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# A multi-method approach with machine learning to evaluating the distribution and intensity of prehistoric land use in Eastern Iberia

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ABSTRACT

The present study seeks to better understand the coupling of social and biophysical systems during the late Pleistocene and Holocene, a period characterized by changing interglacial conditions as well as human population expansion and intensified ecosystem management. The approach consists of a combination of patch-based archaeological survey methods, sediment column sampling for paleoenvironmental data, geospatial analysis, and machine learning for chronological unmixing, allowing the systematic evaluation of the distribution and intensity of prehistoric land use in the study area of eastern Mediterranean Iberia. Occupational and Land Use Intensity maps developed from continuous distributions of surface artifacts as well as a summed probability density curve developed from 14C dates indicate low but steady human presence in the study area during the Middle Paleolithic and Upper Paleolithic with a marked decrease of human presence across the Pleistocene/Holocene boundary. The Early (and Middle) Neolithic saw the most ubiquitous and intensive occupation of the study area followed by a significant decline during the Late Neolithic/Chalcolithic. The charcoal analysis also supports this pattern. Early Neolithic farming strategies may not have been damaging initially during the climatic regime of the Early Holocene but exacerbated the impacts of higher temperatures and summer droughts, with a loss of the most productive farmland, seen at the onset of the Late Neolithic. Similar boom-bust population trends have been documented throughout Europe during these same time spans and may indicate a recursive interaction or “coupling” between global and regional climate events and human land use strategies.

## 1. Introduction

Compared to our globally connected world where humans regularly bypass restrictions of physical space during daily activities, past peoples experienced their world as part of a coupled human-natural system limited by a complex spatial unit called a “region.” We can conceive of a region as a concrete tangible entity that existed as a reference framework for those living there (Contel, 2015; Vujadinovič and Šabić, 2017). Researchers can differentiate regions in the past by identifying areas with shared spatial, climatic, and social traits. If we are interested in fundamental research questions concerning long-term processes affecting coupled human-natural systems and how humans of the past experienced their worlds, we cannot study human and environmental sites in isolation. We must account for regional context and regional, historical contingencies with an understanding that local system dynamics are not independent of regional scale processes. By approaching such research questions at the regional scale, we emphasize the significant spatial variability in which social and environmental processes occur.

This research endeavor seeks to better understand the evolution and consequences of the coupling of social and biophysical systems, and the ways through which humans and their environmental systems developed a dynamic, recursive complex interaction. We argue that, during the late Pleistocene and Holocene, which includes changing interglacial

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conditions, humans greatly expanded and intensified their management of 'natural' ecosystems through resource gathering, farming, herding, and forestry. Over millennia, these practices accelerated a suite of positive feedbacks that led to a modern urbanized world characterized by tightly coupled socio-natural landscapes. To understand the processes resulting in tightly coupled landscapes, a regional-scale approach is necessary and logical.

Regional investigations should rely upon good empirical evidence derived from case studies (Archer, 1993). Our case study is in eastern Iberia within the circum-Mediterranean area, which has one of the longest histories of intensive human land use of any part of the world. Landscapes modified through intensive agricultural land use, like those in eastern Iberia, often result in complex palimpsests of archaeological material that are difficult to interpret using traditional site-oriented methods (Barton et al., 1999; Cherry, 1983; Llobera et al., 2011). Instead, many archaeological survey methods have relied upon identifying artifact concentrations on the surface of the landscape as "sites" that are studied in detail while surrounding materials are largely ignored. However, researchers have shown that analysis of the continuous distribution of surface artifacts rather than a focus only on concentrations defined as sites, can be used effectively to examine the diachronic interactions between prehistoric land use, ecological systems, and their influence on landscape evolution (Barton et al., 2004a,b, 2010; Bernabeu Aubán, 2001; Barton et al., 1999; Bevan and Conolly, 2004; Fanning et al., 2009; Peeples et al., 2006; Snitker, 2018). In other words, the spatial distributions of artifacts across landscapes permit the study of occupational patterns at regional scales, without the need to pinpoint specific sites as loci of human occupation.

Furthermore, our implementation of independent methodologies using multiple lines of evidence and machine learning (ML, also called data-driven models or 'artificial intelligence' in some literature) for chronological control of archaeological assemblages mitigates some of the impediments that researchers who study land use in prehistoric Western Europe before and after the introduction of agriculture have encountered. These impediments, notably chronological control, sampling biases, site versus regional focus, landscape influences, processes affecting discard, and taphonomic processes, often result in a biased representation of the material record. By comparing, at the regional scale, results derived from radiocarbon dates, occupational and land-use measures derived from chronologically-arranged lithic surface collections, and sediment column sampling of charcoal, we can identify trends that cross-cut all analyses and transcend the biases that often plague archaeological datasets.

In collaborative research between Arizona State University, the University of Valencia, and other organizations, we have worked to develop field and analytical approaches to regional-scale prehistory that can overcome the challenges posed by palimpsest archaeological material. Multiple seasons of fieldwork and analyses in eastern Iberia have created a suite of innovative methods that integrate geographic location, ground visibility, and chronology to evaluate changing patterns of prehistoric land use (Barton et al., 1999, 2002, 2004; Bernabeu Aubán et al. 1999a; Barton et al., 1999; 2011, 2018; Pardo-Gordó et al., 2009, 2015). This paper presents the recent application of these approaches in three study areas in the region–Valle de Canal de Navarrés, Hoya de Buñol, and Cocina-Catadau (Fig. 1)–and illustrates how they enable us to gain insight into regional land use patterns over the course of over 100,000 years. We combine patch-based archaeological survey methods, sediment column sampling for paleoenvironmental data, geospatial analysis, and ML for chronological unmixing to systematically evaluate the distribution and intensity of prehistoric land use in this study area.

## 2. Regional setting

### 2.1. Environmental setting

The region in which our study areas are located, including Valle del

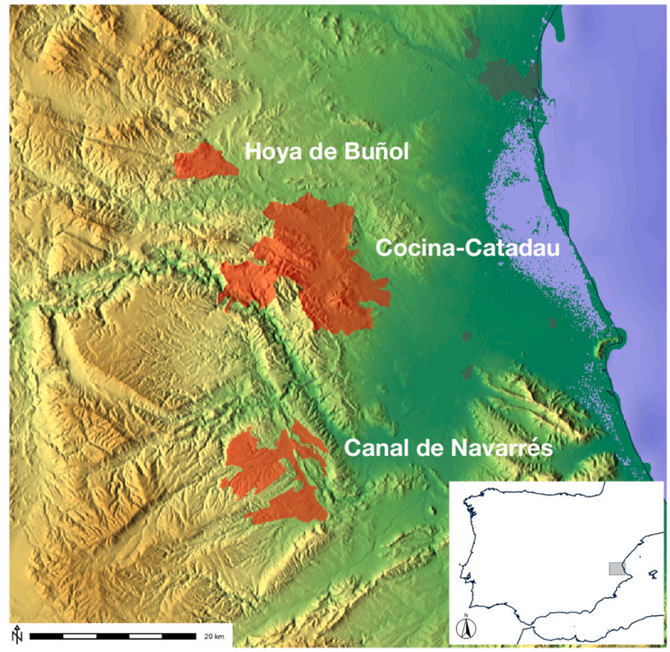


**Fig. 1.** Locations and geographic settings of study areas discussed.

Canal de Navarrés (255 m. a.s.l., 39° 06′ N 0° 41' W), Hoya de Buñol (441 m. a.s.l., 39° 25′ N 0° 47′ W, and Cocina-Catadau (400 m. a.s.l., 39° 17′ N 0° 48′ W) valleys, is situated in the Mesomediterranean vegetation belt, a transitional zone between the lower altitudes of the Mediterranean coast and higher inland climate zones in eastern Iberia. The Mesomediterranean belt experiences dry summers and cool to cold, humid winters (Carrión and Van Geel, 1999; Rivas Martinez, 1987; Specht et al., 1983). Over the course of a year, the temperature can vary between −5 °C and 38 °C. Precipitation varies by season, with a 10-month wet period (late August through early June) and between 11 mm and 42 mm of precipitation and a two-month dry period (late June to early August) where precipitation can average as low as 3 mm (Meteoblue, 2022; see also European Environment Agency, 2002). Modern vegetation communities are characterized by *sclerophyllous* shrublands adapted to dry environments, grasses, and evergreen *Quercus* woodlands with some *Pinus halepensis* in the uplands (García Alix et al., 2021). In lowland areas, agriculture has replaced most endemic vegetation. Regional palynological investigations indicate a shift from *Pinus*-dominant forests during the Late Glacial and first half of the Holocene to *Quercus*-dominated forests and lake infilling by around 6000 to 5500 years B.P (Carrión and Van Geel, 1999; Carrión et al., 2010; Dupré et al., 1998). The introduction of fire associated with Neolithic agricultural practices during the middle Holocene may have influenced the shift to fire-tolerant *Quercus*, *Cistus*, and *Ulex* species (Carrión and Van Geel, 1999; Snitker, 2018).

The study areas exhibit some geomorphic and hydrological differences. The Valle del Canal de Navarrés is a flat-bottomed, northwest-southeast oriented tectonic valley circumscribed by three low-lying ranges—the Massis del Caroig to the west, the Serra de Sumacárcer to the east, and the Serra d'Enguera to the south. Tributaries of the Riu Xúquer actively drain this area from both the north and south. The valley is semiendorhic, resulting in the formation of lakes, peatlands, and travertines throughout the Holocene (La Roca et al., 1996). The modern lakes of Playamonte and l'Albufera d'Anna are evidence of these processes. The Hoya de Buñol lies to the north of the Valle del Canal de Navarrés and is a geological link as well as a natural passage between the Castillian Plateau and the Coastal Plain. Orographically, the area is a valley bordered by a series of mountain ranges—Serra de la Cabrera to the north, Serra de Dos Aguas to the south, and Serras de Malacara and

Martés to the west (Martínez Valle and Fernández Peris, 1989). The watersheds and basins of the endorhic Rambla del Poyo and the Riu Magre, a tributary of the Riu Xúquer, are found within the area (Carmona and Pérez Ballester, 2011; Carmona et al., 2016). The area encompassing Cocina-Catadau is mountainous, developing in the north out of the Serra del Ave and from the southeast out of the Serra del Caballón. The ravines of Fleirón, de la Muerta, de la Fuentecilla, del Bosque, Cazador, and Rambla de la Canal empty into the Riu Xúquer, running south of the town of Dos Aguas. In the east and descending to the sea, the Catadau area is formed by several alluvial plains currently in use for horticultural exploitation. This is an irregular terrain with hills, ravines, and karstic activity (Pardo-Gordó et al., 2017). Material remains at Cueva de la Cocina indicate human presence in the area attributed to the last hunter-gatherers of the Mesolithic through the Neolithic and into the Bronze Age (García Puchol et al., 2017; 2018; Pardo-Gordó et al., 2018).

