in size and age of the marine molluscs between cultural phases: 1) Welch's ANOVA; 2) Kruskal–Wallis; and 3) ANOVA. These statistical metrics obtained on the variance of site elevations are described in 'Investigating resource overexploitation through time' (Results). Finally, *post hoc* tests from Games–Howell (relevant after Welch's ANOVA), Nemenyi (relevant after Kruskal–Wallis) and Tukey (relevant after ANOVA) were applied to identify divergent cultural patterns.

Societal complexity proxies

Funerary practices in archaeological contexts remain one major way to identify the societal development of forager societies (Arias, 2007). Upper Palaeolithic burials are difficult to interpret due to a large variety of mortuary practices (Riel-Salvatore & Gravel-Miguel, 2013). Nonetheless, hierarchic organisations were already emergent in Late Pleistocene hunter-gatherer societies (Wengrow & Graeber, 2015), and burials remain a good proxy for exceptional individuals (Solich & Bradtmöller, 2017). The context, nature, cause, form or meaning of burials are not the focus of this work; instead we use burials as a proxy for the human capacity to create imaginary and transcendent realms, which is one early step toward societal complexity (Bloch, 2008). Few dating records in burial contexts are documented in Cantabrian Spain, even though few more burials exist without associated dating records (Arias et al., 2009). Up to 23 records of burials were gathered from various sources (Arias, 2012; Arias et al., 2009; Cubas et al., 2016, 2019; Drak & Garralda, 2009; Fano et al., 2015; Straus et al., 2011; Tapia et al., 2008). Starting from the Neolithic period, the emergence of the megalithic phenomenon is contemporary to the last human popula-

Table 4. Results of statistical tests performed on marine mollusc sizes and ages. Size data are not normally distributed but show homogeneous variances, hence Levene's test became more relevant for the homogeneity of variance, while Kruskal–Wallis was the most relevant for comparing size distributions between cultural phases. Age data are normally distributed with variance homogeneity, and hence Bartlett's test was more relevant for the homogeneity of variance, with ANOVA to compare age distribution between cultural phases.

Shapiro–Wilk (normality of distribution of data)	Levene (homogeneity of variance)	Bartlett (homogeneity of variance)	Welch's ANOVA	Kruskal–Wallis	ANOVA
No condition	Condition: data not normally distributed	Condition: data normally distributed	Condition: data not normally distributed, heterogeneous variance	Condition: data not normally distributed, homogeneous variance	Condition: data normally distributed, homogeneous variance
Size W = 0.91194 *p*-value = 0.0008466	Size F = 1.0581 *p*-value = 0.3875	Size K^2 = 4.1384 *p*-value = 0.3876	Size F = 72.248 *p*-value = 1.016^{-08}	Size χ^2 = 37.698 *p*-value = 1.293^{-07}	Size F = 50.3 *p*-value = <2^{-16}
Data not normally distributed	Variance homogeneity	Variance homogeneity	Significant differences	Significant differences	Significant differences
Age W = 0.94344 *p*-value = 0.1945	Age F = 0.1149 *p*-value = 0.9757	Age K^2 = 0.27121 *p*-value = 0.9916	Age F = 10.714 *p*-value = 0.003851	Age χ^2 = 16.583 *p*-value = 0.002328	Age F = 13.09 *p*-value = 2.76^{-05}
Data normally distributed	Variance homogeneity	Variance homogeneity	Significant difference	Significant difference	Significant differences

tions that exclusively lived as hunter-gatherers (Lillios, 2019), and is useful as a proxy marking the end of the Neolithization process (Arias, 2007). Up to 49 records of megalithic structures were gathered from two sources in our database (Arias et al., 2000; Fano et al., 2015). Records of both burials and megalithic structures were then presented in a histogram, together with the first records of domestic taxa and ceramics (Fig. 2). It is worth noting that only five Neolithic burials with no megalithic context were identified, indicating a possible research gap. Nonetheless, this particularity does not change our interpretation, as the use of the first appearances of megalithic structures does indicate a new trend on the regional scale.

Results

Investigating human mobility through time

Mean, range and variance values of site elevations differ regarding their cultural phase (Fig. 3). Mean elevations increased over time, except for an abrupt fall to their lowest values in Mesolithic times, which is followed by an even more abrupt rise to their highest value during the Neolithic (Table 5). Upper Palaeolithic cultures show the lowest ranges of elevations, while the Mesolithic is characterised by a higher range of elevations (Table 5). Variance values all increased over time, and three clusters of variance values can be detected: 1) Upper Palaeolithic variance values are the lowest, followed by 2) higher variance values of the Epipalaeolithic and Mesolithic cultures, and 3) the Neolithic shows the highest variance values (Table 5). Interpreting the global variance values, hunter-gatherers in Cantabrian Spain would have

