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RESEARCH

Scales, Sources, and Simulations: Reviewing Studies on Human–Environment Interactions in the Mediterranean from 1000 BCE to 1000 CE

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Abstract

Understanding long-term human–environment dynamics is essential for contemporary debates on resilience and sustainability. This paper reviews approaches to studying humans and their environments in the Mediterranean between 1000 BCE and 1000 CE, with particular emphasis on the role of agent-based modelling (ABM). The region is strongly shaped by human activity, richly documented by archaeological, palaeoenvironmental, and historical written sources, and characterised by complex socio-ecological dynamics throughout the study period. We first synthesise how different sources/archives of evidence have been used to reconstruct past human–environmental links, assessing spatial and temporal resolutions and the methodological challenges of combining different evidence. We then review ABMs that focus on human–environment relationships in the study period and region, examining how they incorporate different datasets, how explicit models are, and to what extent qualitative historical information is translated into formal computational frameworks. Despite the region's relatively exceptional research history, few ABMs directly engage with socio-ecological dynamics, and even fewer exploit the potential of historical texts as structured inputs to simulations. Our review identifies key methodological gaps at the intersection of archaeology, history, environmental science, and modelling practice. We argue that ABM remains underutilised for moving beyond correlational reasoning: it can be used to test proposed causal mechanisms, explore emergent socio-ecological patterns, and link processes operating at multiple scales. We conclude by outlining directions for future ABM research on the Mediterranean that could better integrate diverse sources of evidence and contribute more effectively to debates on long-term resilience and sustainability.

Keywords The Mediterranean · Human–environment interactions · Agent-based modelling · Written sources · Proxies

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Introduction

Understanding past human–environment interactions is essential not only for reconstructing historical processes but also for informing current efforts relating to sustainability and resilience in the context of contemporary environmental changes. The Mediterranean region is important for these studies due to its extensive history of human–environment interactions, ecological sensitivity, and the large amount of research examining its historical and archaeological trajectories (Trincardi et al., 2023). Furthermore, this region is currently under various pressures including pollution, overfishing, overall ecosystem degradation, and biodiversity decline (Cuttelod et al., 2008; Gupta, 2017; Trincardi et al., 2023). This combination of deep-time perspectives together with urgent present-day issues makes the Mediterranean an important area for research on human–environmental links, where clarifying long-term patterns and identifying the legacies that shape current challenges can be most valuable.

The region focused on in this study encompasses the lands surrounding and within the Mediterranean Sea, which contains four large islands (Sicily, Corsica, Sardinia, Crete, Cyprus) and several smaller ones (Fig. 1). The Mediterranean climate is generally mild, characterised by warm, dry summers and mild, wet winters (Torben et al., 2020). However, local and regional conditions vary due to topography, natural environments, and differences in latitude and altitude (Izdebski et al., 2018; Labuhn et al., 2018; Walsh, 2013).

This region has a long history of maritime connectivity and interactions across diverse communities and societies. The capacity for long-distance travel and exchange has fostered a deep history of cultural integration, while simultaneously preserving local and regional variation (Broodbank, 2013; Horden & Purcell, 2000). Consequently, the Mediterranean offers a particularly rich context for comparative research into human–environment interactions.

The period 1000 BCE–1000 CE is marked by important historical, cultural, and socio-political developments that shaped the Mediterranean and adjacent parts of the world: the formation and expansion of states and empires, including the earliest Greek city states, the emergence of the Roman Republic and Empire, and the fragmentation of that empire into Byzantine, Islamic, and Western European powers. The period saw the growth of trade and maritime networks, the emergence of major religious movements, cultural and intellectual exchanges. Environmental and climatic fluctuations have been suggested as contributing factors to societal and political developments and disruptions (*e.g.* Hassan, 2000; Büntgen et al., 2016; Xoplaki et al., 2016; Decker, 2017; Hazell et al., 2022; Norman et al., 2025).

One of the distinctive features of this period, particularly compared to those preceding it, is the quality and quantity of available evidence, although this is unevenly distributed. For some periods and regions, there is extensive textual evidence, while in others the record is fragmentary or entirely absent (Horden & Purcell, 2000). Importantly, even in the best-documented cases, historical texts do not approach the breadth or systematic coverage seen in modern nation-states. Historical sources were usually written for specific audiences (often elites) and

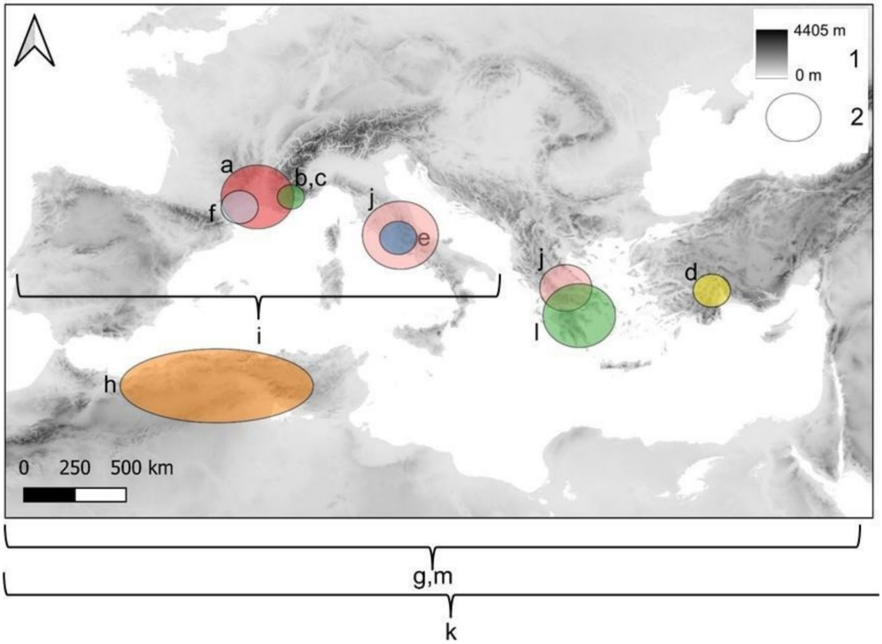

Fig. 1 Study area showing existing ABMs of human–environment interactions throughout 1000 BCE–1000 CE Legend: 1–elevation in meters a.s.l., derived from GTOPO30; 2–locations of case studies in the reviewed ABMs. Reviewed studies: a–Bernigaud et al., 2024; b–Bertoncello et al., 2018a; c–Bertoncello, et al. 2018b; d–Boogers & Daems, 2022; e–Cecconi et al., 2015; f–Crabtree, 2016; g–Dermody et al., 2022 (Roman Empire, Mediterranean Basin); h–Gauthier, 2019; i–Graham, 2006 (Roman Empire, western provinces); j–Graham & Steiner, 2006; k–Turchin et al., 2013 (Afroeurasia); l–Vidal-Cordasco & Nuevo-López, 2021; m–Vlach, 2022 (Roman Empire)

focused on selective topics (generally those of interest to elites, such as politics, religion, or military events).

