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Original Research

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Impacts of sea-level rise on prehistoric coastal communities: land use and risk perception during the Mesolithic-Neolithic transition in central Mediterranean Spain

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ABSTRACT
Mapping methods to represent the interplay between environmental changes and prehistoric communities were investigated through a case study of the Mediterranean Iberia coastal landscape in the context of Holocene sea-level rise. We developed a four-dimension GIS-based analysis of the environmental evolution based on primary data acquisition (fieldwork, laboratory analyses) and spatial modeling of paleo-Digital Elevation Models (paleoDEMs). Five paleoDEMs were computed, representing key stages of the morphogenetic evolution between 9000 and 7000 years ago. Second, each paleoDEM was used as input in a Site-Catchment Analysis (a 1- and 2-hour walking distance from the archeological sites). Finally, we provide a bird-view visualization of the landscape evolution, centered on the perspective of an individual located at the archeological sites. By shifting the focus to the human scale, this GIS-assisted mapping allows refining assessments of the impact of environmental changes on settlement and subsistence patterns during the Mesolithic and Early Neolithic periods.

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Geographic information system; digital elevation model; paleogeography; coastal archeology; Mesolithic; environmental risk

1. Introduction

Coasts have played an important role in modulating Human dispersals, settlement patterns, and subsistence activities throughout Prehistory (Bailey, 2004). Yet coastal environments have sometimes been overlooked in archeological investigations (Bicho & Haws, 2008) due to their highly dynamic nature. For example, the archeological record of coastal areas, and open sites in particular, are especially sensitive to taphonomic bias (e.g. shellfish and bone remains can be affected by chemical dissolution and mechanical damages). Furthermore, large-amplitude sea-level oscillations over Glacial-Interglacial periods can bury former stratigraphies or erode newly exposed ones (Stéphan et al., 2019; Berger, 2021).

Diachronic environmental analyses are essential to understand socio-ecological interactions in coastal areas. Such approaches, however, usually face a major challenge: the heterogeneity of observations in space and time. On the one hand, some studies rely on modeling outputs resulting from regional isostatic models (Lambeck & Purcell, 2005) and apply a uniform propagation of sea-level elevation to the modern topography-bathymetry. This allows obtaining low resolution but large geographical extent reconstructions (e.g. Jordá Pardo et al., 2016; Vacchi et al., 2017). On the other, detailed geomorphological investigations (e.g. Fruergaard et al., 2015) are rich in site-specific evidence, but cover smaller geographical extents. It is thus necessary to find a balance between fieldwork information and a simplification of the paleo-geographical material, as the information of fossil records is inherently incomplete and generally discrete in space and time (Willmes et al., 2020).

Past interactions between Humans and coastal environments have been mapped, for example, for the Gulf of Finland. In this case, lithostratigraphic analyses coupled with radiocarbon dates allowed to reconstruct and map five stages of the paleogeography associated with sea-level changes and that influenced Neolithic hunter-fisher-gatherers settlements and activities (Muru et al., 2017). Coastal wetlands formed by beach-barrier and brackish lagoon systems correspond to a different type of coastal biotope with enormous potential to assess human adaptation to climate change (Van de Noort, 2013). Another relevant study used a GIS-based multiproxy coastline reconstruction of the eastern Gulf of Riga during the Stone Age (Habicht et al., 2017), integrating a LIDAR-derived digital elevation model and ground-penetrating radar profiles. These allowed to highlight the coastal barrier morphology change together with the isolation of a lagoon environment associated with brackish waters.

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In line with these studies, the present paper aimed to create GIS-based paleomap reconstructions at five key dates of the coastal morphogenetic evolution of the beach barrier-lagoon system surrounding two prehistoric archeological sites on Spain's Mediterranean coast: El Collado, dated to the Mesolithic period (9830–8060 cal BP), and El Barranquet, dated to the Early Neolithic (7550–7320 cal BP).

2. Materials and methods

The numerical workflow to compute the paleomap was semi-constrained by field surveys (archeology, geomorphology). It also integrated former laboratory analyses (sedimentology and radiocarbon dates of sediment cores) and was based on modifications of the modern topography and bathymetry. Site-Catchment Analysis then allowed mapping changes in coastal resource accessibility within walking distance from the archeological sites. Finally, we used a bird-view visualization of the landscape evolution to focus on the human scale and address questions on the perceptions of prehistoric communities on the sea-level rise and coastal dynamics.