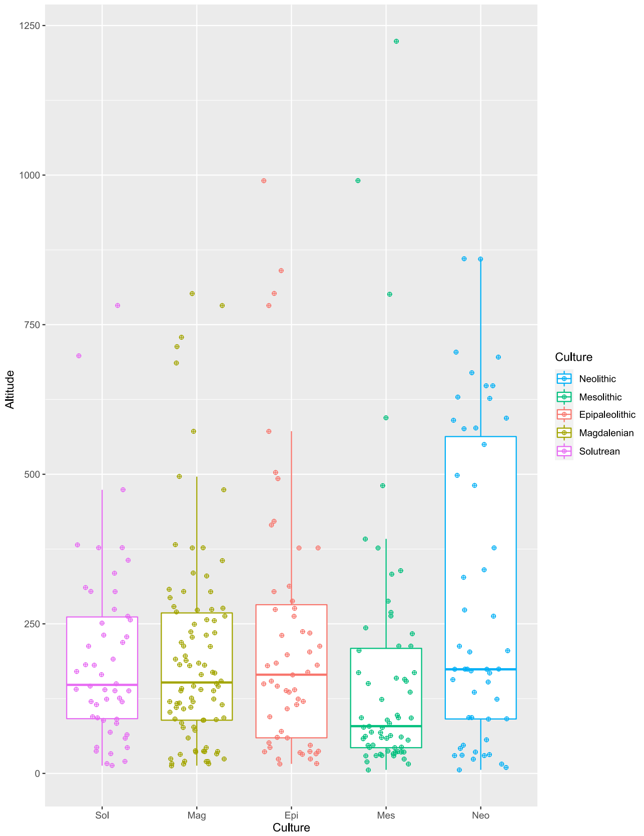

Figure 3. Boxplot of site elevation for each cultural phase. Sol: Solutrean. Mag: Magdalenian. Epi: Epipalaeolithic. Mes: Mesolithic. Neo: Early Neolithic. The elevation is expressed in metres above sea level (m.a.s.l.). [Color figure can be viewed at wileyonlinelibrary.com]

become more mobile through time and/or exploited more predictable seasonal resources.

However, the specific geographic settings of Cantabrian Spain (narrow strips of inhabitable land with a high range of altitudes between the Atlantic coast and the Cantabrian mountains) might have led to a certain bias in our interpretation of the residential/logistical continuum. Archaeological studies consulted show that Upper Palaeolithic sites were concentrated in the lowlands and on the coastal plains due to the harsh climatic conditions and the presence of glaciers in the Cantabrian range, limiting the presence of sites at high altitude (Straus, 2005, 2015). The acceleration of the deglaciation process between the Epipalaeolithic and the consequent colonisation of higher altitudes by human groups increased the range and the variance values of site elevations. Besides local geography favouring high ranges of elevation, seasonal environments and resources were also determinants for exploitation by hunter-gatherers (Alday & Soto, 2017; Clark, 2000; Estévez & Vila, 2006, Straus, 1991).

To investigate this potential bias induced by the geographic characteristics of Cantabrian Spain, variance values for two groups of site elevations were calculated. There are very few sites above 400 m.a.s.l. (three Solutrean, eight Magdalenian, nine Epipalaeolithic, five Mesolithic, and 16 Neolithic) and their altitude varies considerably. The variance of site elevations above 400 m.a.s.l. does not show any historical trend, while the variance of site elevations below 400 m.a.s.l. shows a decreasing trend until the Mesolithic (Table 6). Therefore, it does seem that huge differences in elevation from the few sites at high altitudes are very strongly influencing the global variance of site elevations. While a logistical mobility seems to have been used by human groups below 400 m.a.s.l., a residential mobility pattern seems to have been preferred by human groups above 400 m.a.s.l., probably due to the extreme seasonality of mountain environments. While this trend exists in the long term, we can identify a tipping point during the Epipalaeolithic with a sudden increase in the variance of site elevation above 400 m.a.s.l. This leads to a new mobility regime that was settled during the Mesolithic.

Elevation data were statistically tested (Table 3). The data are not normally distributed (Shapiro–Wilk's test), and the variance of site elevation appears heterogeneous (tests of Levene and Bartlett) (Table 3). Due to the requisites for applications for each test, Welch's ANOVA is the most relevant; however, the others were tested to cross-compare results. Welch's ANOVA fails to show statistically significant differences in the mean site elevations through time, while both Kruskal–Wallis and ANOVA do show significant differences in the mean site elevations between cultures (Table 3). Previous studies also failed to detect any statistically significant difference in the variance values of site elevations (Jones, 2013, 2016).

All three *post hoc* tests (Games-Howell, Nemenyi and Tukey) identify high similarities for Upper Palaeolithic cultures. The Nemenyi test clearly helped to identify a differentiation between the Mesolithic and all the other cultures, while both the Games–Howell and Tukey tests detected significant differences between the Mesolithic and the Neolithic. These divergences might be attributed to the different characteristics of each test, but both the Mesolithic and the Neolithic show a consistently divergent pattern from the Upper Palaeolithic, and are also different from each other. This can also be seen on the boxplot (Fig. 3), where the Mesolithic appears to have the lowest mean value of site elevations for the highest range of elevations, probably influenced by extreme values (sites above 400 m.a.s.l.).