The availability of different types of evidence from 1000 BCE to 1000 CE presents a methodological challenge which requires careful analysis and integration of multiple perspectives within a single study (d'Alpoim Guedes et al., 2016; Izdebski et al., 2016a). One critical issue is the distinction between correlation and causation. While different types of evidence may suggest correlations between environmental and societal changes, these relationships do not inherently indicate causation (Arponen et al., 2019; Foxhall Forbes et al., 2026; Hassan, 2009; Nikulina et al., 2022).

Environments themselves are complex systems, characterised by interactions among heterogeneous components that influence various processes and often exhibit nonlinear dynamics and emergent properties (Craig, 2017; Nikulina et al., 2024; Silva et al., 2022; Zhang et al., 2024). This inherent complexity makes it particularly challenging to establish causal relationships, even when multiple types of evidence are integrated within a single study. One approach that has gained increasing popularity in recent years for studying human–environment dynamics across time and space is agent-based modelling (ABM), a computational modelling technique designed to study complex systems. In ABM, heterogeneous agents (individuals or collective units, such as households, villages, or institutions) interact with one another and with their environment, generating emergent population-level patterns and structures (Romanowska et al., 2019, 2021). One of the strengths of this approach is its flexibility, as it is light in assumptions and allows models to be tailored to a specific research focus (Romanowska et al., 2021). ABM has been applied in studies of the ancient Mediterranean, reviewed below.

This paper has the following aims: (1) to present the variety of sources/archives (historical, archaeological, palaeoenvironmental) which provide evidence on human–environment interactions in the Mediterranean, 1000 BCE–1000 CE, accompanied by examples demonstrating how different types of evidence have been used to interpret socio-ecological systems; (2) to critically evaluate the presence and use of the various evidence types in ABM; and (3) to outline ways to address key challenges in socio-ecological research in the Mediterranean. We do not aim to provide a comprehensive summary of all studies utilising different types of evidence available in the study region. In addition, we do not evaluate whether existing multi-evidence approaches (*i.e.* those incorporating different proxies and historical records) properly align different data types (*e.g.* whether information from written sources accurately corresponds/correlates with events reconstructed via proxies). This remains an important methodological challenge, requiring complex frameworks (Degroot et al., 2021; Izdebski et al., 2016a). Here we complement these efforts by discussing the evidence and the underlying assumptions used in existing ABMs and suggesting possible ways forward for integrating ABM research to address socio-ecological questions.

Sources/Archives of Evidence That Can Be Used to Study Human–Environment Interactions in the Mediterranean, 1000 BCE–1000 CE

Studying past human–environment interactions requires identifying human activities and reconstructing the environmental contexts in which they occurred (such as vegetation patterns, coastlines, and hydrological systems) and assessing how both human activities and environmental conditions changed through time and their broader socio-environmental impacts. Disentangling these processes depends on evidence derived from multiple archives/sources (Table 1).

Because this paper addresses an interdisciplinary audience, it is useful to clarify how different archives and sources vary in spatial and temporal resolution. The term ‘proxy’ refers to observational measurements that can be used to infer properties of systems, particularly those connected to the past, which are otherwise difficult or impossible to measure directly (Boudinot & Wilson, 2020). Proxy data of all sorts differ in form and carry different uncertainties, including those related to analytical precision, measurement accuracy, and interpretation.

Historical written evidence can be highly variable, ranging from a few words (*e.g.* an inscription) to literary narratives of thousands of words (*e.g.* epic poetry). Texts

Table 1 Environmental and cultural archives, historical written evidence and their primary spatial and temporal resolution for studies of human–environment interactions in the Mediterranean, 1000 BCE–1000 CE. Spatial resolution refers to the scale at which specific types of archives/sources reflect or document past processes and human–environment interactions (local, regional, continental, global)

Source/archive type	Examples of proxies/evidence/information	Examples of indicators	Relative spatial resolution	Relative temporal resolution	Case studies' examples
Marine deposits	Microfossils, isotopes, trace elements, biomarkers, ancient environmental DNA	Temperatures, salinity, ocean circulation, carbon cycling, pollution, palaeomagnetism	Local, regional, continental	Centennial, millennial**	Ghilardi et al., 2019; Jalali et al., 2018; Koutsoudendris et al., 2025; Martín-Puertas et al., 2010; Schilman et al., 2001
Ice cores	Isotopes, greenhouse gasses, heavy noble gases, tephra (volcanic ash), dust, heavy metals, black carbon, pollen, methane and carbon monoxide, molecular biomarkers, ancient environmental DNA	Changes in temperature and precipitation, atmospheric circulation, volcanic activity, gas concentrations, pollution, burning, wind transport, biological activity	Local–global	Centennial, millennial****	Cole-Dai et al., 2021; Gabriel et al., 2024
Lake and wetland deposits	Pollen, non-pollen palynomorphs (NPPs), plant macrofossils, environmental ancient DNA, isotopes, elemental composition	Changes in vegetation, climate and land use, past hydrological conditions, carbon cycling, volcanic activity, erosion, pollution, burning	Local, regional*	Decadal, centennial***	Martín-Puertas et al., 2008; Schoolman et al., 2018; Weiberg et al., 2019
Alluvial deposits	Isotopes, elemental composition, pollen, phytoliths, diatoms	Changes in vegetation, climate and land use, past hydrological conditions, burning, erosion	Local, regional*	Centennial, millennial**	Bellotti et al., 2011; Kaniewski et al., 2010
Speleothems	Isotopes, trace elements, luminescence	Climatic and vegetation changes	Local–global	(Sub-)annual, decadal, centennial	Fleitmann et al., 2009; Jacobson et al., 2021; Xoplaki et al., 2016