2.1. Datasets

2.1.1. Primary data

To reconstruct the coastal morphology's evolution over time, we first gathered high-resolution primary georeferenced terrain data that included modern topography and bathymetry elevation contours (Table 1, Figure 1), both having an altimetric resolution of 1 meter. This altimetric accuracy was important because morphological changes evolved at a metric scale every 500 years during this period. As high-resolution bathymetric data covers a depth range of 0–40 meters, this dataset was merged with coarser-resolution bathymetric data to cover the full map extent. To elaborate the Map, we merged this bathymetric data with a lower resolution offshore map. Three layers were included, added to the terrain datasets (Figure 1): the hydrographic network for passive visualization; the geographic coordinates of the coring sites; and the coordinates of the two archeological sites under study (Esquembre Bebia et al., 2008; Fernández-López de Pablo & Gabriel, 2016).

2.2. Secondary data

2.2.1. Defining key dates of the morphogenetic evolution

Previous studies (Brisset et al., 2018, 2020) have explored the paleoenvironmental and morphogenetic evolution of the coastal plain of Pego-Oliva during the Holocene, based on a dense network of 18 sediment cores (Figure 2A, B), sedimentological analyses, and radiocarbon dates (Figure 2C). In brief, these works have shown that an Early- to Mid-Holocene sea-level rise took place (from 10,000 to 7000 calibrated years Before Present – cal BP) and that the former littoral and lagoons were repeatedly flooded (best-modeled age of 9000 cal BP at −20.5 meters, 8800 cal BP at −18.5 m, 8500 cal BP at −15.5 m, and of 8100 cal. BP at −11.5 m) and buried below marine sedimentary facies. This transgressive process ended with a maximal landward migration of 4 km to the modern shoreline (7300 cal BP at −4 m). Those results thus allowed identifying five key dates in the area's morphogenetic evolution, corresponding to significantly different altimetric sea level positions. We aimed to reconstruct them in this study (Figure 2A, C).

2.2.2. Paleo-shorelines and paleo-sea extents feature

The paleo-shoreline positions were approximated for the five key dates based on the depths of the lagoon facies encountered in the cores, that were roughly (altimetric errors < 0.4 m) at the relative sea-level elevation. Accordingly, contour lines corresponding to these key dates were set as paleo-shorelines on the modern bathymetry contour layer for depths of 20.5, 18.5, 15.5 and 11.5 meters. The shoreline corresponding to the maximal transgression (a depth of 4 meters) is located inland, so it was estimated by combining field observations and modern topography contours. The five paleo-sea extents were computed as polygons by clipping the study area polygon adjusting to the corresponding paleo-shorelines.

2.2.3. Paleo-lagoon extents

The presence and extent of inland paleo-lagoons were confirmed via sedimentological analyses of sediment cores (Figure 2A), dated by radiocarbon ages and age-depth modeling (Figure 2C). First, these results were included in a georeferenced attribute table (Table 2), specifying the presence, or absence, of lagoon sediment facies, for the five key dates. Second, paleo-lagoon polygons were manually digitized, based on precise core information and paired with an imprecise estimate of the lagoon extent offshore, which is today underwater. We took into account the following points: (1) lagoons are likely to be closed by a coastal barrier to allow the development of freshwater habitats; (2) the general shape of the Pego-Oliva valley bottom (Torres et al., 2014) and the consistent inland presence of buried lagoon facies, not only at Pego-Oliva, but also over the southern part of the Valencia gulf (Viñals & Fumanal, 1995); and, (3) the presence of relict sand barriers under 10 km away from the modern coastline, intercalated with lagoon facies located 30–80 meters below the modern sea-level in the near-gulf of Valencia (Albarracín et al., 2013).

Table 1. Dataset used for paleosurface reconstructions, and site-catchment spatial analysis.