Table 5. Number of sites, their statistical mean and range of elevations, standard error and variance of site elevations for each cultural phase.

Cultural phase	N sites	Mean elevation (m)	Elevation range (m)	Standard error	Variance
Solutrean	50	196.7	769	22.3656	25,011
Magdalenian	90	201.2	789	18.6383	31,265
Epipalaeolithic	55	227.9	975	30.1432	49,974
Mesolithic	63	169.3	1218	28.6474	51,703
Neolithic	51	292.5	854	35.9607	65,952

Table 6. Variance (no units) of site elevations for each cultural phase, for sites below and above 400 m.a.s.l.

	Solutrean	Magdalenian	Epipalaeolithic	Mesolithic	Neolithic
Below 400 m	11,198	10,464	10,210	9,821	10,066
Above 400 m	25,349	16,064	44,101	89,700	11,434

Table 7. Number of entries, MNI, number of levels and MNI per level in the database for both ungulates and marine molluscs, for the following cultural phases: Solutrean, Magdalenian, Epipalaeolithic, Mesolithic and Neolithic.

	Ungulate				Mollusc			
	Entries in database	MNI	Level	MNI/Level	Entries in database	MNI	Level	MNI/Level
Solutrean	43	1081	48	22.52	5	7601	18	422.28
Magdalenian	58	1988	72	27.61	24	41 820	50	836.40
Epipalaeolithic	15	382	31	12.32	15	30 875	22	1403.41
Mesolithic	10	156	12	13.00	23	75 234	38	1979.84
Neolithic	5	78	7	11.14	9	36 343	14	2595.93

Abbreviation: MNI, minimum number of individuals.

We deduce that the residential/logistical continuum for a description of human mobility is thus not very relevant for the Neolithic culture, as the Neolithic is marked by the appearance of sedentary economies. The variance values of site elevations seem to increase during the Neolithic (Table 5), along with the number of sites at high altitude (mostly in megalithic contexts) showing a different pattern of land use as all altitudes were being colonised by Neolithic communities.

The very first appearance of ceramics is dated at 7565 cal a BP at La Garma A, almost 750 years earlier than the second appearance at Los Canes in 6821 cal a BP (Fig. 2). Both sites have different geographic settings and altitudes, with La Garma A being situated in coastal lowlands in Cantabria, and Los Canes being situated in an inner valley in Asturias, and are almost 100 km apart. It is worth noting that almost half of the radiocarbon dates have standard deviations higher than 400 years due to limitations in the use of the thermoluminescence dating technique applied, and hence the available data are characterised by low accuracy of the dating. Considering the standard deviation, an old estimate of the date is obtained by adding the standard deviation to the dating, and a young estimate of the date is obtained by subtracting the standard deviation (Fig. 2).

Investigating economy patterns through time

The total MNI of both ungulates and marine molluscs were reported for each cultural phase, along with the total number of stratigraphic levels per cultural phase (Table 7). Then the mean MNI per level was determined for each culture. A decrease in ungulate mean MNI per level becomes clear between the Solutrean and Magdalenian on the one hand, and the Epipalaeolithic, Mesolithic and Neolithic on the other (Table 7). In contrast, the marine mollusc mean MNI per level gradually increases from the Solutrean to the Neolithic (Table 7). Hence, a tipping point was identified during the Epipalaeolithic but only concerning ungulate economy.

The first appearances of domestic taxa (37 records) could have occurred during the first half of the VIIth millennium cal a BP according to basic and younger estimates (by subtracting the standard deviation from the dating), but as early as the VIIIth millennium cal a BP according to the older estimates (obtained by adding the standard deviation to the dating) (Fig. 2). Most records are spread across the VIIth and VIth millennia cal a BP (Fig. 2). This shows the appearance of a new economy based on domestic taxa starting during the Neolithic.

Investigating resource overexploitation through time

Young and adult ungulate MNIs were reported for each cultural phase, and the proportion of young individuals among ungulates was calculated (Table 8). The total MNI globally decreases over time while the proportion of young individuals increases from 0.3121 for the Solutrean to 0.5345 for the Mesolithic. Then, the young proportion of individuals decreases to 0.4483 for the Neolithic. It is worth noting that there are few entries for the Epipalaeolithic (8), the Mesolithic (4) and the Neolithic (2), hence the results might be subject to small sample size effect, and might not be too representative of the complexity of reality. Nonetheless, the decreasing size of samples also relates to the decrease of ungulates in archaeological contexts.

The trend of the proportion of young individuals among ungulates for each cultural phase was then plotted (Fig. 4) and shows an increase of young individuals over time, ending with a decrease during the Neolithic. This decrease during the Neolithic can be explained by the appearance of sedentary

Table 8. Young, adult and total ungulate minimum number of individuals, and young ungulate proportion counted for each cultural phase.