Table 1 (continued)

Source/archive type	Examples of proxies/evidence/information	Examples of indicators	Relative spatial resolution	Relative temporal resolution	Case studies' examples
Archaeological sites and surveys	Pollen, tools, structures, plant microfossils, zooarchaeological evidence, phytoliths, chronological proxies (*e.g.* radiocarbon dates), aDNA	Demographic trends, land use and management, climatic and vegetation changes, diet, migration and mobility, trade	Local, regional*	Centennial, millennial**	Antonio et al., 2019; Bintliff, 2023; Knodell et al., 2023; Marcus et al., 2019; Roberts et al., 2019; Skourtanioti et al., 2023; Speidel et al., 2025
Written sources	Narrative histories, annals/chronicles, biographies, letters, lists, laws and other legal texts, tax records, census records, agricultural works, medical texts, scientific writing, sermons, theological texts, inscriptions	Significant/unusual weather and other environmental events, land use and management, water management, crop choices, the tax burden on produce in different areas, demographic trends, information about human labour for working the land, human perspectives/opinions on the environment	Local, regional, continental*	(Sub-)annual, decadal, centennial, millennial	Bernard et al., 2023; Izdebski et al., 2016b; Meier, 2024; Squatriti, 2010

Temporal resolution refers to the precision of the time interval over which past events can be reconstructed using given evidence ((sub-)annual, decadal (2–10 years), centennial (11–100 years), millennial (> 100 years)). While we focus on the primary resolution of sources/archives (*i.e.* most common resolution of currently available evidence), the potential resolution of specific archives/sources depends on different factors (*e.g.* preservation conditions, sedimentation rates, the research strategy, and the analytical approach used including combining multiple evidence within a single study or applying specific modelling techniques). The potential resolution of specific archives and sources can be as follows: *potential for continental or global studies when multiple sources are combined within a single study; **potential for decadal resolution; ***potential for (sub-)annual resolution; ****potential for (sub-)annual and decadal resolution are also produced in diverse genres, such as narrative histories, annals, biographical accounts, letters, scientific treatises, and agricultural manuals, each with specific goals and constraints. Sophisticated historical methodologies are required to extract meaningful insights from the historical record, and no text should be taken as a simple informational statement (Foxhall Forbes et al., 2026; Morley, 1999).

Spatial Resolution

By spatial resolution we mean the scale at which evidence reflects past processes. This can be broadly categorised into local, regional, (sub-)continental, and global levels (Dearing, 2006; Labuhn et al., 2018; Nikulina et al., 2022). The local scale provides the highest level of detail and allows for the identification of both natural and anthropogenic processes at or near a sampling site. The regional scale encompasses a broader area and reflects processes occurring across multiple sites within a region. At the (sub-)continental and global scales, proxies capture large-scale environmental and human dynamics across large geographic areas. Importantly, the spatial relevance of a proxy is not fixed but depends on the nature of the proxy itself.

Ice cores provide information on environmental conditions at a relatively coarse spatial scale, and the current spatial distribution of available ice cores is often insufficient to achieve high-resolution environmental reconstructions, as most cores are from Antarctica, Greenland, and some mountain regions (Dearing, 2006; McCormick, 2019). This geographic bias affects global reconstructions and complicates the downscaling of data from ice cores for regional studies, particularly in regions such as the Mediterranean (Dearing, 2006), where the nearest ice core records are located in the Alps (Gabrielli et al., 2016, 2025).

Similarly to ice cores, marine sediments are primarily used to identify general climatic trends at regional scales (*e.g.* Ghilardi et al., 2019; Jalali et al., 2018; Schilman et al., 2001). Sediments from inland waterbodies are useful for finer scales. Lacustrine and wetland systems can respond relatively rapidly to environmental changes and capture these signals in closer spatial proximity to their source. When multiple records from lakes and wetlands are combined and modelling techniques are applied, the analyses can be extended to continental and global scales (Jenny et al., 2019; Serge et al., 2023; Sugita, 2007a).

Alluvial deposits can be also used to study human–environment interactions. In the Mediterranean, many rivers have steep gradients and tend to be fast-flowing, transporting sediments. The spatial resolution of the sediments from alluvial settings is local–regional with potential for broader continental- and global-scale analyses (Dotterweich, 2008; El Bastawesy et al., 2020; Hatono & Yoshimura, 2020; Hoffmann et al., 2007; Müller et al., 2021; Skreczko et al., 2023; Wang et al., 2021).

Formation of speleothems (chemical deposits in caves) is linked to large-scale ocean–atmosphere–land hydroclimatic processes (Bar-Matthews et al., 2017; Comas-Bru et al., 2019). Isotopic composition of speleothems reflects environmental variables above the cave system where they form and cave-specific processes

(Patterson et al., 2024). Regional syntheses can reveal broader climate patterns (Kaushal et al., 2024; Xoplaki et al., 2016).

Archaeological sites provide different types of evidence (*i.e.* material culture, biological remains of animals and humans) that offer direct evidence of human occupation events, demographic trends, land use practices, associated vegetation changes, *etc.* (Hofman et al., 2015; St. Amand et al., 2020). Evidence from archaeological sites primarily has local and regional spatial resolution. At the same time, archaeological evidence may also indicate larger-scale exchange, mobility, and connectivity (Leppard et al., 2021; Witcher, 2006a). For example, if grain for Rome arrived from Egypt (Erdkamp, 2005; Garnsey, 1988), the archaeological record in Rome might not show clear evidence of immediate local economic and environmental conditions. In such cases, the site becomes evidence for the broader systems within which it was embedded.