Data	Type	Description	Format	Altimetric & horizontal resolutions	Source
Primary	Topography	Elevation contours (city administrative level), derived from airborne LIDAR.	Shapefile	1 meter 1/5000	Institut Cartogràphic Valencià catalogo.icv.gva.es
	Onshore bathymetry	Elevation contours (provincial administrative level) derived from the national seismic coast survey conducted by the Dirección General de la Costa y el Mar (altitudinal range: 0 to −40 m).	Shape file	1 meter 1/1000	Ministerio para la Transición Ecológica
	Offshore bathymetry	Elevation contours (European sea) derived from merging selected bathymetric survey, composite DEMs, and satellite-derived bathymetry completed by GEBCO model.	Shapefile	1 meter 115 m	EMODnet Digital Terrain Model emodnet-bathymetry.eu
	Hydrographic networks	Digitized vector line of the streams (city administrative level).	Shapefile	0.5 meter 1/5000	Institut Cartogràphic Valencià catalogo.icv.gva.es
	Coring sites	Points of the location of the sediment cores and attribute table (presence/absence of lagoon facies per key date).	Shape file	0.5 cm 1 m	This study
	Archeological sites	Location points of the 2 archeological sites and attribute table (site names).	Shape file	0.5cm 1 m	This study
Secondary	Paleo-shorelines	Vector extracted from the modern bathymetry corresponding to the elevation of sediment facies in cores.	Shapefile	1 meter 1/1000	This study
	Paleo-sea extents	Polygon produced from clipping each paleo-shoreline to the study extent.	Shapefile	1 meter 1/1000	This study
	Paleo-lagoon extents	Polygon produced by merging the results of the positive presence of lagoon facies in cores, and a probable presence of coastal barrier separating the sea from the lagoon.	Shapefile	1 meter 1/1000	This study
	Paleo-DEMs	Digital Elevation Models computed based on masks of the modern topography and bathymetry contours.	Raster	1 meter 5 meters	This study
	Site-Catchments	Polygons resulting from the Site-Catchment Analysis results.	Shapefile	1 meter 1/1000	This study

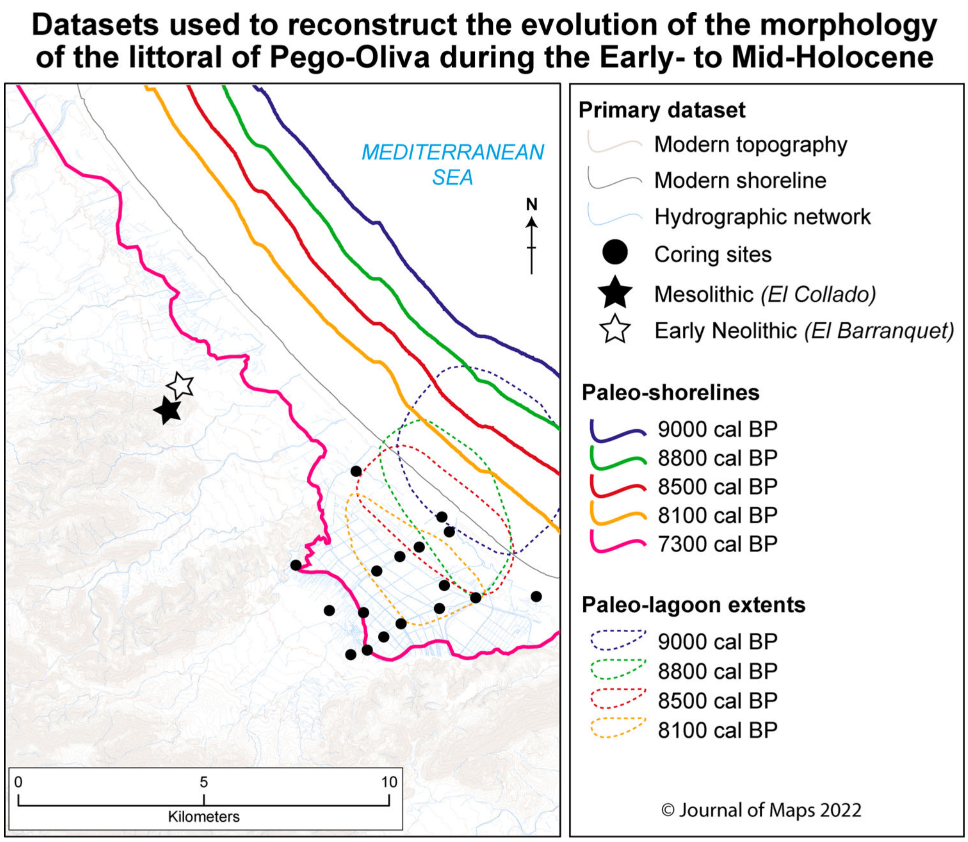

Figure 1. Main datasets used to reconstruct the evolution of the coastal morphology of the Pego-Oliva littoral during the Early- to Mid-Holocene.