	Adult	Young	Total	Young proportion
Solutrean	399	181	580	0.3121
Magdalenian	509	249	758	0.3285
Epipalaeolithic	159	108	267	0.4045
Mesolithic	27	31	58	0.5345
Neolithic	16	13	29	0.4483

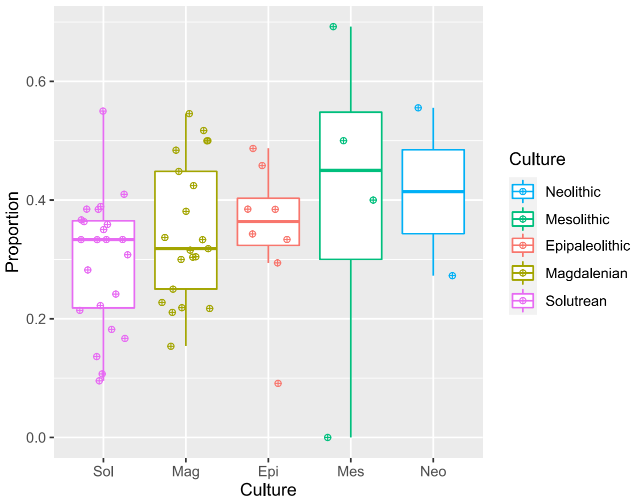

Figure 4. Trend of young ungulate proportion in archaeological contexts over time. [Color figure can be viewed at wileyonlinelibrary.com]

economies which provided cereals and meat, allowing populations to gather enough energy and avoid dependence on wild fauna. Hence, agriculture and pastoralism acted as a buffer against a shortage of wild resources. Nonetheless, statistical analyses (ANOVA, p = 0.4650; Kruskal–Wallis, p = 0.5259; and Welch's ANOVA, p = 0.6996) fail to show significant differences between each cultural phase.

Means and weighted means of both the size and age of marine molluscs for each cultural phase appear almost identical (Table 9), hence we consider it is safe to apply statistical analyses over non-weighted data. An abrupt decrease in the mean size of marine molluscs appears between the Magdalenian and the Epipalaeolithic, while an abrupt decrease in mean age appears between the Epipaleolithic and the Mesolithic (Table 9). These differences are clearly visible when represented as boxplots (Fig. 5).

Statistical exploration of data shows that size data are not normally distributed but have homogeneous variances, hence Levene's test is more relevant to test the homogeneity of variance, and the Kruskal–Wallis test is the most relevant to compare size distributions between cultural phases (Table 4). Age data are normally distributed with homogeneous variance; hence Bartlett's test is more relevant to test the homogeneity of variance, and the ANOVA is the most relevant to compare the age distribution between cultural phases (Table 4). ANOVA, Kruskal–Wallis and Welch's ANOVA always succeed at revealing differences in both size and age between cultural phases (Table 4).

The boxplot in Fig. 5 shows an abrupt decrease between Solutrean and Magdalenian sizes on the one hand, and Epipalaeolithic, Mesolithic and Neolithic on the other. This was confirmed by *post hoc* tests (Tukey, Nemenyi and Games–Howell). Another abrupt decrease concerns the age

Table 9. Mean and weighted mean of marine mollusc sizes and ages for each cultural phase.

	Marine mollusc size		Marine mollusc age	
	Mean	Weighted mean	Mean	Weighted mean
Solutrean	42.7	42.8	5.0	5.0
Magdalenian	40.3	41.7	5.0	4.9
Epipalaeolithic	30.2	30.5	4.9	5.0
Mesolithic	26.6	26.1	3.8	3.8
Neolithic	25.6	26.3	3.5	3.5

of marine molluscs, between the Upper Palaeolithic on the one hand, and the Mesolithic and the Neolithic on the other (Fig. 5). Again, the three *post hoc* tests confirm this trend.

Investigating societal complexity through time

The first appearance of burials is dated from 18 993 cal a BP (Magdalenian culture) at El Mirón cave, and is the only case of Upper Palaeolithic burial material remains in Cantabrian Spain. Interestingly, burials were already present during the earlier period of the Gravettian but not during the Solutrean, and reappeared later during the Magdalenian (Riel-Salvatore & Gravel-Miguel, 2013; Solich & Bradtmöller, 2017). One interpretation is that Solutrean societies were reorganising themselves and adapting to new ecological niches during the LGM (Solich & Bradtmöller, 2017). Other burials are dated from Mesolithic and Neolithic times, between the beginning of the Xth millennium cal a BP and the beginning of the VIth millennium cal a BP (Fig. 2). It is worth noting that two non-dated Epipalaeolithic burials have been documented at Los Azules and La Paloma sites (Arias et al., 2009b), and hence were not considered in our database. Megalithic structures first appeared at the end of the VIIth millennium cal a BP, during the Neolithic period, and sites with evidence are regularly present until the end of the time period covered in our study, in the mid-Vth millennium cal a BP. These results show that funerary practices mainly emerged from the Mesolithic onward, and that both single burials and megalithic burials coexisted in Cantabrian Spain during the Neolithic. Funerary practices are one way to investigate societal complexity. We argue that from the Mesolithic onward, burials started to expand rapidly, as was also the case for megalithic structures during the Neolithic.