### 2.2. Previous archaeological research

The regional chronology of Middle Paleolithic (*circa* 350,000–40,000 BP) and Upper Paleolithic (39,000–11,000 cal. BP) occupations is reconstructed through well-documented sites such as Abric del Pastor, Abrigo de la Quebrada, Cova Beneito, Cova Negra, Cova del Parpalló, Cova de les Cendres and Volcà del Faro (Aura Tortosa et al., 2020; Barton et al., 1999; Eixea et al., 2020; Fernández Peris and Villaverde Bonilla, 2001; Martínez-Alfaro et al., 2021; Riel-Salvatore and Barton, 2004; Snitker et al., 2018; Vidal Matutano and Pardo-Gordó, 2020). Most of the Middle Paleolithic assemblages are dated to OIS4-3, spanning the end of the last Interglacial to just before the beginning of the Last Glacial Maximum (see Zilhão, 2021 for chronological discussions) (Fernández Peris and Villaverde Bonilla, 2001). Upper/Late Upper Paleolithic industries recovered from Cova Beneito, Cova de Parpalló, and Cova de les Cendres among others have shaped the interpretation of late Pleistocene occupations and chronologies throughout the region (Fernández Peris and Villaverde Bonilla, 2001; Martínez-Alfaro et al., 2021; Villaverde Bonilla et al., 2012). Assemblages from these and other sites are dated to the end of OIS-3 to the end of OIS-2.

Regional Mesolithic and Neolithic chronologies have been built through several decades of systematic excavations in caves, rockshelters, and open-air contexts. Evidence of hunter gatherer occupations during the Mesolithic (11,000–7600 cal. BP) has been identified primarily through diagnostic lithic technologies, including specific types of geometric microliths. Regionally, the Early Mesolithic, also called Notches and Denticulates Mesolithic, is represented at the site of Santa Maira (Aura Tortosa et al., 2006) and the burials from El Collao (García Guixé et al., 2006; Gibaja et al., 2017). The Late Mesolithic, regionally defined as Geometric Mesolithic (Martí Oliver et al., 2009), has been identified in several sites throughout the region including Abric de la Falguera (García Puchol and Aura Tortosa, 2006) and Cueva de la Cocina (Fortea Pérez, 1973; García Puchol et al., 2017).

The earliest Neolithic occupations date to 7600–7500 cal. BP, associated with the *Impressa* horizon, at sites such as Mas d'Is and El Barranquet (Bernabeu Aubán and Pardo-Gordó, 2020; Molina Balaguer et al., 2020). By 7400 cal. BP, cardial ceramics and evidence of domesticated plants and animals are widespread at multiples sites, including Abric de la Falguera (García Puchol and Aura Tortosa, 2006), Cova de les Cendres (Bernabeu Aubán and Molina Balaguer, 2009), Cova de l'Or (Martí Oliver, 2011; Martí Oliver et al., 1980), Cova de la Sarsa (García Borja, 2017; García Borja et al., 2011) and Benàmer (Torregrosa Giménez et al., 2011). Although excavations in caves and rockshelters have provided reliable ceramic and lithic chronologies for the Valencian Neolithic period, open-air sites such as Mas d'Is (Bernabeu Aubán et al., 2003), Niuet (Bernabeu Aubán et al., 1994), Les Jovades and Arenal de la Costa (Bernabeu Aubán, 1993), and Ereta del Pedregal (Fletcher Valls, 1964; Juan Cabanilles, 1994, 2008; Pla Ballester et al., 1983) offer insights into the changing land use patterns and social organization that accompany the Neolithic and Bell Beaker (Chalcolithic) periods (Pérez Jordà and Peña Chocarro, 2013). Ereta del Pedregal established the chronology of middle Holocene occupations for Valle del Canal de Navarrés and nearby valleys. Initial investigations at Ereta del Pedregal in the 1940s and later excavations in the 1980s revealed early examples of stone building construction, a circular stone enclosure, and numerous artifacts including lithics and decorated bone associated with Late Neolithic (5000–4500 cal. BP), Chalcolithic (4500–3800 cal. BP), and early Bronze Age (3800–3250 cal. BP) (Juan Cabanilles, 2006; Pla Ballester et al., 1983).

## 3. Material and methods

### 3.1. Patch-based survey and paleoecological sampling in the three regions

#### 3.1.1. Survey objectives and background

The objective of the archaeological survey in all three regions was to evaluate the distribution of surface artifacts and collect associated paleoenvironmental data to test models of human land use and landscape evolution to better understand the changing interactions between social and ecological systems (Diez Castillo et al., 2016; García Puchol et al., 2014; Snitker et al., 2018). To accomplish this, we have developed and adapted data collection methods and analytical techniques that have proven successful in expanding the interpretation of highly mixed surface assemblages. The work presented here builds on several decades of field-based studies and experimentation conducted throughout the Comunitat Valenciana in eastern Iberia (Barton et al., 1999, 2002; Barton et al., 2004b).

Pedestrian archaeological survey in the Mediterranean Basin remains relatively rare, due to the perception that centuries of agriculture, terracing, and other ground disturbing activities have redistributed artifacts so extensively that they no long retain useful chronological information (Barton et al., 1999, 2002; Barton et al., 2004a; Cherry, 1983; Snitker et al., 2018). However, experimental studies show that while many such formation processes indeed move artifacts from their original positions, the extent of horizontal disturbance is limited at regional scales, and that surface artifacts are representative of a larger population of materials present in the agricultural disturbance zone (Ammerman, 1985). Moreover, as described in more detail below, we use probabilistic models to assign age estimates to surface materials. This allows us to consider surface artifacts as residues of a spatially and temporally varying distribution of human activities across the landscape. Rather than focusing on identifying archaeological "sites," we identify statistically representative samples of landscape "patches" from which we collect information, including any artifacts that may be present in a patch. This strategy is advantageous for operationalizing a regional perspective on human-natural systems by enabling evaluation of a more complete spectrum of land use activities that encompass, but are not limited to, settlements or other persistent activity loci. Additionally, sampling and studying samples of landscape patches provides insights into how artifacts may have been transported throughout the landscape due to erosion, deposition, or other formation processes (Barton et al., 2021).

At the core of this strategy is the division of each study area into a continuous series of patches (spatially delimited data collection units) that are sampled using a stratified random survey strategy and subsequently can be queried, subsampled, or interpolated throughout the study area. This sampling design helps ensure that the archaeological materials collected in the survey are statistically representative samples of surface artifact distributions in each study area. Each study area was organized into three hierarchical levels: survey strata (termed "zones"), which are subdivided into survey blocks (termed "sectors"), which contain patches (termed "subsectors" and delimited by small, usually terraced, agricultural fields) (Fig. 2). Survey zones were delineated within each study area to ensure that all major changes in topography

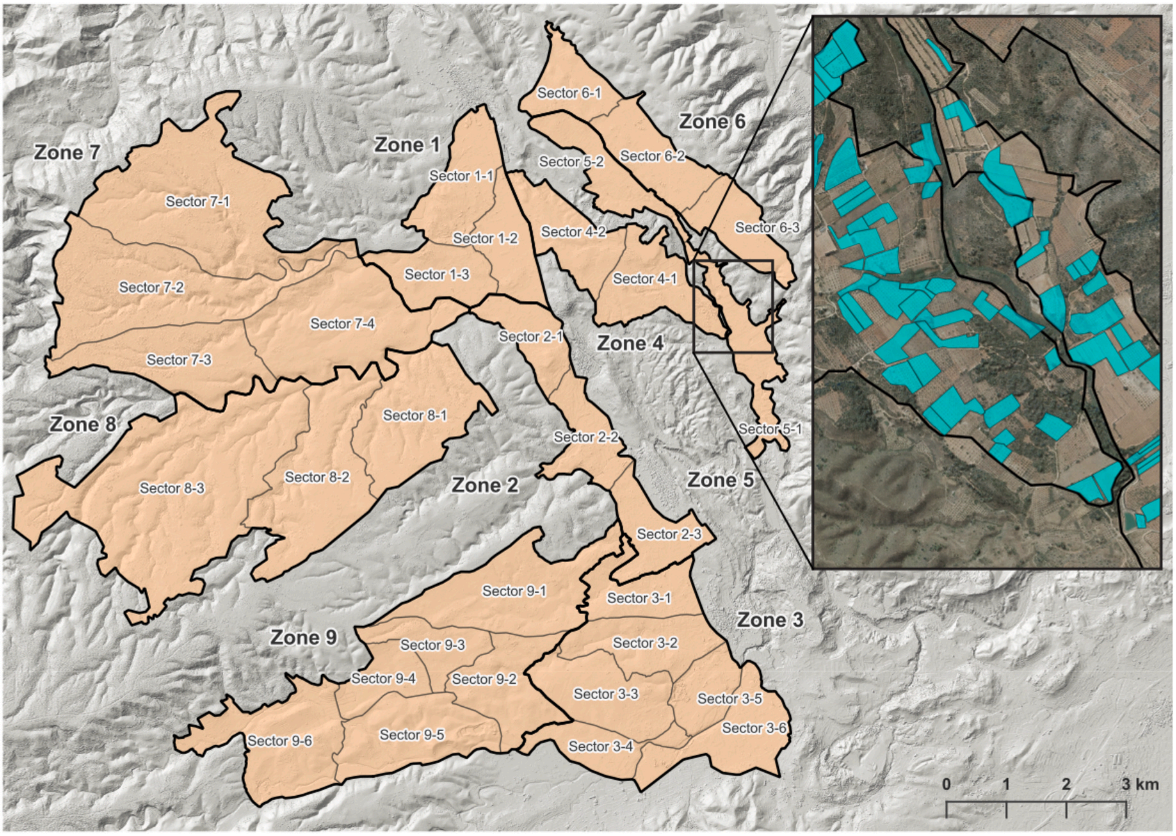


**Fig. 2.** Map of survey sampling strategy as implemented in the Navarrés study area. Map is overlaid on a relief map from a 5 m LiDAR-derived DEM. Inset shows an orthophoto (1 m resolution) of a section of two survey blocks (sectors) with surveyed patches in light blue. See text for details.

and vegetation communities were sampled. Each zone was subdivided into sectors of approximately equal sized areas that were randomly selected for data collection. Patches within each sector are defined by small agricultural fields that are ubiquitous across the region. Teams of three to six crew members surveyed the patches by walking transects in 10-m intervals and collected all prehistoric artifacts encountered. Based on materials identified in the stratified, random sample, the team also targeted a small number of patches outside of the original survey zones to provide additional data on prehistoric land use. Over 1500 patches, representing nearly 7 $km^2$ were intensively surveyed for artifact collection across the three study areas (Table 1).

### 3.1.2. Data collection

All data collection for each patch, regardless of whether artifacts were present, was conducted using GIS-enabled tablets, used to record spatial information, survey results, metadata, and photographs. Base maps were uploaded into each tablet for spatial reference and to identify patches sampled. Map layers included topography derived from 5 m LiDAR DEMs, orthophotos at 1 m resolution, and cadastral vector maps of all fields used as collection patches (Fig. 2). The Institut Cartogràfic Valencià (https://icv.gva.es/va/) provided all geospatial base maps. Each survey team in all study regions utilized the same digital survey form created in CartoMobile® 1.4.4 (CartoMobile, 2016), a GIS data entry and visualization application for iOS mobile devices. This insured consistency and replicability between all study regions and throughout the duration of the project. Additionally, each team recorded GPS tracks of survey transects within each collection unit to satisfy reporting requirements for the Valencian Directorate of Cultural Heritage and Museums, and to add an additional layer of redundancy in case spatial data recorded on the tablets was lost or corrupted (Barton et al., 2004a,b, 2016; Snitker et al., 2018).