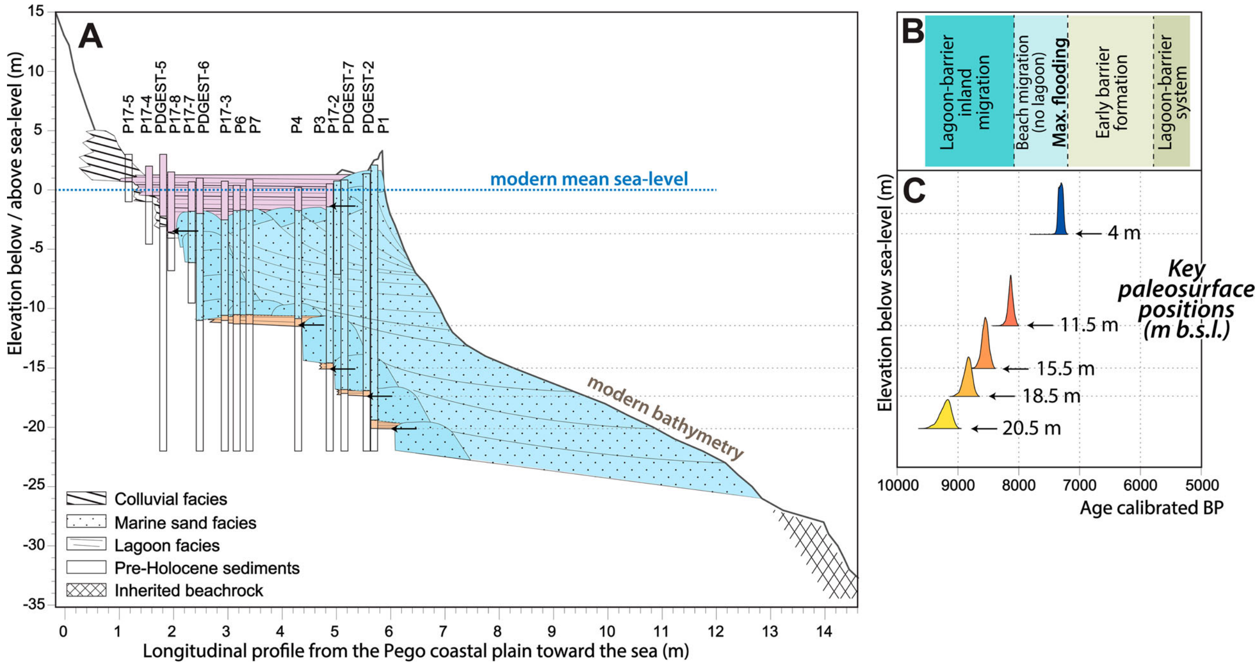

Figure 2. Main lithostratigraphic and geochronological results obtained for the Pego-Oliva coastal plain (Brisset et al., 2018). (A) Interpretative sketch of the sediment infilling signaling the presence of lagoon facies buried below the modern sea level at five key dates of the morphogenetic evolution. (B) Synthetic paleoenvironmental evolution during the Early to Mid-Holocene. (C) Age probability density function obtained for the five key dates of the morphogenetic evolution.

2.2.4. Paleotopographic modeling

Following the general paleosurface reconstruction procedure, we considered a semi-automated method coupled with modern morphometry derived from the Digital Elevation Model (DEM) dataset as a general basis, improved by field-knowledge for the area of particular interest, i.e. in this case, the coastal band. This approach resembles that of Brisset et al. (2014) who reconstructed key morphogenetic evolution dates (sediment deposition and erosion) of a mountain catchment over the Holocene, applying selective masks of the modern Digital Elevation Model as a general basis, inserting new constraints obtained by field measurements, and finally re-interpolating the morphological dataset. The three elevation contour datasets (Topography, Bathymetry On-shore, and Bathymetry Offshore) were imported into a Geographic Information System (Coordinates system: ETRS 1989 UTM Zone 30N). They were then joined and clipped to the study area extent to represent the modern topo-bathymetry. Additional constraints, which differed depending on the key dates, were added, and new raster paleo-DEMs were calculated using consistent parameter settings (format: GeoTIFF, algorithm: Natural Neighbor, Pyramids Level: 5, cell size: 5 m) described below.

- At 9000 cal BP, the modern elevation layer was edited by: (1) deleting the elevation lines of the interval from +4 to −26 m (included); (2) changing the

Table 2. Attributed table of the coring sites GIS layer, specifying the presence (value = 1), or absence (value = 0) of lagoon sediment facies for each of the five key dates of the area's morphogenetic evolution in the 18 sediment cores.