Reconstructing energy regimes

The Standard Solar regime is mainly defined by the exploitation of wild resources (Vlachogianni & Valavanidis, 2013). Two subcategories can be defined within the Standard Solar regime: Immediate Return and Delayed Return societies (Feeney, 2019; Woodburn, 1980). Immediate Return societies are characterised by little planning and specific strategies (e.g. following the migration patterns of big mammals). Delayed Return societies are able to plan the exploitation of their environment (e.g. forest burning for a profitable future). They used sites seasonally, and exchange or trade of resources is a reliable subsistence strategy (Woodburn, 1980).

From the results presented in this work, we know that Solutrean, Magdalenian and Epipalaeolithic societies in Cantabrian Spain were characterised by a residential-like mobility, and inhabited mostly coastal and inner valley lowlands. This is coherent with the results of previous studies (Jones, 2013, 2016; Clark et al., 2019). Mobility patterns

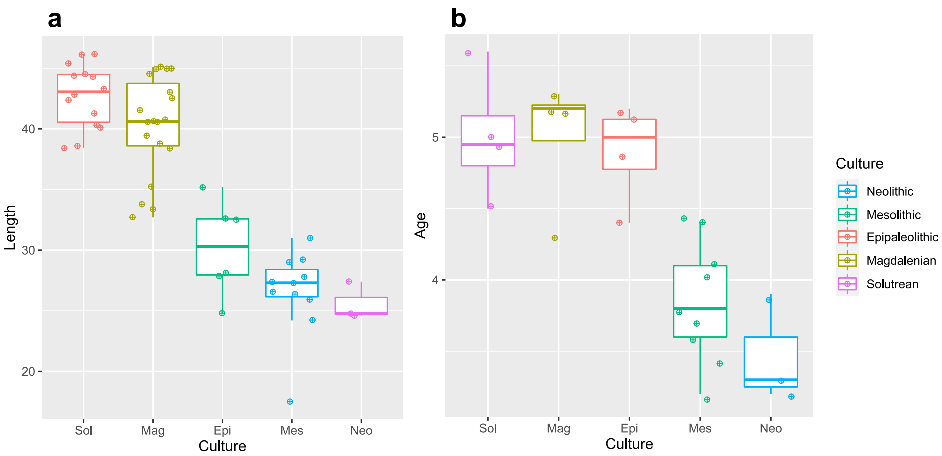

Figure 5. Boxplots of a) marine mollusc sizes (in mm), and b) marine mollusc ages (in years), for each cultural phase. [Color figure can be viewed at wileyonlinelibrary.com]

reached a tipping point during the Epipalaeolithic, with a sudden expansion to a wide range of altitudes in mountain areas, which were opened after the retreat of the glaciers during the warmer Bølling–Allerød period (a warm/wet climatic sequence from *ca.* 14.7k cal a BP to *ca.* 12.9k cal a BP) (Martinez et al., 2022). Hunter-gatherer groups started to exploit these new environments and set up seasonal camps at the confluence of eco-zones where they could access different resources at different times of the year (Zeder, 2012). These changes probably enhanced the progressive transition from residential to logistical mobility, leading to a better understanding of resource predictability by hunter-gatherers. Interestingly, logistic features were possibly identified for Gravettian groups in the Northern Meseta (south of the study area), while residential features were identified for Gravettian groups in the Western Pyrenees (Calvo & Arrizabalaga, 2020), in an ecological and climatic context closer to our study area. Even though the Gravettian and the Northern Meseta are outside the scope of this work, the LGM and related perturbations of human ecological niches could have forced these populations to reorganise their subsistence strategies leading to important behavioural changes in the Solutrean onwards (Solich & Bradtmöller, 2017). The trend from residential-like to logistical-like societies highlights a shift in resource and energy extraction strategies from the environment. Hunter-gatherers that organised themselves in logistical societies could anticipate resource and energy availability and extraction.

The Epipalaeolithic period also marks a tipping point in the decreasing trend of ungulate MNI per stratigraphic level and in marine mollusc size reduction. While the reduction in the size of marine molluscs might be attributed to environmental factors (Bailey & Craighead, 2004), it seems that the abrupt decrease of ungulates in archaeological contexts is probably not related to any biological (Sæter et al., 2002; Jacobson et al., 2004; Grøtan et al., 2008) or ecological (Alados & Escós, 2003; Carranza, 2004; Pérez Barbería & García González, 2004; Mateos-Quesada, 2005) factor, as ungulates are more dependent on food availability than on climate (Mariezkurrena, 1983). Hence, the reduction of ungulates in archaeological contexts might be human-induced (Marín-Arroyo, 2013). The exploitation of marine molluscs thus probably increased to compensate for the energy loss from the reduction in ungulate consumption.

The reduction of ungulates, starting during the Epipalaeolithic, would have induced a loss of energy availability and use for human populations, and this missing energy had to be found elsewhere. Meanwhile, the number of marine molluscs per stratigraphic level constantly increases over time (Table 6), partly compensating for the energy loss from the decreasing consumption of ungulates. Our results are coherent with previous research attesting to more consumption of low productivity species (Marín-Arroyo, 2013) and marine molluscs (Gutiérrez-Zugasti, 2011) in archaeological contexts alongside the decreasing trend of ungulates.