The team recorded surface visibility for each patch surveyed on an ordinal scale of 'good', 'medium', or 'poor' to control for the effects of ground cover on the recovery of surface artifacts. Similar procedures were followed in earlier surveys (Barton et al., 2002). Results of the analysis of artifact recovery and surface visibility are shown in Fig. 3. Similar to the results of prior work, no statistically significant differences exist in artifact collection rates with different levels of surface visibility for reasons discussed in our earlier study (see also Bevan and Conolly, 2004).

## 3.2. Chronological "unmixing" of surface collections

While survey enables the collection of archaeological data at regional scales, several challenges must be overcome in order for the data to contribute to understanding the dynamics of past land use. Key

**Table 1**
Aggregate survey statistics for all three study areas.

| Study Area | Total Area (m2) | Total Surveyed (m2) | % Surveyed | Patches Surveyed | Patches with Artifacts |
|---|---|---|---|---|---|
| Hoya de Bunyols | 22,990,805 | 1,608,302 | 7.0% | 500 | 101 |
| Cocina Catadau | 187,242,988 | 1,014,306 | 0.5% | 214 | 86 |
| Canals de Navarrés | 82,040,888 | 4,107,582 | 5.0% | 770 | 199 |
| ***Total*** | ***292,274,681*** | ***6,823,157*** | ***2.3%*** | ***1501*** | ***386*** |

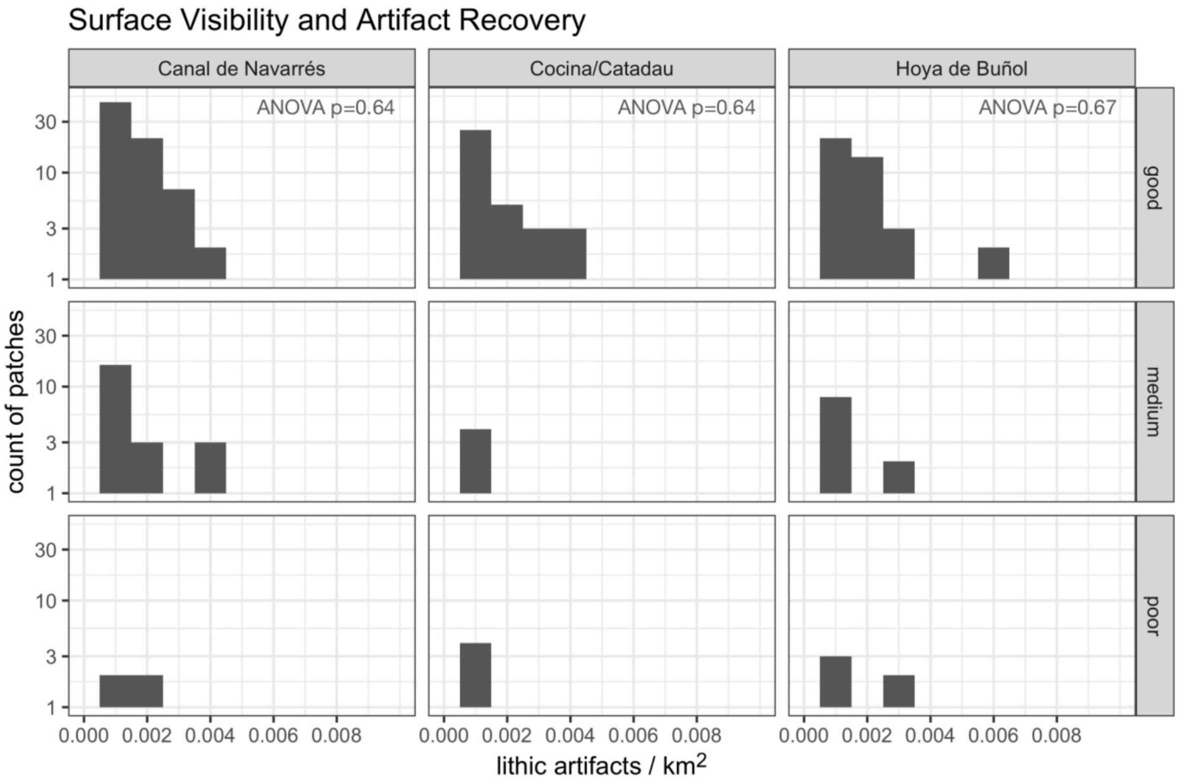


**Fig. 3.** Histograms of artifact recovery rate for three surface visibility levels in each study areas. Probabilities that the different visibility levels represent different recovery rates were tested using analysis of variance (p values are shown).

among these is chronological control, necessary to assess what parts of the landscape were occupied at what time(s), and how intensively. Estimating relative and numerical ages of artifacts from excavated contexts is rarely as straightforward as portrayed in textbooks. Surface collections have an additional issue of lacking stratigraphic context, so that artifacts used and discarded at different time periods can be mixed in palimpsests from multiple human occupations.

Authors on this paper have explored quantitative methods to 'unmix' palimpsest surface collections for over two decades to study changing patterns of prehistoric land use. All these methods depend on the fact that some artifact forms have bounded time spans during which they were commonly used. Initial efforts at unmixing used expert assessment of the likelihood that a surface collection derived from a period of time if the collection included some artifact forms and lacked others, representing a kind of "decision tree" (Barton et al., 1999, 2002; Barton et al., 2004b; Bernabeu Aubán et al.,1999b, Martínez Valle et al., 1989; Bernabeu Aubán et al., 2000). This assessment was made independently for each of a series of time intervals, for each surface collection. More recently, we have used expert decision tree assessment or dated collections from excavated contexts to calculate Bayesian prior probabilities that different artifact forms were discarded during different time periods. These were then applied to surface collections, using Bayes' equation, to calculate posterior probabilities that each collection dated to each of a series of past time periods (Fernández-López de Pablo and Barton, 2013; Snitker et al., 2018; Gironès Rofes et al., 2020).

Here, we use an ML protocol to statistically 'unmix' surface collections. In addition to being robustly reproducible, an important advantage of this approach is that it allows us to evaluate the reliability of the data-driven model prior to applying it to undated surface collections. The goal of ML is to create a model that can accurately predict the classification of cases in a dataset based on other variables. A common feature of ML approaches is the analytical workflow used regardless of the computational algorithm chosen for classification. An initial dataset is acquired in which the classification of cases is known (or estimated based on clustering or other grouping procedure). This dataset is divided into a training set and a test set, and a predictive analytical model is created from the training set. The model can be derived from regression, Bayesian estimate (e.g., prior probabilities), decision tree, or a more exotic algorithm. The model is then applied to the test set and the predicted classifications are compared with the known classifications to evaluate the accuracy of the model. In a process called cross-validation, the known data can be iteratively divided into different training and test sets to make use of all the data and create a more accurate predictive model. Larger training and test sets can produce more reliable and often more accurate models (though dataset size alone is not a guarantee of a better model). It is also good to avoid algorithms that 'tune' a model so finely to accurately predict the test set classification that they are much less accurate on different data (i.e., 'overfitting'). More detailed discussions of ML for archaeological classification can be found in Klassen et al. (2018), Yaworsky et al. (2020), and Pawlowicz and Downum (2021).

As in previous work, our goal here is to estimate the independent probabilities that a collection of artifacts from the surface of a landscape patch was deposited during each of several time periods. For the training/test data, we used 129 artifact assemblages recovered from radiocarbon-dated, excavated contexts across the Comunitat Valenciana. Importantly, these dated assemblages contained artifact forms that matched those that we collected during survey. We limited the artifact forms to 15 types of lithics, excluding unretouched flakes that occur in all time periods (Table 2). We also excluded ceramics, groundstone, and other artifact forms because of their rarity in our surface collections. However, it is not necessary to focus on any single material type for this type of analysis and multiple artifact materials could be included in other analyses if found consistently in surface collections. After some experimentation, we grouped the dated training/test set assemblages into six time periods that could be distinguished reliably: Middle Paleolithic, Upper Paleolithic, Epipaleolithic, Geometric Mesolithic, Early Neolithic, and Late Neolithic (Table 3).

**Table 2**
Lithic forms used for chronological unmixing.

| Type Code | Type Name | Description | Used in Model |
|---|---|---|---|
| undiag. lithics | undiagnostic lithics | undifferentiated lithics, including: unretouched flakes, chunks/debris, irregularly or minimally retouched flakes, and unprepared flake cores | no |
| flake.core | flake cores | prepared flake cores (e.g., levallois and discoidal cores) | yes |
| MP.tools | Middle Paleolithic retouched artifacts | Large bifaces (“handaxes”), Mousterian points, and side scrapers (all forms) | yes |
| notch.dent | notches & denticulates | single notches & series of notches (denticulates) | yes |
| blade.tech | prismatic blade/ bladelet technology | unretouched blades/bladelets, prismatic blade cores, & core preparation/rejuvenation flakes | yes |
| burins | burins | burins (all forms) | yes |
| end.scraper | end scrapers | end scrapers (all forms) | yes |
| ret.blade | retouched blades | marginally retouched blades | yes |
| invret. blade | invasively retouched blades | invasively retouched blades | yes |
| microburin | microburins | microburins | yes |
| backed | backed pieces | backed bladelets, backed points, and backed small flakes | yes |
| trapeze | trapezes | trapeze microliths | yes |
| triangle | triangles | triangle microliths | yes |
| truncation | truncations | truncated blades and bladelets | yes |
| bifacial.pt | bifacial points | bifacial projectile points (all forms) | yes |
| dent.sickle | denticulated sickle blades | denticulated sickle blades (usually with silica sheen) | yes |

**Table 3**
Chronological divisions used in analysis prehistoric land use.

| Period | Time Range (years BP) |
|---|---|
| Late Neolithic (includes Chalcolithic) | 5000–3800 |
| Early Neolithic (includes Middle Neolithic) | 7500–5000 |
| Geometric Mesolithic | 11,000–7500 |
| Epipaleolithic | 15,000–11,000 |
| Upper Paleolithic | 40,000–15,000 |
| Middle Paleolithic | 120,000–40,000 |

We selected a Random Forest (RF) ML algorithm to classify assemblages into the six time periods. RF is a *bagged* (bootstrap aggregated) decision tree algorithm (Breiman, 2001). Archaeologists commonly use decision tree approaches subjectively to estimate the age of a collection based on the artifact forms absent or present and in what quantities, as we did in prior approaches to dating surface collections. An RF algorithm builds many decision trees from random selections of cases and variables in the data to predict the classification of a training set. The trees are then “bagged” or combined by averaging the values of continuous variables or taking the most common occurrence value of categorical variables from each tree. This protocol reduces the chance of overfitting and provides a model with low variance (i.e., robust to additions or deletions in the training set) (Breiman, 2001; Yaworsky et al., 2020). RF, like other machine learning algorithms, has begun to be applied in archaeology only recently but has considerable promise for robust and reproducible classifications (see, for example, Burke et al., 2018; Castiello and Tonini, 2021; Elliot et al., 2021; Garcia Molsosa et al., 2021). To our knowledge, this is the first application of RF to chronological unmixing. In addition to RF, we explored several other commonly used ML algorithms, including logistical regression, naive Baysian, and boosted decision trees. RF produced the highest predictive accuracy for chronological unmixing, with an overall accuracy of 80%. Table 4 and Fig. 4 show the performance of the RF model with cross-validation. RF models described here were created using the Tidymodels package for R (Kuhn and Wickham, 2020). Details of the ML implementation used here, and the complete R code needed to replicate it, are published and openly accessible on Zenodo at: https://doi.org/10.5281/zenodo.8096982 (Barton et al., 2023).