ID	Shape	Name	9000 cal BP	8800 cal BP	8500 cal BP	8100 cal BP	7300 cal BP	modern
0	Point ZM	PDGEST_1	0	0	0	0	0	0
1	Point ZM	P4	0	0	0	1	0	1
2	Point ZM	P3	0	0	1	1	0	1
3	Point ZM	P1	1	1	1	0	0	0
4	Point ZM	PDGEST_2	0	1	1	0	0	0
5	Point ZM	P6	0	0	0	1	0	1
6	Point ZM	P17_8	0	0	0	0	0	0
7	Point ZM	PDGEST_5	0	0	0	0	0	0
8	Point ZM	P17_5	0	0	0	0	0	0
9	Point ZM	P17_7	0	0	0	0	0	1
10	Point ZM	P17_3	0	0	0	1	0	1
11	Point ZM	P7	0	0	0	1	0	1
12	Point ZM	P17_4	0	0	0	0	0	0
13	Point ZM	PDGEST_7	0	1	0	0	0	1
14	Point ZM	PDGEST_3	0	0	0	0	0	0
15	Point ZM	PDGEST_4	0	0	0	0	0	0
16	Point ZM	PDGEST_6	0	0	0	0	0	1
17	Point ZM	P17_2	0	0	0	1	0	1

attribute of the elevation line +5 m to a value of −19 m (depth of lagoon facies in the cores PDGEST-1 and P1); (3) deleting modern topography anomalies (highway, port infrastructure); (4) creating one line to produce a flat coastal plain (necessary to develop a lagoon), that intersects these cores, and set at −20 m, as obtained in the cores.

- At 8800 cal BP, the modern elevation layer was edited by: (1) deleting the elevation lines from +5 to −16 m, (included); (2) creating one line (elevation: −17 m) to produce a flat plain that intersects the cores P1, PDGEST-2, PDGEST-7, and excludes the others.
- At 8500 cal BP, the modern elevation layer was edited by: (1) deleting the elevation lines from +5 to −15 m, (included); (2) creating one line (elevation: −14 m) to produce a flat plain that intersects P1, P3, PDGEST-2, and excludes the others.
- At 8100 cal BP, the modern elevation layer was edited by: (1) deleting the elevation lines from +5 to −12 m, (included); (2) creating one line (elevation: −11 m) to produce a flat plain, that intersects P6, P4, P3, P17-3, P17-2, P7, and excludes the others.
- At 7300 cal BP, the modern elevation layer was edited by: (1) deleting the elevation lines from +5 to −5 m (included); (2) creating one line (elevation: −4 m) to allow an inland sea transgression at the depth of appearance of the marine facies in all the cores except P17-8, PDGEST-5, P17-4, P17-5.

2.3. Spatial analysis

Based on the principles of the Optimal Foraging Theory, Site Catchment Analysis (SCA) is a well-established technique to delimitate the accessibility of potential resources, from a given location, considering traveling time/or energy expenditure (Cannon, 2003). For the purposes of the present study, the SCA was undertaken to visualize the impact of the sea-level rise on prehistoric land use considering a 1- and 2-hour walking distance from the Mesolithic site of El Collado and the Neolithic site of El Barranquet. In the case of hunter-gatherer societies inhabiting temperate biomes, a catchment area corresponding to a 2-hour distance of travel was a realistic estimation of time expenditure for hunting expeditions departing from a residential camp. This estimation is supported by both ethnographic literature (Kelly, 1995), and archeological case studies in Iberia (Arroyo, 2009). In the case of small-scale agriculturalists, according to recent studies on Early Neolithic settlement patterns (Atiénzar, 2009), a 1-hour distance SCA defines the area where most of the field crops are located with respect to the villages.

The SCAs were computed according to the following steps: first, we calculated an anisotropic cost-of-passage raster (Conolly & Lake, 2006) based on the slope and the lagoon water bodies for each of the five paleo-DEMs elevation models. In our cost-of-passage rasters, the cost of moving was weighted at 70% for the slope and 30% for the lagoon bodies. We then calculated an accumulated cost-surface by applying the Tobler's hiking function (Tobler, 1993) as a spreading algorithm. Finally, we vectorized the accumulated cost-of-surface in 60-minute isolines and selected 60 and 120-minute isolines to delineate the site's 1- and 2-hour catchment areas.