Geographical information from textual sources varies since an author may describe a local situation or make generalisations (informed or otherwise) about a large geographical area. Understanding the spatial representativeness of different textual sources is, therefore, crucial when integrating them into broader socio-environmental analyses.

Temporal Resolution

Temporal resolution refers to the precision of the time interval over which past events can be reconstructed. Different types of evidence offer varying levels of temporal resolution, from (sub-)annual high-resolution to millennial-scale low-resolution records (Nikulina et al., 2022).

Ice cores can now in some cases provide (sub-)annual reconstructions, although such records remain relatively uncommon (Cole-Dai et al. 2021; McCormick, 2019; More et al., 2017). Marine sediments can be mainly used in studies with centennial–millennial (with potential for decadal) temporal focus (*e.g.* Ghilardi et al., 2019; Jalali et al., 2018; Schilman et al., 2001). Lakes and wetlands may preserve comparatively higher-resolution signals because of higher average sedimentation rate (Boyall et al., 2024; Martín-Puertas et al., 2010; Perennou et al., 2012; Salimi et al., 2021; Springer et al., 2015). Despite extensive research on alluvial deposits, their continuous annual-resolution sediments are uncommon, while decadal temporal resolution, though still relatively rare, is more feasible (Kolker et al., 2012). Commonly, alluvial studies use centennial and millennial scales (Liu et al., 2020; Nian et al., 2022). In contrast, speleothems can be dated by the uranium–thorium method and have a temporal resolution of less than 10 years on average (Bar-Matthews et al., 2017; Fleitmann et al., 2003, 2022).

Archaeological evidence with annual and decadal temporal resolution is also rare because of the limitations of dating methods and the nature of archaeological deposits, which represent accumulated layers of materials resulting from different natural and anthropogenic processes (Farrand, 2001; Stein et al., 2003; Whittlesey et al., 1982). Dendrochronology (dating of tree rings in wooden artifacts and structures) offers (sub-)annual temporal resolution by assigning exact calendar years to each growth ring. In the Mediterranean, dendrochronology has been used in constructing precise historical timelines and reconstructing environmental conditions (Kuniholm et al., 1996; Manning et al., 2023; Pearson et al., 2012; Touchan et al., 2014). Radiometric techniques such as radiocarbon or optically stimulated luminescence (OSL) dating usually provide date ranges with uncertainties spanning several decades or more. Achieving centennial and millennial resolution in dating archaeological sites is more feasible. However, in some Mediterranean regions with long-standing research tradition and dense archaeological coverage, especially for the Roman period, ceramic and numismatic typo-chronologies allow relatively fine-grained temporal and spatial analysis. This is because material culture changed frequently and can be traced over vast areas (Collins-Elliott, 2019; Hayes, 1972; Keay & Williams, 2014; Palmisano et al., 2021; Peacock, 1983).

The temporal resolution of texts depends not only on when events were recorded but also on the textual history and reliability of the source. Premodern historical written evidence is, on the whole, patchy and discontinuous. Texts were sometimes written shortly after the events they recount. In other cases, they describe events from decades or even centuries earlier (including, sometimes, mythological narratives or events which may never have happened) (Halsall, 2008). Many texts include information from multiple periods, being copied, modified, and reinterpreted across generations (McKitterick, 2008). This cumulative process complicates efforts to assign a discrete temporal resolution to historical written sources. Nevertheless, when critically evaluated and cross-referenced, written sources can be used to refine and contextualise other evidence.

A key methodological problem is determining how far in space and time a pattern observed in available evidence can be generalised. This question of representativeness and generalisation lies at the core of long-standing debates among historians, archaeologists (Wickham, 2007; Witcher, 2006b), and environmental scientists (Boudinot & Wilson, 2020; Labuhn et al., 2018; Navarro et al., 2025). Therefore, it is critical for any attempt to integrate diverse forms of evidence in models of past human–environment interactions. Precise chronological control is essential for interpreting evidence at appropriate temporal scales and for evaluating potential causal relationships (Labuhn et al., 2018). Self-evidently, a causal event must precede its effect, but the temporal resolution of different evidence types is often insufficient to establish either a clear relative chronology or causation with certainty (Table 1).

Examples of Studies Using Different Types of Evidence

For the Mediterranean, several studies have integrated archaeological and historical written evidence with palaeoclimate records primarily derived from marine, lake sediments and speleothems (Deij et al., 2026; Finné et al., 2019; Hazell et al., 2022; Labuhn et al., 2018; Lüning et al., 2019; Roberts et al., 2008; Weiberg & Finné, 2022). Some studies integrate evidence from both marine cores and terrestrial archives (*e.g.* Koutsodendris et al., 2025; Martín-Puertas et al., 2010) to identify climatic fluctuations and anthropogenic impacts on the environment, such as lead (Pb) pollution often associated with mining and production of silver (McCormick, 2019). Research on early medieval Italy used evidence from lakes in the Rieti Basin (Lazio region, Italy) to argue that landscape changes were driven mainly by human management rather than climate.

In particular, the deforestation of the ninth century is identified as a long-term consequence of human activity, largely influenced by monastic land control (Schoolman et al., 2018).

As part of the multidisciplinary study on the Tiber River delta and its coastal evolution, Bellotti et al. (2011) analysed alluvial-marshy sediments, extracting different proxies (faunal remains, pollen, and isotopic data) and integrating them with archaeological and historical written evidence related to Ostia (Italy). The authors highlight salty water intrusion into a freshwater system around 600 BCE. This study showed how difficult it remains to distinguish natural and anthropogenic drivers. The Romans may have actively transformed coastal marshes into saltworks. However, archaeological evidence indicates that Ostia's settlement only expanded and gained importance in the fourth century BCE which makes it challenging to identify whether substantial human-induced changes were feasible before that time (Bellotti et al., 2011).

Xoplaki et al. (2016) combined speleothems with archaeological, written, and other palaeoenvironmental evidence (tree rings, pollen records, and climate simulations) to reconstruct precipitation patterns and moisture availability in the Byzantine Empire between 850 and 1300 CE The findings indicate that climatic fluctuations, including cooling and aridification associated with the 1257 Samalas eruption, were important for the empire. The authors also suggested that climate fluctuations were not the sole drivers of change, with socio-political pressures contributing to economic decline and territorial losses.