The RF model, trained on dated assemblages, was then applied to undated surface collections to provide independent probabilistic estimates of occupation in each of the patches during each of the six time periods. Lithic artifacts were collected from 386 patches, out of a total of 1501 surveyed (Table 1). Collections from some of the patches had evidence of past human presence in the form of unretouched flakes or other knapping debris but lacked any of the temporally sensitive lithic forms used in the model. We treated such patches as having an equally low (but non-zero) probability that they were occupied in any of the six time periods. For these survey units, we calculated the cutoff for the lower 10th percentile of probabilities for all time periods in all the other patches that had forms used in the random forest model and assigned that value to all time periods for units with artifacts that were not chronologically sensitive.

### 3.3. Prehistoric charcoal analysis

As a complement to the archaeological survey, sedimentary charcoal was sampled from exposed, vertical banks of intermittent watercourses within the Navarrés study area. Sediments collected from these watercourses were transported and deposited in these locations through a variety of geomorphic processes, including channel flow, sheet wash, and other fluvial processes. Charcoal contained within these sediments provide a cumulative record of both fire and vegetation within the watershed upstream and thus a landscape-scale paleo-fire record that can be compared to the archaeological survey results (Roos et al., 2010; Snitker, 2019). While similar alluvial features and exposed sediments exist within all the study areas highlighted in this regional study, the Navarrés study area was selected for intensive charcoal sampling due to its relatively closed basin, meaning sediments from adjacent valleys are

**Table 4**
Confusion matrix and accuracy statistics for random forest model with cross-validation used for chronological unmixing.

| Predicted Age (rows) | True Age (columns) | | | | | |
|---|---|---|---|---|---|---|
| | *Middle Paleolithic* | *Upper Paleolithic* | *Epi-paleolithic* | *Geometric Mesolithic* | *Early Neolithic* | *Late Neolithic* |
| *Middle Paleolithic* | 50 | 0 | 0 | 0 | 1 | 0 |
| *Upper Paleolithic* | 0 | 11 | 0 | 0 | 4 | 0 |
| *Epipaleolithic* | 1 | 4 | 1 | 0 | 0 | 0 |
| *Mesolithic* | 0 | 2 | 1 | 11 | 5 | 0 |
| *Early Neolithic* | 0 | 1 | 0 | 2 | 26 | 0 |
| *Late Neolithic* | 0 | 0 | 0 | 0 | 4 | 5 |

Accuracy: 0.8062.
95% CI: (0.7274, 0.8705).
No Information Rate: 0.3953.
P-Value [Acc > NIR]: <2.2e-16.
Kappa: 0.7379.

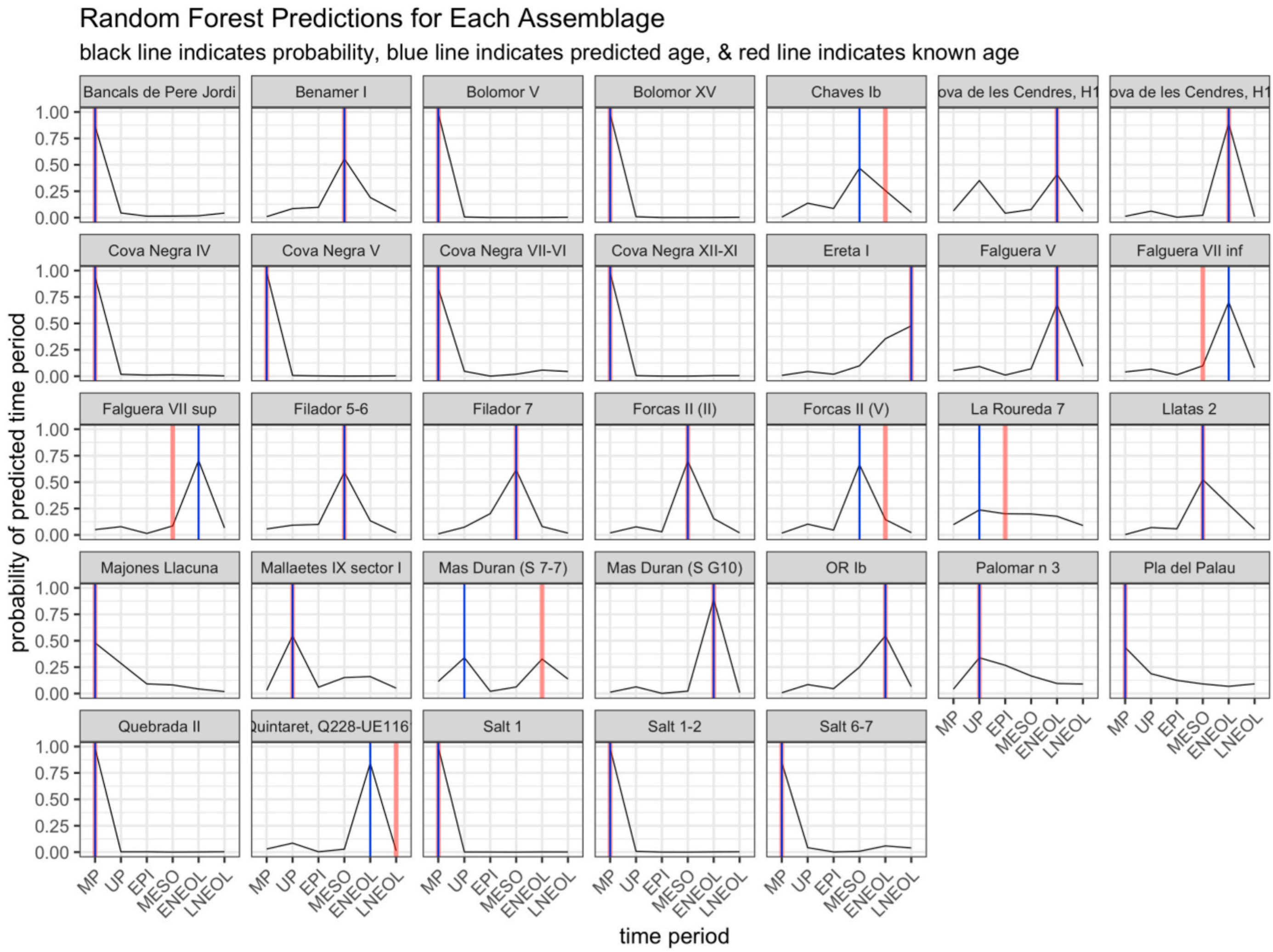


**Fig. 4.** Results of Random Forest model, generated from a randomly selected 75% subsample of dated excavated assemblages (training set) applied to the remaining 25% subsample of dated assemblages (test set). Each graph is a dated archaeological assemblage. The black line graph represents the probability that the assemblage dates to each time period; the most probable age predicted by the Random Forest model is indicated by the blue vertical line; the known age is indicated by the red vertical line. See text for more details.

not significantly contributing to the deposition within the valley. Furthermore, Carrión and Van Geel (1999) cored peat deposits (Navarrés-3) within the valley floor of the Valle del Canal de Navarrés and reconstructed vegetation change and fire activity, which provides an excellent comparison to the archaeological and sedimentary charcoal data collected in this study.

Sampling occurred in four watersheds with small catchment areas (<40 sq. km) in proximity to areas surveyed for archaeological material to the core analyzed by Carrión and Van Geel (1999). A sediment column from each watershed was sampled in continuous, 5 cm levels where possible (Snitker, 2019). Sediment column locations are shown in Fig. 5. Samples were processed for sedimentary charcoal analysis by deflocculating sediments and mildly oxidating organic materials to visually isolate charcoal fragments (Roos, 2008; Snitker, 2020; Whitlock and Anderson, 2003). Charcoal fragments larger than 250 μm were quantified using a digital microscope at 50*x* magnification and CharTool, a suite of open-access charcoal and sedimentological analysis tools for ImageJ (Snitker, 2020). Charcoal counts for each watershed were converted to charcoal accumulation rates (CHAR, frags $cm^{-2}$ $yr^{-1}$) using age-depth models derived from AMS-C14 dated positions within each sediment column. Details regarding the materials selected for AMS-C14 dating, calibration of each date, and the construction of each age-depth model are described in Snitker (2019).

## 4. Results

### 4.1. Occupational Ubiquity

The probability that the artifacts found in a patch date to a chronological period is referred to as Occupational Ubiquity (Barton et al., 2004a; Barton et al., 2004b). Occupational Ubiquity is an estimate of the likelihood that people were present in that landscape patch during a given time interval. Fig. 6a shows Occupational Ubiquity for two collection units in the Navarrés study area. In patch Navarrés-2-7-400173, there is a low probability of occupation during the Paleolithic (<0.04), a higher probability of occupation during the Geometric Mesolithic (0.15), a high probability of occupation during the Early Neolithic (0.71), and a low probability of occupation during the Late Neolithic (0.06). Occupational Ubiquity for patch Navarrés-5-1-100181 is quite different. There is a moderate probability of occupation during the Middle Paleolithic (0.13), a high probability of occupation during the Upper Paleolithic (0.38), a low probability of occupation during the Epipaleolithic (though higher than in the other unit at 0.07 vs. 0.01), a moderate probability of Mesolithic and Early Neolithic occupation (0.17 and 0.19 respectively), and a low probability of Late Neolithic occupation (0.05). Note also that while Occupational Ubiquity is unimodal for Navarrés-2-7-400173, it is multi-modal for

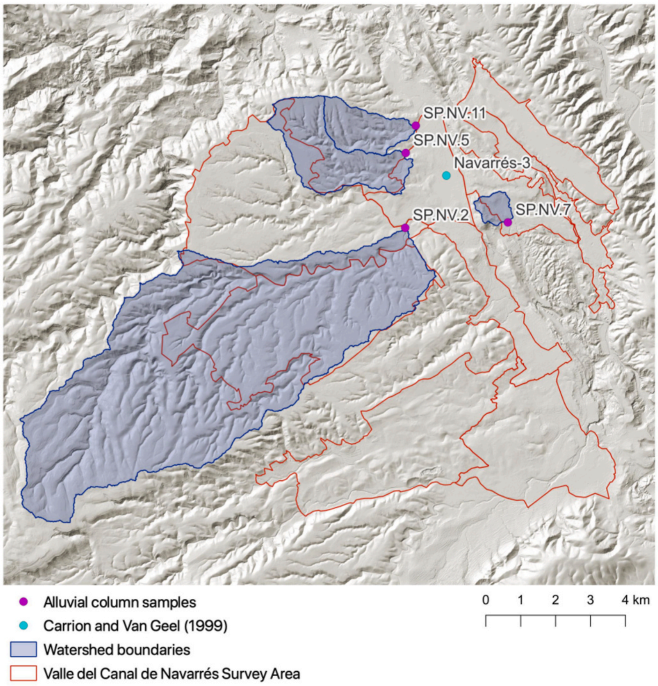


**Fig. 5.** Location of sediment columns and cores extracted for paleocharcoal analysis. Magenta dots are sediment columns collected during the surveys described in this paper and blue shading are the watersheds that drain through outlets where the columns are located. Turquoise dot is the location of core described by Carrión and Van Geel (1999). See text for more details on data collection and analysis.