3. Results

3.1. The composite map

The map represents the Pego-Oliva marshland's Holocene paleogeographic evolution over five different temporal slices. Maps at 9000, 8800, 8500, and 8100 cal BP reflect the changes in coastal biotopes that occurred during the human occupation of the El Collado Mesolithic site. For its part, the 7300 cal BP snapshot depicts the coastal configuration during the Early Neolithic occupation of the El Barranquet site. We represented 1- and 2- hour traveling distance catchment areas of the site for all time slices, in light and dark gray dashed lines, respectively. The composite map also represents the location of the lagoon cores that provided positive or negative evidence of lagoon sedimentary facies. This sedimentary data was used to estimate the paleo-lagoon features for each time slice.

For the Mesolithic period, the composite map clearly shows the impact of the Early Holocene sea-level rise (ca. 9000–8100 cal BP), and the concomitant marine transgression on the 2-hour SCA of the El Collado site. Within the 2-hour SCA, we found a monotonic reduction in the extent of the biotopes corresponding to coastal plains and marshes. Preliminary zooarchaeological data from El Collado faunal assemblages (Fernández-López De Pablo et al., 2015) indicate the exploitation of ungulates inhabiting lowlands, such as aurochs and red deer, and mountain ungulates such as ibex, as well as forest adapted species, like wild boar. The narrowing of coastal plains might have affected the density of the ungulate prey that inhabited lowland areas, especially red deer and aurochs. The map also shows how the paleo-lagoon features are located between the 1- and 2-hour SCA isochrones. The proximity of the coastal lagoons along the Mesolithic occupation of El Collado is consistent with the data on mollusks and fish bone assemblages. The latter showed the dominance of the Mediterranean cockle (*Cerastoderma glaucum*), in addition to other inhabiting lagoon mollusk species, such as *Cerithium vulgatum*, *Hexaplex trunculus* and the overwhelming representation of the gilt-head seabream (*Sparus aurata*) (Fernández-López de Pablo & Gabriel, 2016). The Early Holocene dynamics of this lagoon-barrier coastal system show a progressively inland migration and a contraction of the extent of the lagoon water bodies. Again, this observation fits well with the diachronic trends observed in the mollusk assemblages from the El Collado site. The latter depicts a significant decrease in the relative frequencies of lagoon species, replaced by edible land snails.

Finally, during the Neolithic occupation of the El Barranquet site, at 7300 cal BP, we identified the maximum impact of the inland marine transgression in the 1- and 2-hour SCAs. All the analyzed cores provided negative evidence of lagoon facies, supporting the replacement of the coastal lagoons by a fully coastal (infralittoral) biotope, delineating a small bay.

3.2. 3D bird-view visualization

Finally, we complemented the map series with an animated 3D bird-view visualization (Supplementary Online Material), displaying the coastline inland migration and changes in biotope configuration for the coastal sector between the archeological sites of El Collado and El Barranquet southward, towards the Pego-Oliva lagoon and Nao cape. This visualization strategy aimed to focus on the anthropic perception of major transformations in coastal biotopes, affecting daily subsistence and mobility practices by prehistoric communities. This, in turn, informs on the risk perception embedded in very dynamic human-environmental interactions such as: (i), the continuous narrowing of hunting territories and shellfish collection areas along the Mesolithic, impacting local scale environmental carrying capacity (ca. 9000–8100 cal BP); and (ii), the exposure to storm surge events during the Early Neolithic (ca. 7300 cal BP).

4. Conclusion

We highlighted the potential impacts of coastal biotope dynamics, associated with sea-level rise, on prehistoric community subsistence and mobility practices using paleo-geographical maps of a coastal area of central Mediterranean Spain during the Early- to Mid-Holocene. Our study provides a baseline to interrogate the archeozoological, bioarcheological and malacological records of this area of the Western Mediterranean coast. Paleo-dataset visualization products are particularly informative about past perceptions, at inter-generational time scales, of the sea level rise and the flooding of coastal plains, of ecological resource availability and exposure to hydroclimatic hazards.

Software

Dataset georeferencing, manual digitization, shapefiles, and attribute table edition, as well as COST raster computations were carried out on ArcGIS Desktop 10.6 (©ESRI). The paleo-DEM rasters were computed on ArcMap 10.6 using the Spatial Analyst extension (©ESRI). The map layout was performed on ArcMap 10.6 (©ESRI) and finalized on Adobe Illustrator 2021 (©Adobe Systems Inc.). The bird-view visualization was performed on ArcScene 10.6 (©ESRI) and the video compiled on PowerPoint 2019 (©Microsoft).