Taken together, these studies demonstrate recurring challenges: the difficulty of separating natural and anthropogenic signals, the importance of local and regional studies with relatively high resolution, and the need to integrate different evidence including archaeological and written together with environmental reconstructions. A consistent conclusion is that environmental change was not the sole factor shaping developments in the Mediterranean.

At the same time, some studies (particularly those focused on societal stress, decline, or 'collapse') adopt more deterministic assumptions about human–environment relationships. Here, rapid societal change is interpreted as a direct response to climatic or environmental fluctuations (Büntgen et al., 2016; Großmann et al., 2023; Norman et al., 2025). Such interpretations risk oversimplifying socio-ecological dynamics, since demographic or structural transformations can occur independently of external environmental triggers (Bistinas et al., 2013; Bons et al., 2019; Middleton, 2012, 2025; Nikulina et al., 2025). Therefore, causal relationships need to be demonstrated rather than assumed.

ABM-Based Studies on the Mediterranean, 1000 BCE–1000 CE

Formal modelling is a broad term that covers the application of computational techniques to test hypotheses through mathematically structured representations of reality (Brughmans et al., 2019). It can be contrasted with conceptual models, which provide abstract representations of a phenomenon focused on theoretical structure or explanatory logic rather than quantitative formulation (Brughmans, 2022; Thalheim, 2011). For example, in studies of the Roman economy, conceptual models are often expressed in natural language, which some argue can obscure underlying assumptions and reduce transparency (Brughmans, 2022). Formal models also present challenges because they require quantitative inputs. As a result, they depend on reliable numerical data and struggle to incorporate elements of conceptual models that are difficult to quantify (*e.g.* emotional responses or social memory).

Different formal modelling approaches have been used to study interactions between past humans and Mediterranean environments (Brughmans et al., 2019; Goodchild & Witcher, 2010; Rubio-Campillo et al., 2018; Zeviani et al., 2025). Despite this, the use of formal models remains relatively limited–even in parts of the discipline with relatively rich research histories and data availability, such as Roman studies (Brughmans et al., 2019).

ABM and Studies on Past Human–Environment Interaction

A simulation is a formal model which represents the operation or behaviour of a system or process over time (Brughmans, 2022). All simulation-based methodologies share the following features: the formal abstract representation of a study phenomenon, a defined set of processes that drive model dynamics, independent variables that do not change, and dependent variables (outcomes) that change as the simulation progresses (Brughmans, 2022). ABM is a type of simulation which is used to study complex systems, where multiple interacting factors can produce non-linear dynamics. In such systems, it is assumed that understanding the whole cannot be achieved through analysis of individual components alone. Emergent features arise from the interaction of system elements and can be used to explore and suggest potential scenarios of complex system behaviour and function (Romanowska et al., 2019, 2021).

Despite the availability of formal modelling approaches, studies on human–environment interaction do not have standardised and unified protocols. Frameworks have been suggested (*e.g.* Morrison et al., 2021), but consistent guidelines and methods for data manipulation remain absent. It may not even be feasible to develop a single universally applicable approach (Navarro et al., 2025). Challenges arise due to different epistemologies across disciplines, combinations of qualitative and quantitative methods, and data sources (Dearing, 2006; Elsawah et al., 2020; Moran, 2010; Navarro et al., 2025; Partelow, 2018; Silva et al., 2022).

There are also specific challenges related to ABM, such as explicitly determining the assumptions that define ‘decisions’ made by agents within the model, particularly those that capture the complexity of human behaviour (Larooij & Törnberg, 2025; Müller et al., 2013; Wijermans et al., 2023). The Overview, Design Concepts, and Details (ODD) protocol was specifically developed for ABM to offer a standardised framework for model description, promoting transparency and reproducibility (Grimm et al., 2020; see Kanters et al. (2021) on modifications to the original protocol for presentation and analysis of ABM results; see Müller et al. (2013) and Laatabi et al. (2018) on ODD + D (Decisions) and ODD + 2D (Decision and Data)). While the ODD (+ 2D) protocol has improved reproducibility significantly, it is not intended to address or resolve all the specific challenges of studies on humans and their environment.

In archaeological studies on past human–environment interactions, ABM has been widely applied for various regions and periods (*e.g.* Barton et al., 2010, 2015; Cegielski & Rogers, 2016; Heckbert, 2013; Janssen, 2010; Kohler et al., 2012; Lake, 2000, 2014; Nikulina et al., 2025, 2025; Riris, 2018; Scherjon, 2019; Stonedahl, 2010). The application of ABM in historical research (studies primarily reliant on written sources in comparison to archaeological research) is more limited (Düring, 2014). ABM has the potential to contribute to historical research by helping to make underlying assumptions explicit and to test the internal consistency of historical narratives (Ewert & Sunder, 2018; Gavin, 2014). Importantly, historical ABMs should be thesis-driven and based on both original evidence and existing scholarship (Gavin, 2014). Simulation-based approaches are not intended to replace traditional historical interpretation but rather to complement it, especially where an empirical record is unavailable or fragmented (Ewert & Sunder, 2018).

The period from 1000 BCE to 1000 CE presents a unique opportunity for interdisciplinary research in regions where palaeoenvironmental, archaeological, and written evidence is available. ABM with a focus on human–environment interactions has been applied for this period across various regions (*e.g.* northwest Europe) (*e.g.* Groenhuijzen & Verhagen, 2015; Joyce, 2019; Verhagen et al., 2021), although these fall outside the spatial scope of the current review. ABMs related to human–environment interactions in the Mediterranean have focused on earlier periods (*e.g.* the Neolithic and Bronze Age) (*e.g.* Arıkan, 2023; Arıkan et al., 2021; Barton et al., 2010; Symons & Raine, 2009). ABMs align well with questions posed in studies that draw heavily on the natural sciences, where abstract rules can capture essential dynamics despite sparse data (Cegielski & Rogers, 2016; Düring, 2014; Lake, 2014). As a result, most work has concentrated on other world regions or on the prehistoric Mediterranean, where the absence of textual evidence removes the methodological challenges posed by historical written sources. Yet the potential gains from addressing these issues in the historic Mediterranean are considerable.