Navarres-5-1-100181, providing a means to estimate and quantitatively express the potential for palimpsest surface collections and multiple occupations of a landscape patch.

Because of the survey sampling design, we can treat the surveyed patches as a representative sample of spatially continuous Occupational Ubiquity in each valley. This allows us to use spatial interpolation methods to estimate Occupational Ubiquity across entire study areas, whether they were inspected or not. Spline surfaces of Occupational Ubiquity were generated through bilinear spline interpolation for each study area, using *v.surf.bspline* in GRASS GIS (version 7.4.4). A 300 m spline step and a Tykhonov regularization parameter of 0.01. Contour lines were added to emphasize changes in Occupational Ubiquity at 0.05 value intervals. Additional details of the interpolation commands to replicate this analysis are published and openly accessible on Zenodo at: https://doi.org/10.5281/zenodo.8096982 (Barton et al., 2023).

The result is shown in Fig. 7 which displays the changing patterns of human presence in the three valleys through time. All three valleys display similar, though not identical, patterns of Occupational Ubiquity, indicating a similar human presence across all three regions. There are several notable characteristics that will be discussed more below. Humans are present throughout the Upper Pleistocene (and possibly earlier) as indicated by Middle and Upper Paleolithic ubiquity values in all three valleys. However, human presence almost completely disappears at the Pleistocene/Holocene transition, with a lack of appreciable ubiquity for the Epipaleolithic. Ubiquity begins to grow in the Mesolithic, increasing significantly by the Early Neolithic, and then falls significantly in the Late Neolithic. Finally, areas of each valley with the highest probability of occupation–implying that they were more attractive for human use–were spatially stable through all periods examined.

### 4.2. Land use intensity

Knowing when and where people were present is an important component of land use research but examining the intensity of land use is important as well. Land use intensity involves a combination of characteristics like population density, length of occupation, and types of activities performed. In general, we can make a reasonable assumption that the quantity of artifacts found in a landscape patch is proportional in some way to the intensity of land use (i.e., the number of people occupying a patch and/or the length of time they occupy it)–with some caveats. Combining artifacts from different technologies could bias results. For example, societies that produce both lithics and ceramics might discard more artifacts than societies lacking ceramics, even with no differences in land use intensity. Likewise, complex societies with specialist production or mass production of material culture may discard more artifacts than less complex societies with household production even with similar land use intensities. For the valleys and time periods discussed here (Paleolithic - Late Neolithic), most material culture was probably made by the individuals who used it. Additionally, we use an estimated accumulation rate of only lithic artifacts as a proxy for Land Use Intensity. While different activities also could affect the rate at which lithics accumulated, a series of empirical, theoretical, and modeling studies shows that the length of time a patch is occupied and/or the number of people occupying it strongly conditions the rate of lithic artifact accumulation (e.g., Parry and Kelly, 1987; Riel-Salvatore and Barton, 2004; Barton et al., 2011; Barton and Riel-Salvatore, 2014).

Of course, post-depositional processes also can alter apparent artifact densities, and hence estimates of accumulation rates. In a prior study, estimates of the impacts of erosion/deposition on artifact densities were made for survey in a different valley than those discussed here (Barton et al., 2002). However, the approach used in the earlier study was not possible with the surface characteristics of the three valleys discussed here. Recent land use also has the potential to alter the distribution of surface artifacts. Plowing, especially, will disperse artifact clusters, with the potential to reduce apparent densities. Yet, experiments in plowed Mediterranean landscapes indicate that such dispersal reaches an equilibrium that should have minimal effect on density estimates at the scale of landscape patches used here (Ammerman, 1985). Crops grown and field fallowing can affect surface visibility and, hence, apparent artifact densities. As described in section 3.1.2, however, we recorded artifact visibility as affected by varying agricultural land use (e.g., different crops and whether or not a patch was fallowed or recently cultivated). This had no significant impact on estimates of lithic artifact accumulations. Overall, then, we can be reasonably confident that surface lithic artifact densities and estimated accumulation rates described below represent a reliable proxy for land use intensity under the natural and social conditions (past and present) of the three study areas.

Because we collected artifacts within agricultural fields for which we have georeferenced digital polygons, we can transform the artifact counts in each survey patch to densities per unit area, values that are comparable across different sized units. We use the Occupational Ubiquity values to weight these artifact densities. For example, in a patch in which the probability of occupation during the Early Neolithic is near 1.0 and the probabilities of occupation during other periods is near 0, it is likely that nearly all the artifacts collected are of Early Neolithic age. Likewise, if the probability of occupation during the Upper Paleolithic is near 0, it is likely that few, if any, artifacts found in that patch date to that period. Finally, different periods have different durations. A collection of 50 artifacts deposited during the approximately 250 centuries of the Upper Paleolithic represents a much lower rate of accumulation than the same 50 artifacts deposited during the roughly 30 centuries of the Early Neolithic. Hence, we calculate an index of Land Use Intensity with the following simple equation:

$$Land\ Use\ Intensity = \frac{artifact\ density \times Occupational\ Ubiquity}{period\ duration}$$

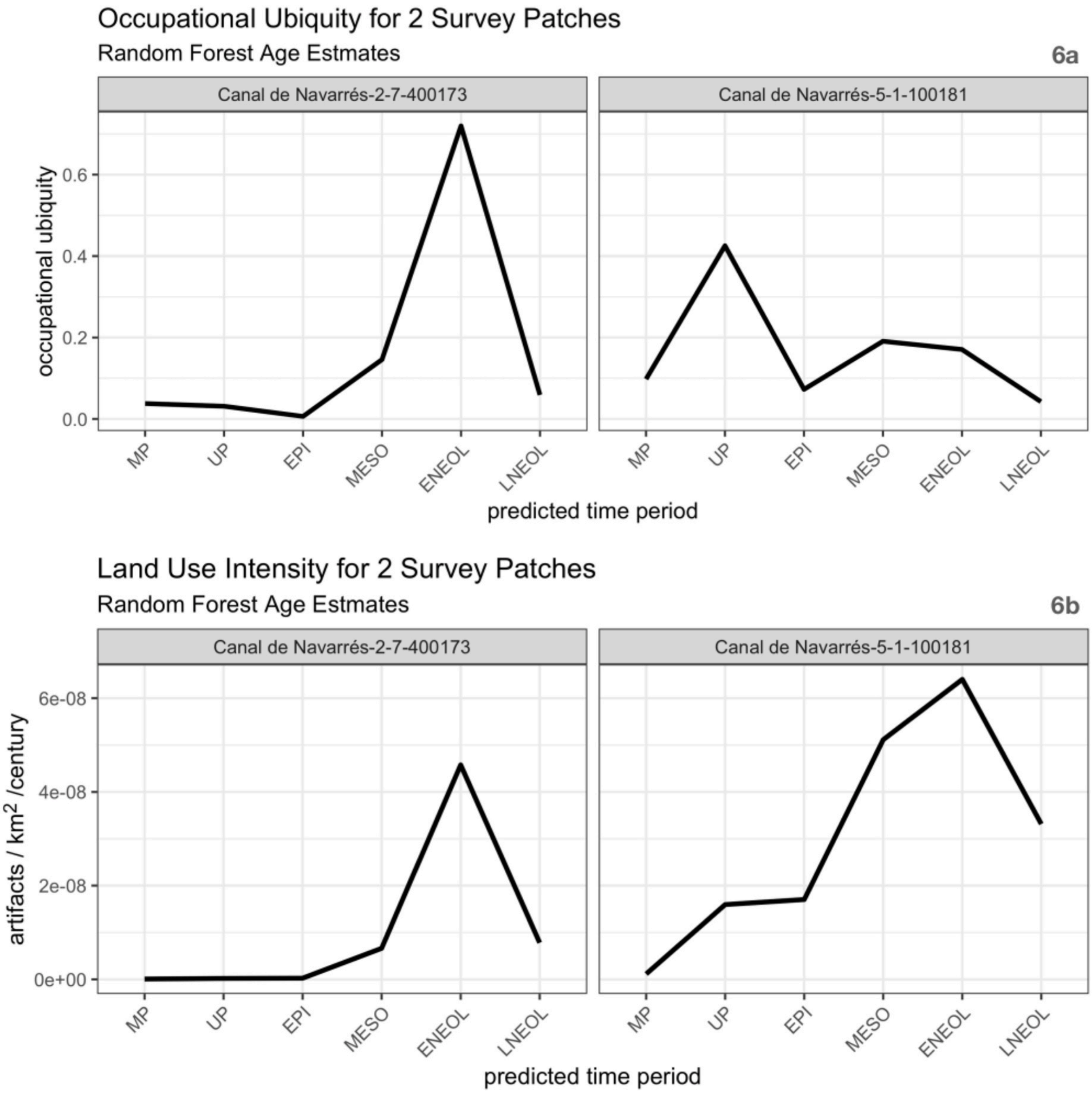


**Fig. 6.** Example Occupational Ubiquity (probability of human presence) and Land Use Intensity (artifact accumulation rates) curves calculated by applying Random Forest model to assemblage from two patches in the Navarrés study area.

The results can be seen in Fig. 6b displaying Land Use Intensity through time for the same example survey patches for which Occupational Ubiquity is discussed above. While the overall pattern of Land Use Intensity is very similar to that of Occupational Ubiquity for patch Navarrés-2-7-400173, these two metrics differ significantly for patch Navarrés-5-1-100181. Despite moderate to high ubiquity for the Paleolithic, artifacts in this patch Navarrés-5-1-100181 that dated to these periods could have accumulated over long time spans, making their intensity values low. Conversely, Mesolithic and Early Neolithic artifacts accumulated over much shorter periods, resulting in higher Land Use Intensity values, despite moderate ubiquity values for these periods. As was the case for Occupational Ubiquity, we calculated Land Use Intensity values for all survey units with artifact collections and then interpolated from surveyed patches to the entire survey region within each valley using the same bilinear interpolation methods and parameters mentioned previously. The results are shown in Fig. 8.