The rise of the sea level through time due to improving climate is certainly important. With the sea being *ca.* 120 m below the present-day level during the LGM, the palaeocoastline was between 9 km and 12 km further north than the present coastline (Fig. 1). The sea level, and hence the coastline, stabilised at its current position during the Mid-Holocene (around Neolithic times). Thus, older coastal archaeological sites are nowadays most likely underwater. Consequently, the retreat of the coastline over time might be partly influencing the regular increase of the marine mollusc mean MNI per level. However, the Epipalaeolithic coastline was already most often between 500 m and 1500 m from the current shoreline (Fig. 1), hence it no longer has much influence on the marine mollusc mean MNI per level.

Based on this interpretation, we identify Upper Palaeolithic (Solutrean and Magdalenian) populations in Cantabrian Spain as being organised in Immediate Return societies (Table 1). Important changes in mobility and economy occurred during the Epipalaeolithic, but there is still no clear evidence of reduced mobility, overexploitation of resources or societal complexity. Therefore, we argue that Epipalaeolithic populations lived in a transitional phase between Immediate Return and Delayed Return societies (Table 1).

Our results showed that the Mesolithic mobility pattern is marked by the lowest mean value of site elevations for the highest range of elevations. This is coherent with the complexification of Mesolithic societies, with different communities living independently on the coast and in the mountains, as attested by previous research using isotope analyses to determine the diet of these populations (Arias, 2005, 2007; Arias & Fano, 2005; Cubas et al., 2016; Lillios, 2019; Fano, 2004). Hunter-gatherers eventually became less mobile and adopted territorial behaviours as early as the Mesolithic (Alday & Soto, 2017; Estévez & Vila, 2006). The shift from residential to logistical mobility, and then territorial behaviours, shows an evolution in the strategies of extraction of resources and energy from the environment. Logistical societies anticipate resource extraction and manage their environment. When Mesolithic hunter-gatherers became more territorial (Arias & Fano, 2003;

Uzquiano, 1995; Zapata, 2000), resources were extracted from smaller areas by a growing population, indicating a first step towards the intensification of energy extraction from the environment.

Economic trends that started during the Epipalaeolithic continued during the Mesolithic, but clear evidence of overexploitation is now visible with the abrupt and human-induced decrease in marine mollusc ages (Gutiérrez-Zugasti, 2011) and the development of burials and funerary practices. Moreover, the proportion of young individuals in ungulate assemblages constantly increases through time, indicating a depletion of adult individuals that would provide more energy return than young individuals. Hence, the question arises whether human communities extracted more energy than the natural environment could provide, and thus whether they already lived in an unsustainable energy regime. Changes in mobility and economic patterns during the Mesolithic relate to Delayed Return societies (Table 1).

Profound changes suddenly occurred during the Neolithic. The appearance of ceramics and storage vessels indicates a second phase of reduction of mobility after the shift from residential to logistical mobility. However, the residential–logistical continuum is no longer very relevant because of the sedentary economy that developed at any altitude during the Neolithic. The emergence of sedentary sources of energy (domestic plants and animals) probably limited pressures on hunting for wild taxa. Hence, the sedentary economy probably acted as a buffer against a shortage of resources.

These results are coherent with previous research results from López-Merino et al. (2010) and Peña-Chocarro et al. (2005). Other works have equally shown an increasing proportion of domestic taxa in archaeological contexts over time (Altuna & Mariezkurrena, 2009) as well as a long continuity in subsistence strategies from the Solutrean onward, indicated by both the occupation of specialised hunting sites (Altuna, 1980; Arias, 2012; Marieskurrena, Altuna, 1995) and the foraging exploitation of a large diversity of wild plants (Uzquiano, 2018; Zapata, 2000). This is consistent with the results of our work.

Our results show an increase in the proportion of young individuals among ungulates over time, meaning that gradually fewer adult individuals were to be found. The consumption of younger individuals provides less energy to humans than adults, so this trend indicates a depletion of wild resources. The size and age patterns of marine molluscs also indicate a depletion of resources. There is no tipping point in the increase of the proportion of young ungulate individuals, while marine mollusc size decreases suddenly during the Epipalaeolithic, and marine mollusc ages during the Mesolithic.

Results from previous studies have considered environmental drivers (Bailey & Craighead, 2004) to demographic pressures (Jones, 2016; Straus, 2009) as possible drivers for these changes. Gutiérrez-Zugasti (2011) showed that climate warming and an increase of sea temperature were likely to cause the decrease in size of marine molluscs during the Epipalaeolithic, while overexploitation of marine molluscs during the Mesolithic would have led to the depletion of adult individuals. Another work on resource depletion was conducted by Marín-Arroyo (2013), who investigated the expansion of hunting territories, with hunter-gatherers having to process meat at the kill site and then carry it to the base camp (Cannon, 2003; Marín-Arroyo, 2009). Consequently, they brought back the body pieces with the highest energy return (Speth, 2004; Munro, 2009). Although an in-depth analysis of this issue is beyond the scope of this paper, Marín-Arroyo (2013) has shown that the expansion of hunting territories and the selection of the more productive body parts by hunter-gatherers started in Cantabrian Spain during the Epipalaeolithic.