Existing ABMs on Human–Environment Interactions in the Mediterranean, 1000 BCE–1000 CE

In this review, we include models that explicitly focus on the period 1000 BCE–1000 CE, with a little leeway either way (Table 2). Most of the available models are built in NetLogo, the most popular ABM tool in archaeology (Romanowska et al., 2021; Wilensky, 1999). NetLogo is a free and accessible modelling platform with its own Model Library and numerous application examples available online. It includes built-in extensions (*e.g.* GIS for working with spatial data and 3D visualisation), can be integrated with other programming languages (*e.g.* R and Python), and offers relatively readable code along with a relatively gentle learning curve (Antelmi et al., 2022; Romanowska et al., 2021).

The available models covering societies within the 1000 BCE–1000 CE window in the study area address a broad range of topics related to human behaviour,

Table 2 Overview of existing ABM-based studies on human–environment interactions in the Mediterranean, 1000 BCE–1000 CE

Reference	Study area	Study period	Sources used			Spatial resolution*	Step*	ODD and code publicly available?	Name of the model, ABM modelling tool/environment
			Environmental	Archaeological	Textual				
Graham, 2006	Roman Empire, western provinces	~3–4 c. CE	▲	▲	●	–	1 cycle?	Code: link is provided, but downloadable file is unavailable; ODD: no/not identified	NetLogo
Graham & Steiner, 2006	Central Greece, Central Italy	900–700 BCE and 1000–700 BCE	▲	●	▲	–	–	Code: link is provided, but downloadable file is unavailable; ODD: no/not identified	TravellerSim, NetLogo
Turchin et al., 2013	Afroeurasia	1500 BCE–1500 CE	●/▲	●/▲	●/▲	100 × 100 km	2 years	No/not identified	–
Cecconi et al., 2015	Italy (Southern Etruria)	~2300–~750 BCE	●/▲	●	○	5 ha	2 years	No/not identified	–
Crabtree, 2016	Southern France (Languedoc-Roussillon region)	~600–~100 BCE	▲	●	▲	–	1 year	Code: no/not identified; ODD: yes	NetLogo
Bertoncello et al., 2018a	South-Eastern France	2 c. BCE–3 c. CE	●/▲	●	●/▲	–	–	No/not identified	ModelAnSet project, NetLogo
Bertoncello et al., 2018b	South-Eastern France	2 c. BCE–3 c. CE	▲	●	●/▲	–	–	No/not identified	ModelAnSet project, NetLogo
Gauthier, 2019	Roman North Africa	Roman Imperial period (~ 1 c.–3 c. CE)	●/▲	●	▲	Hexagonal grid cells with a radius of 5 km	1 year	Code: yes; ODD: no/not identified	Silvanus, R

Table 2 (continued)

Reference	Study area	Study period	Sources used			Spatial resolution*	Step*	ODD and code publicly available?	Name of the model, ABM modelling tool/environment
			Environmental	Archaeological	Textual				
Vidal-Cordasco & Nuevo-López, 2021	Southern Greece (Aegean region)	1350–930 BCE	●	●	▲	4.2×4.2 km	1 year	Yes	BACO, NetLogo
Boogers & Daems, 2022	South-Western Anatolia (Sagalassos region)	1000–25 BCE	●	●	●/▲	100×100 m	1 year	Code: yes; ODD: no/not identified	SAGAscape, NetLogo
Dermody et al., 2022	Roman Empire with focus on the Mediterranean Basin	~2 c. CE	●	●/▲	●/▲	5 arc-minute (~9×9 km)	1 year	Code: link is provided, but downloadable file is unavailable; ODD: no/not identified	Grain production and trade model of the Roman world, NetLogo
Vlach, 2022	Roman Empire	165–190 CE	●	●	●/▲	20×20 km	1 day	No/not identified	NetLogo
Bernigaud et al., 2024	Southern France (Southern Gaul)	6 c. BCE–7 c. CE	●	●	●	8×8 km	1 year?	Yes	ROMCLIM, NetLogo

●, used as one of the main types of evidence; ○, not used evidence; ▲, used indirectly/partially in the model (*e.g.* to establish context; use of scholarship); –, not applicable/not clear from the paper. Combined symbols (*e.g.* ●/▲) denote ambiguous or intermediate use where this could not be clearly evaluated from the published description

*In the table, we report only the time steps and grid cell sizes of the models themselves, not those of all input datasets natural processes, and their reciprocal relationships: trade and interaction, settlement dynamics, land and resource use (Bernigaud et al., 2024; Bertoncello et al., 2018a, 2018b; Boogers & Daems, 2022; Cecconi et al., 2015; Crabtree, 2016; Dermody et al., 2022; Gauthier, 2019; Graham, 2006; Graham & Steiner, 2006; Vidal-Cordasco & Nuevo-López, 2021), health (Vlach, 2022), and conflict (Turchin et al., 2013) (Fig. 1).

Although the first models appeared in 2006, there was a notable gap until 2013, after which new models were published with increasing regularity (typically at least one per year with multiple studies published in 2022, Table 2). These trends broadly correspond to wider patterns in the increasing use of ABM in archaeology over the period 1970–2021 (Romanowska & Scherjon, 2023).

There are also models where exploration of environmental factors is not the primary focus; and some incorporate limited environmental features (*e.g.* terrain or water distribution) or only briefly acknowledge environmental influences without detailed modelling (*e.g.* Brughmans & Poblome, 2016a, 2016b; Carrignon et al., 2020, 2022; Fousek et al., 2017; Graham, 2017; Hanson & Brughmans, 2022; Kanters et al., 2021; Lawall & Graham, 2018). These studies primarily focus on social and economic behaviours, such as trade dynamics, ceramic distribution, and market integration. Although not explicitly modelling human–environment interactions, they are relevant for understanding past socio-environmental dynamics. They show how institutions, economies, social networks, and technologies function and change. Models of trade or material culture distribution, for example, can inform about population movements, agricultural intensity, and, consequently, on broader landscape changes. Moreover, these studies provide practical approaches that can be adapted to incorporate environmental factors. Yet, despite the region's size and its rich textual, palaeoenvironmental, and archaeological record, ABMs explicitly addressing human–environment interactions during this period remain remarkably rare (Table 2, Fig. 1).