Despite high ubiquity values, Paleolithic land use was low intensity, as would be expected for mobile hunter-gatherers. Land Use Intensity increases somewhat in the Geometric Mesolithic, particularly in the Navarrés study area. Paralleling the ubiquity results, Land Use Intensity is highest in the Early Neolithic and falls off again in the Late Neolithic, though less significantly for the Cocina-Catadau study area than the other two.

### 4.3. Holocene fire activity

Charcoal accumulation rates from each of the Navarrés study area watersheds (Fig. 9) demonstrate patterns that match well with the rates observed by Carrión and Van Geel (1999). Prior to the Early Neolithic, charcoal accumulation rates are minimal, suggesting that landscape fires were regional and rare events within the study area. However, the beginning of the Early Neolithic marks a significant change in fire activity, with peaks in charcoal accumulation observed in Navarrés-3, as well as in the watersheds with data that extend to that period. The later portion of the Early Neolithic is characterized by a decline in charcoal accumulation. However, it is clear from Navarrés-3, SP.NV.11, SP.NV.7, and SP.NV.5 that local, landscape fire was still a regular occurrence in the Navarrés study area during this time. The Late Neolithic again sees increased charcoal accumulation in Navarrés-3, SP.NV.11, SP.NV.7, and SP.NV.5, although peaks in charcoal do not co-occur across each

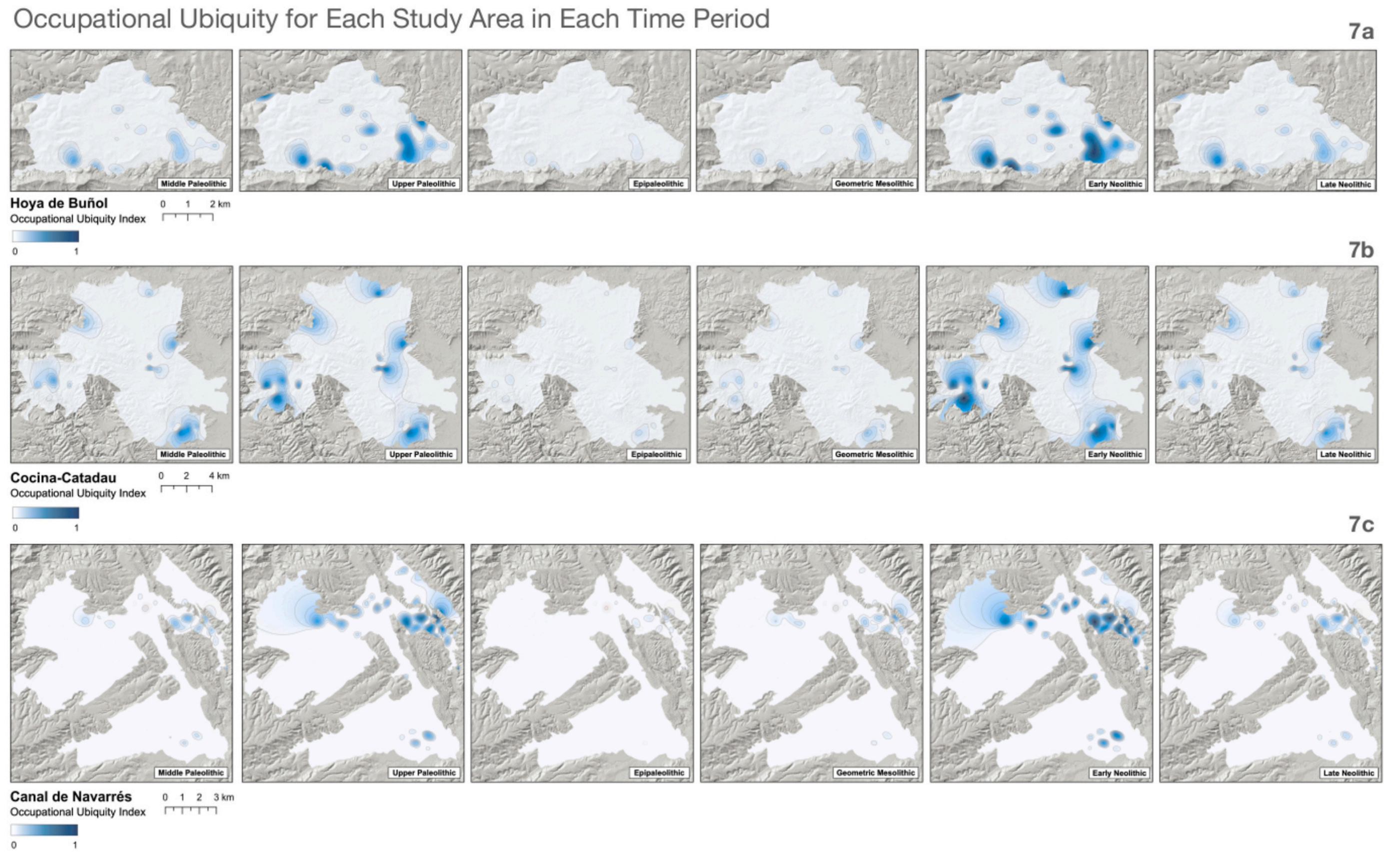


**Fig. 7.** Spline-based interpolation of Occupational Ubiquity for each time period for patches in each study area. Base maps are derived from 5 m DEMs in each study area.

watershed and the Navarrés-3 core. This suggests some spatial and temporal heterogeneity in local fire activity during the Late Neolithic. Finally, charcoal accumulation decreases following the Late Neolithic period in Navarrés-3, SP.NV.11, SP.NV.7, and SP.NV.5 and increases in SP.NV.2. This pattern suggests that local fire activity may have shifted away from the valley and adjacent hillslopes to more distant uplands after the Late Neolithic.

Alone, these patterns of charcoal abundance and accumulation do not provide direct evidence of human actions, such as land clearance, intentional burning, or other cultural burning practices. Nonetheless, the synchronization of increased charcoal accumulation and archaeological evidence for land use does suggest anthropogenic ignitions likely contributed to the frequency and spatial distribution of fire within the Navarrés study area throughout the Holocene. This is most evident during the Early and Late Neolithic, when the northern portions of the Navarrés study area exhibit high Land Use Intensities in proximity to watersheds with increased charcoal abundance.

## 5. Discussion

The methods outlined above allow us to contribute to the broader discussion on European Paleolithic and Neolithic demographic trends as well as to systematically evaluate the distribution and intensity of prehistoric land use at a regional scale.

During the Middle Paleolithic and Upper Paleolithic, the Occupational Ubiquity map developed for our study for each valley indicates low but steady human presence (or low density) in all valleys with a marked decrease of human presence during the Epipaleolithic, across the Pleistocene/Holocene boundary. This lack of human presence can be seen clearly in the maps of Occupational Ubiquity (Fig. 7) as well as a graph of Aggregate Occupational Ubiquity in each valley over time (Fig. 10a).

Fernández-López de Pablo et al. (2019) conducted an analysis of the radiocarbon record of Iberia to test different models of demographic growth during the Last Glacial-Interglacial transition. Using a summed probability density (SPD) curve based on the radiocarbon record, the authors document a regime of exponential population increase during the Late Glacial warming period (ca. 16.6–12.9 ka), followed by population contraction during the Younger Dryas and the first half of the Early Holocene (12.9–10.2 ka). We also generated an SPD curve from over 2000 14C from archaeological sites spanning the Upper Paleolithic through Late Neolithic/Chalcolithic in eastern and southern Iberia (Fig. 10). This SPD curve matches the land use data, as well as demographic patterns reported by Fernández-López de Pablo et al. (2019). The SPD curve indicates a low, but stable population density for this region in Iberia from the early Upper Paleolithic until the Late Pleistocene, with a significant decrease on either side of the Pleistocene/Holocene boundary.

Paleogenetic evidence indicates that the temperate areas of Western Europe like Northern Iberia served as refugia for human populations during the Last Glacial Maximum (Pala et al., 2012). The population contraction during the Late Pleistocene might be attributable to the dramatic climatic fluctuations of the terminal Pleistocene, with the rapid and intense warming of the Bølling-Allerød followed by the equally rapid and intense Younger Dryas cold and dry interval (Carlson, 2013; Barton et al., 2018; Fernández-López de Pablo et al., 2019), although archaeologists still debate the nature of the relationship between global climatic events and human demographic trends in Iberia and Europe generally (Shennan et al., 2013; Bernabeu Aubán et al., 2016; Fernández-López de Pablo et al., 2019; McClure et al., 2009). Overall, the demographic trends indicated by the broader geographic analysis conducted by Fernández-López de Pablo et al. (2019) and our analysis