The emergence of domestic plants and fauna during the Neolithic marks an important shift in terms of energy use, although continuity in the long-term increasing trend of marine mollusc consumption is also attested (Table 7). Hence, we can ascertain that two energy sources corresponding to foraging and sedentary economies coexisted during the Neolithic. Domestication was the next phase of intensification in the extraction of energy from the environment, following the territorial behaviours that arose during the Mesolithic. Domestication is a way to concentrate the solar energy in a specific area to either grow plants or raise cattle.

This concentration of resources and energy allowed human communities to increase their demography on a given territory, which is consistent with Clark et al. (2019), demonstrating that demographic changes increased rapidly from the Mesolithic onward. The concentration of individuals in restricted areas allow societies to become more complex, and provided enough workforce to make the construction of megalithic structures possible. Previously, Zeder (2012) has stated that with the reduction of mobility, and the development of the notion of ownership of resources and land, territories became better defined, understood and exploited. The energy return provided by territories was sufficient to make it worth investing and defending them (Martinez et al., 2022). Therefore, the Neolithic period is associated with the transitional phase from the Standard Solar to the Agrarian Solar regime (Table 1).

It is worth noting that a division needs to be made between the Early and Late Neolithic at *ca.* 6300 cal a BP, with the appearance of open-air settlements (Cubas et al., 2016) and the 'apogee of megalithism' evidenced by a more homogeneous distribution of megalithic sites across the study area (Fano et al., 2015). Interestingly, environmental studies identified the first anthropogenic impact (mostly deforestation) on the environment at the same time period, with the systematic use of fire to open lands to facilitate human activities such as pastures and slash-and-burn agriculture (Pérez-Díaz et al., 2016; Carracedo et al., 2018).

The Chalcolithic succeeded the Neolithic *ca.* 5300 cal a BP, bringing new changes in Cantabrian societies. Productive economies (slash-and-burn agriculture, extensive cattle raising) became predominant compared with foraging activities (Ontañón-Peredo, 2003). While the cost in energy for foraging activities was low and energy returns immediate, much more energy was being spent along the year in agropastoralist activities and its energy return was deferred in time. Moreover, strong societal organisation, with separation and specialisation of activities, developed with the appearance of new industries such as copper mining and metallurgy (Ontañón-Peredo, 2003). The first evidence of heavy metal pollution in the environment corresponds to this period (Martínez-Cortizas et al., 2016). This societal complexity led to increased flows of energy between specialised industries, such as copper and ceramic industries, and extensive food production. These characteristics allow us, based on the results of this study, to identify the kick-off of the Agrarian Solar regime most likely with the start of the Chalcolithic period.

The transition from the Standard Solar regime to the Agrarian Solar regime in Cantabrian Spain occurred after contacts with overseas settlers that brought productive economies and their related knowledge and culture to the Iberian Peninsula. The equivalent transitional process was totally different in areas where productive economies developed *ex nihilo*, such as in the Levant. A rapid comparison between the two processes is of use to better understand what ERs can bring to the scientific debate.

In the Levant, productive economies appeared during the Late Natufian period, between 12 500 cal a BP to 12 000 cal a BP, coinciding with a climatic change toward the cold and dry conditions of the Younger Dryas (Bar-Yosef, 1998; Kuijt & Goring-Morris, 2002). There is evidence of intensive and extensive harvesting of wild cereals (Bar-Yosef, 1998) and plant manipulation (Wright, 1991) by hunter-gatherers earlier during the Natufian, as mild climatic conditions during the XIVth millennium cal a BP provided a wealth of food resources (Bar-Yosef, 1998). Contemporaneous population growth made human groups more vulnerable to abrupt climatic fluctuations, leading to the need to control food resources (Bar-Yosef, 1998). Semisedentism and then sedentism developed due to the need for human groups to intensify cereal, fruit and legume exploitation (Henry, 1985; Bar-Yosef, 1995); as well, sedentism itself enhanced the intensity of the exploitation of these resources (McCorriston & Hole, 1991). The first evidence of clear plant domestication and cultivation is dated from the Late Natufian (Smith, 2001), but animal husbandry appeared later, during the following Pre-Pottery Neolithic A period (from 11 700 cal a BP to 10 500 cal a BP) (Kuijt & Goring-Morris, 2002).