The spatial and temporal scales of ABMs of human–environment interactions vary substantially (Table 2, Fig. 1). Most of the developed models focus on regional scales (*i.e.* across areas large enough to encompass multiple archaeological sites) (Bernigaud et al., 2024; Bertoncello et al., 2018a, 2018b; Boogers & Daems, 2022; Cecconi et al., 2015; Crabtree, 2016). This spatial focus allows one to explore how localised (*e.g.* household- or individual-level) decisions aggregate into broader socio-environmental patterns within regions. Other models have a broader, empire-wide or (sub-)continental scale focus. Dermody et al. (2022) model grain production and trade across the Roman Empire with specific focus on the Mediterranean. Vlach (2022) simulates the impact of the Antonine Plague across imperial territories. The model presented by Turchin et al. (2013) explores the long-term evolution societies across the entirety of Afroeurasia.

Although the ODD protocol was first introduced in 2006 (Grimm et al., 2006), not all reviewed models have a publicly available version (Table 2). This does not mean that protocols do not exist for the models included in our review (*e.g.* Bertoncello *et al*. state that they used the ODD protocol), but rather that they are not readily accessible, and perhaps remained unpublished. We identified publicly available ODD protocols for only three models (Table 2). In all other cases, it is not possible to reconstruct the full model from the information provided in the papers. This is expected given journal word limits and the expectation that more technical details are reported in other formats such as ODD.

A similar issue applies to code availability. Only four models have downloadable code, and three studies provided links to code, but the files were not downloadable or accessible. Overall, we identified only two cases in which both the code and the ODD protocol were publicly available (Table 2). This likely reflects changing expectations around open and reproducible ABM documentation over time since these two models were published relatively recently (in 2021 and 2024). As a result, the limited number of available models together with uneven documentation and shared codes makes it difficult to investigate trends in formal model set-up, data sources, and other aspects of the reviewed ABMs.

From the information available, we can say that ABMs with a socio-ecological focus developed for the study region and period use a wide range of evidence to establish the research context, inform model inputs, and assess modelling outputs (Table 2). This evidence includes historical written sources and various types of spatial data, such as palaeoenvironmental reconstructions (*e.g.* land cover, past temperature and precipitation patterns), archaeological site distributions, estimates of land use and population sizes. Historical written sources, whether cited directly or indirectly (*i.e.* based on discussions and interpretations in scholarly works), contribute to conceptualising, model development, and interpretation of results.

The combination of evidence used generally relates to the spatial scope of a study. Larger-scale models tend to rely more on aggregated historical and environmental datasets than on detailed archaeological evidence, reflecting ABMs' broader scope, as seen in Turchin et al. (2013) and Dermody et al. (2022). Vlach's study on the Antonine Plague (Vlach, 2022) provides another example: rather than validating results against a single empirical dataset, the plausibility of the modelled scenarios is assessed through comparison with estimates and discussions drawn from other studies.

By contrast, smaller-scale models are more likely to incorporate locally specific archaeological data. These ABMs generally still depend on interpretations of obtained results rather than formal (quantitative) assessments. For example, the study by Gauthier (2019) which focuses on demography and food production in Roman North Africa (roughly corresponding to present-day Tunisia, Algeria, and Libya) assesses simulated rural population densities against the known settlement distributions. This comparison is based mainly on spatial correspondence and visual overlay, rather than on formal quantitative validation. On the other hand, Crabtree (2016) compares simulated outputs with observed patterns in amphora distributions more explicitly via a pattern-oriented approach which links the model and archaeological evidence from Languedoc-Roussillon directly. Bertoncello et al. (2018a, 2018b) also refer to comparisons with archaeological records, but this aspect remains only partially developed since they do not present a full quantitative comparison between simulated outputs and archaeological data.

Two studies incorporate sensitivity analysis to understand model dynamics and identify the most important parameters for ABMs' outputs. This small number of studies means that sensitivity analysis is not a standard practice among the reviewed studies. In addition, this suggests a weak temporal trend towards more systematic assessment of developed ABMs and their results in recent studies. Beyond sensitivity analysis, other approaches such as approximate Bayesian computation (ABC) and genetic algorithm are not used in the reviewed studies.

Bernigaud et al. (2024) use a one-factor-at-a-time (OFAT) sensitivity analysis, varying each parameter separately while holding the others constant. Their results indicate that viticulture and olive growing are driven mainly by climate, whereas grain is more dependent on economic factors (market prices, transport costs).

Vidal-Cordasco and Nuevo-López (2021) also use sensitivity analysis, again explicitly with OFAT but combined with statistical analysis. They run 1296 experiments in total and analyse the outputs via Spearman rank correlations to test associations between inputs and outputs and random forest to estimate the relative contribution of each parameter to each outcome. The results indicated that resilience and vulnerability of the Late Bronze Age society depended on three factors: rainfall, soil erosion, and population's dietary patterns.

The role of written sources varies across studies, and there is no clear link between the scale of the model and the use of written sources. In some cases, it is explicitly acknowledged that the breadth of the historical record is beyond the scope of the developed model; however, selected written evidence is still used to frame assumptions about trade (*e.g.* Crabtree, 2016). In other studies, written sources and existing scholarship are used primarily to establish the study context rather than directly inform the model (Graham & Steiner, 2006; Vidal-Cordasco & Nuevo-López, 2021). This is especially useful in cases when the available written evidence is highly fragmentary given that incompleteness is a general feature of historical evidence. In some studies, the role of historical written evidence remains unclear or appears primarily intended to establish the research context.

There are examples of research where written sources play a more central role in model development. For instance, Bertoncello et al. (2018a, 2018b) mention that landowners' behaviour in their model is defined in accordance with written and archaeological data. However, it remains unclear how this specific evidence is translated into formal decision rules or parameters and how strongly it constrains model behaviour (Table 2).