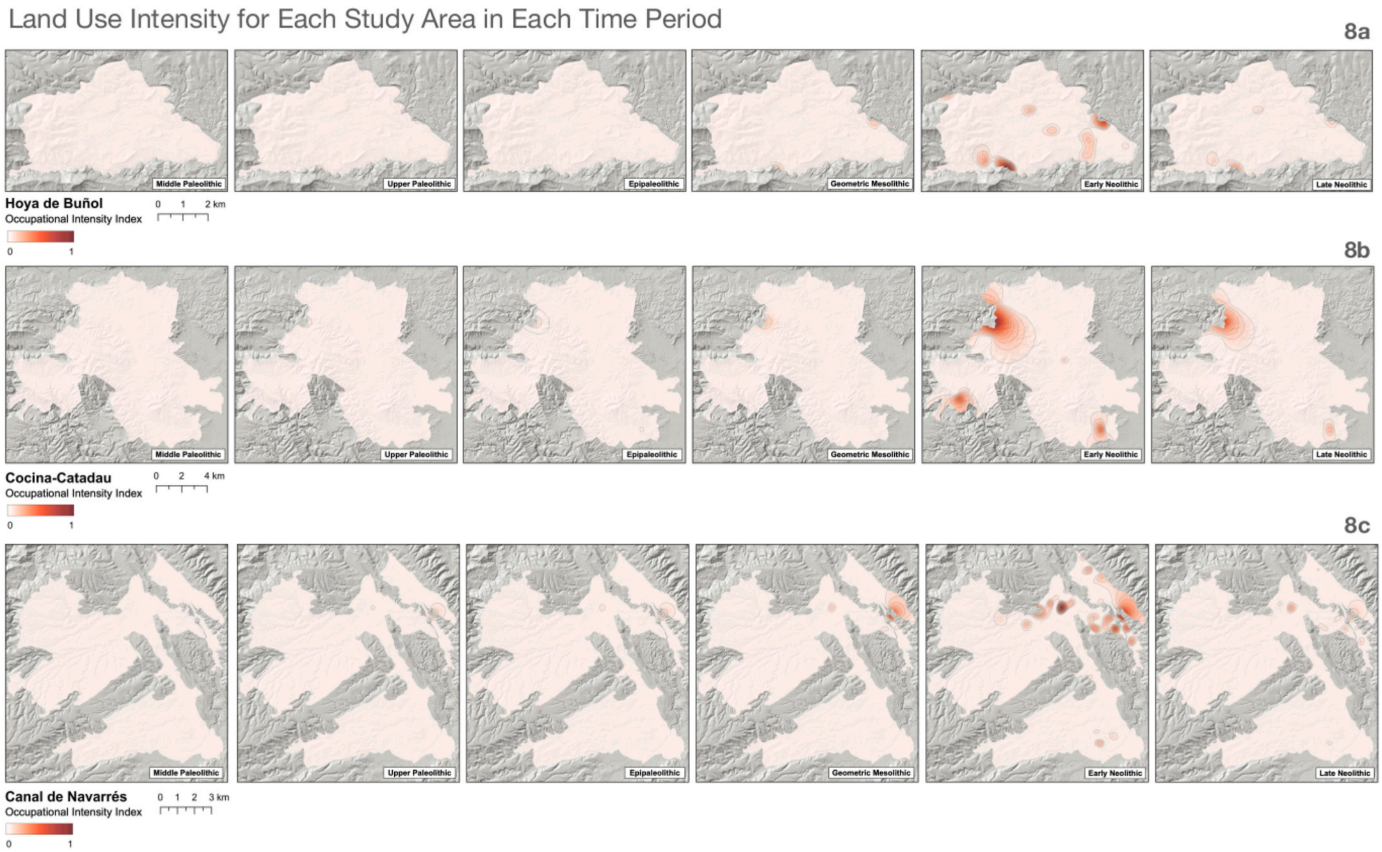


**Fig. 8.** Spline-based interpolation of Land Use Intensity for each time period for patches in each study area. Base maps are derived from 5 m DEMs in each study area.

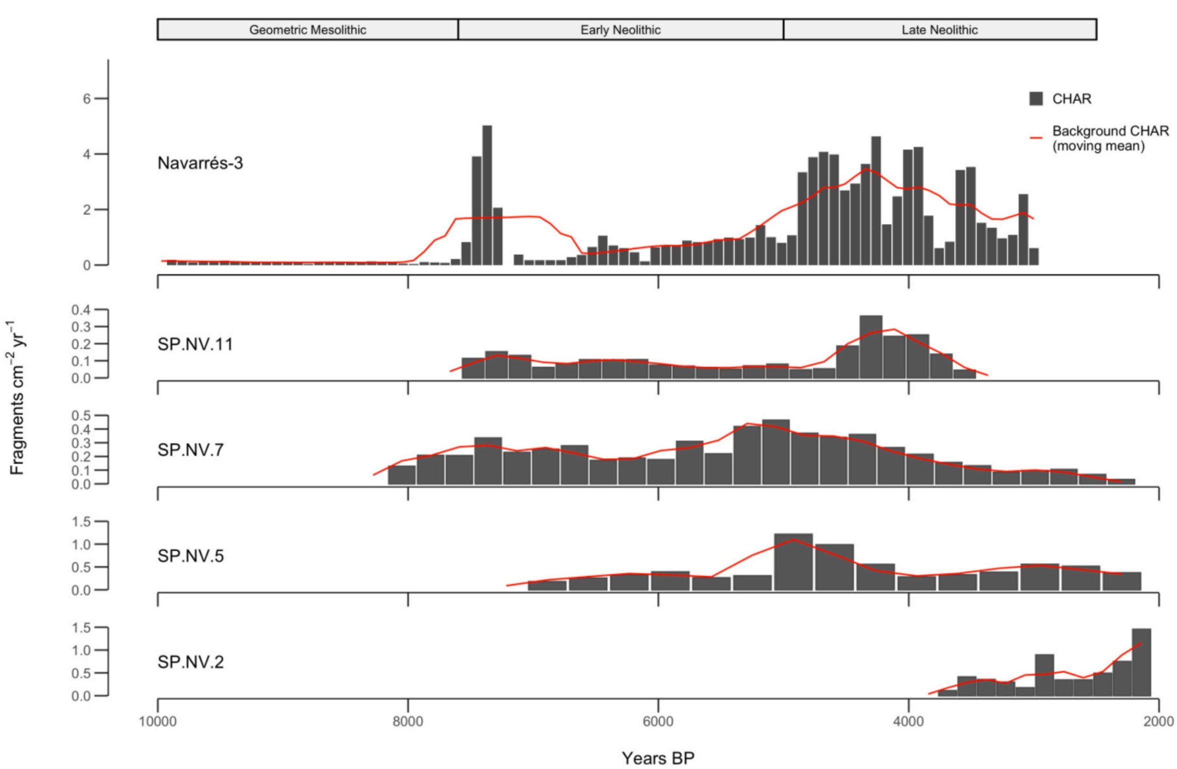


**Fig. 9.** Paleocharcoal analysis results from Navarrés study area. Top graph is from core described by Carrión and Van Geel (1999). Bottom four graphs are from data collected by Snitker (2018, 2019, 2020).

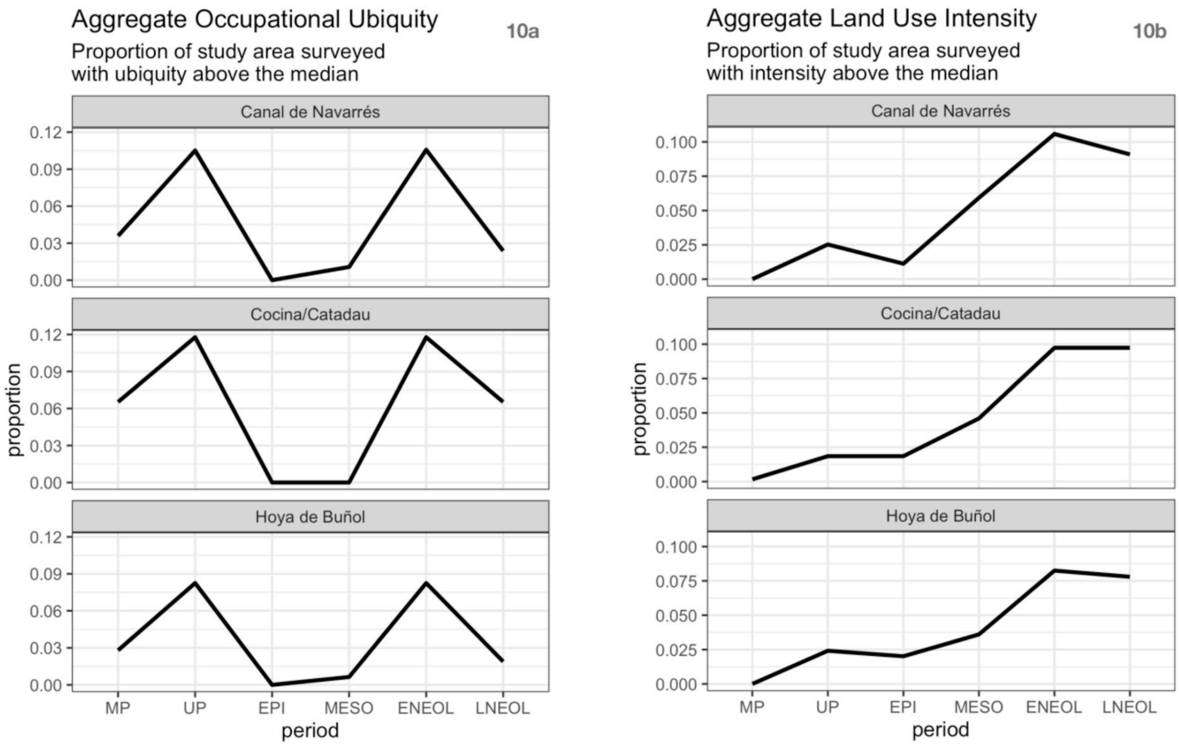


**Fig. 10.** Aggregate Occupational Ubiquity and Land Use Intensity. Proportion of total area surveyed in each study area occupied by patches with ubiquity and intensity values above the median for all three study areas.

limited to the southern and eastern regions for Iberia correspond well with each other.

The overall low intensity of human occupation throughout the Pleistocene can be seen in the Land Use Intensity map (Fig. 8), as well as in the aggregate Land Use Intensity map (Fig. 10b). As discussed earlier, we can see that while the overall pattern of Land Use Intensity is similar to that of Occupational Ubiquity, on a patch-by-patch comparison, these two metrics can differ. Thus, patches high in Occupational Ubiquity but low in Land Use Intensity for the Paleolithic, may represent the slow accumulation of artifacts over a long time span. Fig. 8 shows that Land Use Intensity slowly increased through the Epipaleolithic and the Geometric Mesolithic in limited areas of each valley, but this increase appears incremental compared to the Land Use Intensity 'boom' that characterizes the Early Neolithic.

The period following the Geometric Mesolithic marks the transition to agriculture. Researchers in European archaeology have noted several pan-European demographic trends that occur during this transition to the Neolithic that correspond with the results of this research. Agriculture began its spread throughout Southeast Europe around 8500 years ago reaching Iberia around 7650 cal BP, introducing changes in food production and consumption, anthropogenic landscapes and residential areas, domestic strategies, and mortuary practices but also increases in population growth rates and densities (Bocquet-Appel, 2008, 2011; Greenfield, 2010; Fuchs et al., 2019). Bocquet-Appel (2008) proposed the term Neolithic Demographic Transition (NDT) to describe the population increase typically seen after the arrival of agriculture to Europe.

In recent years, researchers have refined research on Neolithic demographic changes using radiocarbon dates and SPD curves for various regions in Europe, noting that a population 'boom' pattern was not uniform across Europe, nor did the arrival of agriculture produce steady population growth as previously assumed (Shennan et al., 2013; Balsera et al., 2015; Downey et al., 2014; Fyfe et al., 2019; García Puchol et al., 2021). Based on SPD curves for various regions in Europe, Shennan et al. (2013), Balsera et al. (2015), Downey et al. (2014), Fyfe et al. (2019), and Fernández-López de Pablo et al. (2019) all note data anomalies that follow the introduction of a mixed farming economy, namely a population 'boom' followed by a 'bust.' Shennan et al. (2013), who examined radiocarbon probability curves from 10,000 cal BP forward as demographic proxies for all of Western Europe except Iberia and Italy, found a boom-bust population pattern for the Neolithic characterizing Western Europe in general.

This boom-bust trend has been noted in SPD analyses of the Iberian peninsula by Balsera et al. (2015), Bernabeu Aubán et al. (2016), Drake et al. (2017), and Fyfe et al. (2019). Results generated specifically for Iberia by Balsera et al. (2015) support the hypothesis that the introduction of agriculture to the Iberian peninsula caused an increase in population density by 5300 cal BC followed by a reduction by 5150 cal BC. Other authors note differences in Neolithization regionally within Iberia. Drake et al. (2017), using summed calibrated date analysis for the Iberian Peninsula, found that Neolithic population expansion occurred earliest along the Mediterranean perimeter of the peninsula with non-synchronous expansion across inland regions. Furthermore, results from Fyfe et al. (2019) indicate that while characteristic boom-and-bust cycles are apparent in their study of SPD curves from Iberia, no clear synchronism exists between northeast and southeast Spain other than the rise of Neolithic farming. Our spatial analysis of land use also indicates a population boom-bust pattern with the most ubiquitous and intensive occupation of all three study areas occurring during the Early (and Middle) Neolithic (Figs. 7, 8 and 10). This is followed by a significant decline in both occupational and land use measures during the Late Neolithic/Chalcolithic. Our study's SPD curve for Southern and Eastern Iberia (Fig. 11), likewise shows a population boom occurring at about 7000 cal BP, after the arrival of the Neolithic in Iberia, followed by a rapid decline.