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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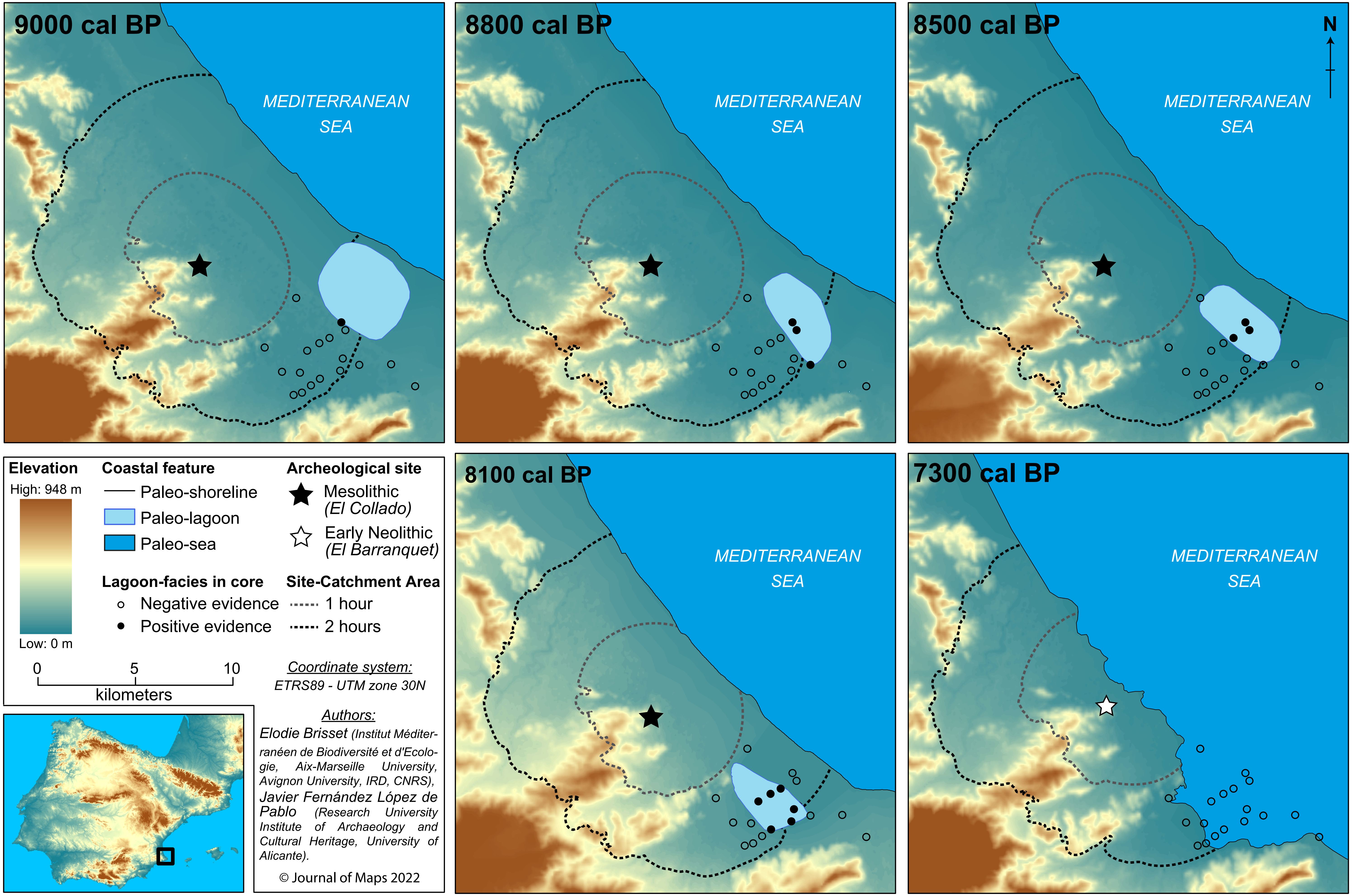
Snapshots of the Holocene paleogeographic evolution at Pego-Oliva:

Land use and risk perception during the Mesolithic-Neolithic transition in central Mediterranean Spain



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