Villages larger than 1000 m^2 developed as soon as the Late Natufian, with separate residential and storage buildings (Bar-Yosef, 1998; Kuijt & Goring-Morris, 2002). Large structures such as the tower of Jericho (Israel), requiring planning and collective labour, were also built (Kuijt & Goring-Morris, 2002). At this period, funerary practices were standardised with different treatment for children and adults (Kuijt & Goring-Morris, 2002). Besides these large camps, often situated on fertile alluvial terraces, small logistical sites have been uncovered on and adjacent to mountain ridges, with specific activities such as wood provision and harvesting of cereals to supply the biggest camps (Kuijt & Goring-Morris, 2002). Other ephemeral sites are found in arid environments, with a high residential mobility, probably used by other groups of more mobile hunter-gatherers (Kuijt & Goring-Morris, 2002). Only later during the Late Neolithic (from 8250 cal a BP to 7800 cal a BP) pottery technologies appeared at sites such as Jarmo and Tell Hassuna (Iraq) in the form of clay figures (Maisels, 1993).

While the detailed transition from the Standard Solar regime to the Agrarian Solar regime in the Levant is outside the scope of this work, this process was entirely different from that in Cantabrian Spain. Different timing, climate, environment, ecology and resources were involved. The key innovative step toward productive economies such as domestication of plants and fauna as well as pottery technologies, appeared at different times (much earlier in the Levant than in Cantabrian Spain) and in a different order between each region, and for different reasons. The two case studies and their context are too different to allow any comparison between them in the classical archaeological framework. ERs add a new layer of understanding, based on the functioning of past societies, and more precisely resource and energy use.

While the case of the Levant is entirely different from the case of Cantabrian Spain, the same need for human societies to increase energy input and the same dependency on certain resources are outlined. In both cases, productive economies came as a buffer against a shortage and/or failure of wild resource provisioning. Climatic, environmental and ecological contexts are of major importance in the transitioning processes from foraging to productive economies. Applying the framework of ERs to archaeological contexts would provide much more understanding of the functioning of past societies, expressed with proxies (resources and energy uses) that are applicable to present-day societies. Indeed, the IPCC (2022) highlights the challenges that resource and energy management represent for modern societies. By identifying the trends, issues and solutions of resource and energy management from the past, it becomes possible to inform current decision-making processes based on past experience, successes and failures. If the world is currently facing unprecedented climate and societal challenges, including the current energy transition, the theoretical framework of it, i.e. ER transitions, were already faced by our ancestors.

Conclusion

There are limitations to the ability of conventional cultural phases to describe the past societies that are linked to them, isolating archaeological case studies in a bounded space and time context. However, they are still prevalent in archaeology, hence it is unrealistic to completely ignore them. However, ERs provide a common language that can be used to compare archaeological sites from any time period and any region of the world, including also ethnographic studies. In Cantabrian Spain, combining cultural phases and ERs is one plausible solution for the limitations of classical archaeological studies using only cultural phases and can help to expand archaeological studies beyond their scientific niche.

Hunter-gatherer and early farmer/herder subsistence strategies were explored using proxies of mobility, economy, overexploitation of resources and societal complexity. Exploration of the data and statistical analyses allowed us to unravel the main economic and societal trends and connect cultural phases with ERs. At a later stage, the expansion of the ER framework beyond the Neolithization could be an asset to document the long-term evolution of agrarian societies in Cantabrian Spain, as well as the evolution of their ERs through time. This would also enable the comparison between Cantabrian hunter-gatherer societies facing challenges in the transition towards the agrarian regime, and our current society transitioning to more sustainable economies in a time of climate emergency.

The long-term history of Cantabrian foraging societies shows that no societal change is sudden but rather evolves as a continuum of adaptations of subsistence strategies that are embedded in equally dynamic environmental settings. Productive economies and industries abruptly emerged in the area, being brought by settlers, but local foragers maintained their economic system until depletion of wild resources (i.e. an unsustainable foraging economy) and/or they integrated a new and more encompassing societal organisation with both foraging and productive economies. New settlers also needed the knowledge of local foragers about their territories in order to effectively develop and implement their economic activities. This shows that no transition is possible without the consent and active participation of the local population, but also that locals generally waited until they faced a resource/energy crisis before eventually adopting novel economies and energy regimes. Finally, it is also important to indicate how landscape management abruptly shifted with the adoption of productive economies, resulting in systematic deforestation processes, largely altering wild biomass and wild animal habitat. Although plant and animal domestic taxa were introduced as a buffer against a shortage of wild resources, this reduction in biomass most likely worsened the conditions of the wild taxa, also risking bringing the human populations to a dangerous dependency on productive economies, with no alternative resources to rely on in the event of food production failure. This indicates that the consequences of entering a new energy regime and adopting new land management must be anticipated. Thus, exploring and describing past ER transitions are applicable, significant and of major importance to inform and evaluate the climatic and societal challenges that our present-day societies are facing.

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Data availability statement

All data used in this work come from already published or freely accessible data. The original sources of all data used in this work are explicitely cited in the list of reference and/or provided in the Appendix 1.

Supporting information

Additional supporting information can be found in the online version of this article.

Appendix 1. Database of archaeological evidence to document proxies and indicators of energy regimes.

Abbreviations. BP, before present; ERs, energy regimes; GIS, geographic information system; IPCC, intergovernmental panel on climate change; LGM, last glacial maximum; MNI, minimal number of individuals; YD, younger dryas.

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