Several researchers have proffered explanations for the population boom-bust pattern seen across Europe and regionally after the arrival of agriculture (McClure et al., 2009; Shennan et al., 2013; Downey et al., 2014; Balsera et al., 2015; Bernabeu Aubán et al., 2016). Shennan et al. (2013) tested for any correlative significance between major, global climatic events and the population boom-bust episodes revealed by their

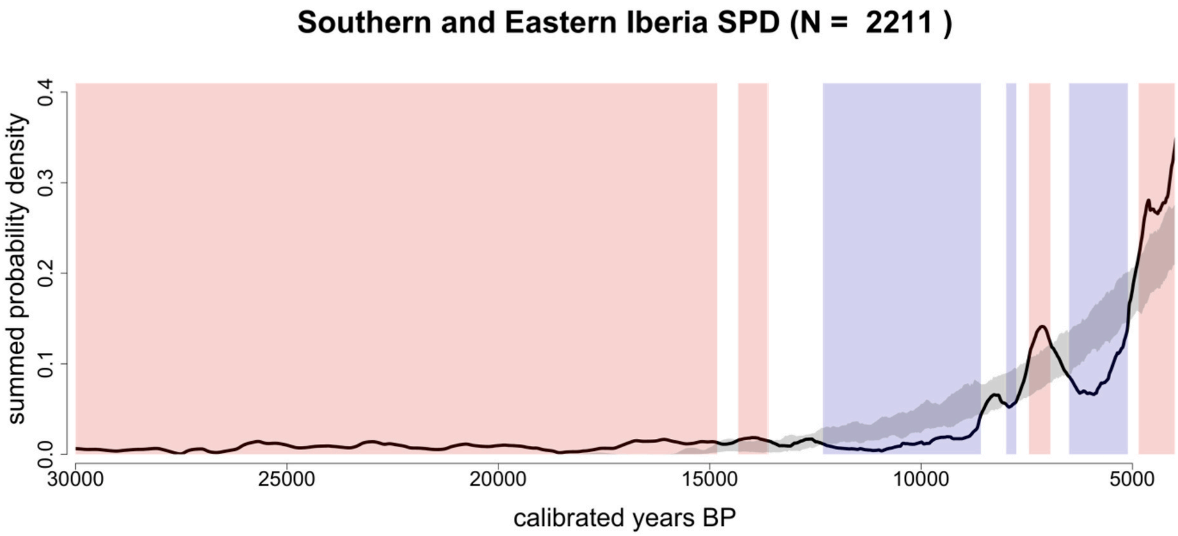


**Fig. 11.** Summed probability distribution (SPD) curve (black line) for Pleistocene and Holocene radiocarbon dates from eastern and southern Iberia. Grey area represents 95% CI for simple exponential model of growing human population and increasing preservation of datable material through time. Significant deviations above and below model are indicated by red and blue shading. Analysis created using rcarbon package for R (Crema and Bevan, 2021).

analysis. The authors conclude that no clear relationship exists between these climatic events and the boom-bust episodes and suggest looking at endogenous causes of the demographic trends. While Bernabeu Aubán et al. (2016) concur that endogenous cause should be investigated, the authors note a broad co-occurrence of global climatic events, namely the 7.1 ka cooling event, and the observed decline in Neolithic radiocarbon dates during the Late Neolithic–conclusions supported by Balsera et al. (2015) using a broader radiocarbon data set. However, through further exploration of SPD curves at a sub-regional scale, Bernabeu Aubán et al. (2016) conclude that climatic events affected human societies, but the consequences were regionally variable. In fact, Botić (2021) has shown for western Transdanubia, that the 7.1 ka event seems to have had a stronger impact at the micro-regional scale on the dispersal of the Neolithic culture than at the macro-scale.

Regarding endogenous causes for the boom-bust patterns, McClure et al. (2009) discuss landscape degradation as a possible endogenous driver. They note that Early Neolithic settlement in eastern Iberia consisted of scattered farming communities on fertile riverine headwaters and valley bottoms– the most productive patches for swidden and hoe agriculture. While initially successful, this strategy may have increased vulnerability to erosion due to intensive cropping, pasturing, and deforestation creating a potential for greater sediment transport and erosion. Early Neolithic farming strategies may not have been damaging initially during the climatic regime of the Early Holocene but exacerbated the impacts of higher temperatures and summer droughts, with a loss of the most productive farmland, seen at the onset of the Late Neolithic. The peaks in charcoal accumulation associated with the Early Neolithic in the Navarrés study area (Fig. 9) are consistent with such land clearance. Following these peaks, charcoal accumulation declines markedly, only returning to Early Neolithic values after 5000 cal BP (when the demographic proxy in the SPD curve of Fig. 11 also increases) in three of the four cores that span this period.

At the micro-scale, we can compare the Occupational Ubiquity and Land Use Intensity maps for each study area through time to analyze micro-regional similarities and differences in demographic trends and disentangle possible causes for these patterns. The Occupational Ubiquity and Land Use Intensity maps (Figs. 7–8) show that land use choices were similar through time with population dispersals and contractions occurring in the same locations that appear to have been favorable for both foragers and early farmers. Miller and Barton (2008), in a study of three valleys in eastern Spain, noted that spatial patterning in land use remained unchanged throughout the Middle and Upper Paleolithic and topography seemed to govern occupational patterning.

At the regional scale during the Early Neolithic, our study indicates that Land Use Intensity and dispersal out of core areas increased in all three study areas, followed by contractions in Land Use Intensity back to core areas during the Late Neolithic. However, at the micro-regional level, this pattern is less apparent in the Cocina-Catadau study area than the other two. Aggregate Occupational Ubiquity measures (Fig. 10), or the proportion of the study area surveyed with Occupational Ubiquity above the mean, indicate that the population bust affecting all three valleys during the Late Neolithic may have been less intense in the Cocina-Catadau valley. In other words, Cocina-Catadau experienced the smallest decrease in Aggregate Occupational Ubiquity of the three valleys and no decrease in Aggregate Land Use Intensity. In this regard, the Cocina-Catadau study area may have been more desirable than the other two study areas for Neolithic farmers during unstable environmental periods. In general, however, all three valleys show similar demographic trends through time.

## 6. Conclusions

In addition to reporting on four years of archaeological research in eastern Iberia, a primary goal for this work is to show the importance of regional analysis in understanding the evolution of coupled socio-natural landscapes. Using an inherently transdisciplinary approach combining multiple lines of evidence ranging from fieldwork and analysis to new ML methods for chronologically 'unmixing' palimpsest surface collections, has enabled us to estimate the probability of prehistoric human occupation in three valleys in prehistoric Iberia during multiple time periods and to compare these probabilities with wider Western European trends. Computational modeling, associated with this work, is an additional tool we have applied to better understand how even small-scale human decisions and practices can lead to regional scale change over long time spans (e.g., Barton et al., 2015, 2016, 2021; Bergin, 2021; Bernabeu Aubán et al., 2015; Pardo-Gordó et al., 2017). We show how data derived from potentially disturbed or mixed surface contexts can provide a wealth of information about human behavior if gathered through survey methods like those detailed here and analyzed using chronological statistical unmixing methods.

Overall, we have been able to demonstrate that similar demographic trends characterize the study areas through time. Populations stayed stable through much of the Paleolithic at lower Occupational Ubiquity levels than in the later Neolithic. Land Use Intensity also remained low.

Populations dropped during the Epipaleolithic, possibly attributable to the dramatic climatic fluctuations of the terminal Pleistocene, and increased marginally during the Geometric Mesolithic. At the onset of the Neolithic, our analysis corroborates the trend for Western Europe noted by other researchers, a population boom in all three valleys. This boom was followed by a bust during the Late Neolithic. Again, this boom-bust pattern has been demonstrated by other regional researchers and is mirrored in our SPD analysis of radiocarbon dates as well as in our sediment charcoal sampling analysis.

The fact that similar trends are seen across all three valleys in our study (and, in fact, across much of Western Europe) suggests that global or at least pan-regional factors exerted similar influences on human populations in the study area between the Middle Paleolithic and the Late Neolithic. The introduction of agriculture to a region appears invariably to cause a population boom, often followed by a bust. The reasons for these boom-bust events are still speculative but researchers have argued that the introduction of agriculture causes an increase in fertility and settlement aggregation but, over time, may produce land erosion resulting in a population bust (Bocquet Appel, 2008; McClure et al., 2009; Balsera et al., 2015). Yet, the milder drop in Aggregate Occupational Ubiquity and Land Use Intensity values during the Late Neolithic for the valley of Cocina-Catadau may indicate differential impacts of the arrival of agriculture on human presence and use of the landscape at the valley level (i.e., Cocina-Catadau may have served as a refugia or survived the impacts of events that caused demographic declines in other areas during the Late Neolithic.) Other researchers in Iberia have demonstrated the differential impacts of the introduction of agriculture at the regional micro-regional levels, notably Drake et al. (2017), Fyfe et al. (2019), and García Puchol et al. (2021) who state that the booms were not always followed by busts, and that booms and busts occurred at different times and at differing intensities in the various regions of their study areas.

Our regional perspective has enabled us to use ML to chronologically order and then extract patterns from surface collections and further compare these results to other independent analyses (sediment charcoal sampling and SPD curves) to investigate land use and occupation in prehistory. Furthermore, the research and results presented here are comparable with other analyses of the same time periods in Iberia and Western Europe investigating interactions between demographic change and land use before and during the Neolithic. Thus, this research contributes to our greater understanding of how changes in land use strategies like the introduction of agriculture may recursively interact or "couple" with the environment to produce the boom-bust population trends seen after the introduction of agriculture to a region.

## Author contributions

All authors have made substantial contributions to this manuscript. Cegielski drafted and organized the manuscript; Snitker drafted sections of the manuscript, generated figures, assisted in map production, and conducted the charcoal analysis; Barton assisted in drafting the manuscript, figure generation, and conducting data analysis; Bernabeu Aubán co-directed fieldwork and carried out initial artifact analyses; Cortell-Nicolau and Pardo-Gordo contributed Spanish archaeological data and drafted sections of the manuscript, Diez Castillo collected original archaeological data and organized datasets; Bergin collected original archaeological data, advised on analysis, and assisted with editing the manuscript. All authors have approved the final manuscript.

## Data availability

All data and analysis scripts used in this paper are published on Zenodo at: https://doi.org/10.5281/zenodo.8096982 (Barton et al., 2023).

## 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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