Bernigaud et al. (2024) take a more detailed approach, combining written evidence from ancient agronomists with palaeobotanical and palaeoclimatic data to reconstruct agricultural production in southern Gaul. In practice, these texts are used to define the key elements of the model. Cato's agronomic treatise provides estimates of farm size and labour inputs, while Columella's recommendations on seeding rate inform grain production. This information from historical written sources was then combined with potential cereal, grape, and olive yields generated by an emulator of the Lund-Potsdam-Jena managed Land (LPJmL) agroecosystem model, driven by reconstructed climate variables. The market value of production is informed by Diocletian's Edict (301 CE), which provides maximum prices (listed in the supplementary material of the publication by Bernigaud et al. (2024)) for different commodities, while the user of this ABM selects the specific market price within the range. Nonetheless, the historical texts are not extensively critically evaluated or contextualised. Their geographical and temporal relevance (such as the applicability of texts written probably in Central Italy to southern Gaul) remains unaddressed, leaving the underlying assumptions about agricultural practices and environments insufficiently discussed.

Historical written evidence also plays an important role in the study by Dermody et al. (2022), particularly in relation to irrigation practices. But here this type of evidence is largely used through previous scholarship rather than historical sources directly. Historical and archaeological studies are used to support the assumption that irrigation was widespread and important in Roman agriculture, while the model itself applies irrigation in regions where it increases grain yields, where water can be transported at relatively low energetic costs, and where yield variability due to climate is high.

These two studies (Bernigaud et al., 2024; Dermody et al., 2022) stand out as examples in which written sources are used not merely for background but as core inputs shaping the simulation of agricultural processes. Nonetheless, both face challenges in transparency, particularly in showing the relevance and applicability of specific textual evidence and how it is translated into modelling assumptions.

Thus, ABMs for the Mediterranean between 1000 BCE and 1000 CE are still relatively rare, and only a limited subset explicitly model human–environment interactions. Given the low number of existing models and uneven documentation, it is challenging to identify trends in focus and the evidence used. Written sources are included unevenly, ranging from general contextual background to directly informing models, as in Bernigaud et al. (2024). Evaluation of modelled outcomes is also uneven, and only a few studies use sensitivity analysis or directly compare ABM results with empirical evidence. Overall, this review highlights both the growing potential of ABM for studying past socio-environmental systems and the continuing need for clearer documentation and more transparent use of different types of evidence, especially historical written sources.

Discussion

Current Interpretations of Societal Changes in the Mediterranean Throughout 1000 BCE–1000 CE and Methodological Challenges

Studying human–environment interactions in the Mediterranean presents several challenges, including differences in the resolution of available evidence and uncertainties regarding the extent to which such data permit broader generalisations (Table 1). Integrating multiple lines of evidence is essential, as the limitations of one dataset can be mitigated by the strengths of another.

Although numerous studies adopt such integrative approaches, proposed causal links between climatic or weather fluctuations and socio-political change often rely heavily on chronological correlations, and these interpretations remain debated (*e.g.* Harper, 2019; see criticism in Haldon et al., 2018a, 2018b, 2018c). For example, climatic changes and extreme weather conditions have been linked to major societal disruptions including shifts in subsistence strategies, migration, disease outbreaks, and the end of the western Roman Empire (*e.g.* Hirschfeld, 2006; McCormick, 2019; Norman et al., 2025; Ziegler, 2016). Such interpretations sometimes cast environmental factors as primary drivers acting upon societies, with humans shown as having limited agency in their responses. This reflects a broader challenge in studies of human–environment interactions: determining the appropriate weight to assign to human actions and finding a balance between portraying humans as active agents versus passive recipients (Silva et al., 2022).

Compared with earlier periods, later periods such as 1000 BCE–1000 CE often (but not always) provide a broader and more diverse evidential base, including historical written sources alongside archaeological and palaeoenvironmental data. The role of historical texts is to serve as a source of evidence for understanding the underlying mechanisms of long-term socio-environmental interactions (Silva et al., 2022). However, even with this richer evidence, it remains difficult to identify the relative importance of causal drivers such as comparatively short-term human decisions and long-term environmental changes, both of which define the dynamics of human–environmental connections (Silva et al., 2022). The potential mismatch between the scales at which social and ecological processes operate within the same system also presents challenges (Dearing, 2006; Silva et al., 2022). Human activities and decisions can occur over short timeframes and at local or regional levels, whereas ecological processes (*e.g.* climate change or soil degradation) may operate over centuries and across larger areas.

As a result, it remains an open question how much generalisation is possible in studies of human–environmental interactions based on archaeological, palaeoenvironmental, and written evidence, which scales of analysis are most appropriate across time and regions, and how to move between different scales (*i.e.* how processes on macro scale fit into localised dynamics and vice versa). While broader trends may offer an accurate general pattern, recent studies have shown that attention should be paid to local environmental conditions and how exactly these were affected by larger-scale climatic change: some regions do not reflect broader climatic trends, and even in areas in relatively close proximity, responses to changing conditions can differ (Haldon, 2019; Haldon et al., 2018a; Labuhn et al., 2018).

Given the inherently multi-scalar nature of human–environment interactions, it has been suggested that the search for a single ‘correct’ scale of analysis may be misguided. No level of analysis is sufficient to fully explain the combinations of environmental conditions and human activities that led to outcomes such as adaptation, resilience, and phase shifts (Silva et al., 2022).

Recent years have seen progress in scaling up local evidence through coordinated regional and global studies aimed at identifying broad socio-environmental patterns (Dearing, 2006; Magliocca et al., 2018; Marlon et al., 2013; Morrison et al., 2021; Stephens et al., 2019). One suggestion involves transforming written, archaeological, and palaeoenvironmental data into standardised, comparable time series (Silva et al., 2022), potentially facilitating studies with artificial intelligence (AI)–based methodologies. However, the current empirical record remains relatively sparse and uneven in spatial coverage, and there are ongoing difficulties in integrating diverse theories, concepts, and datasets related to long-term environmental and societal changes (Silva et al., 2022).

Thus, research on long-term human–environment interactions in the Mediterranean has several persistent challenges. These include uneven, incomplete, and biased evidence across sub-regions even though the Mediterranean is relatively well studied and offers diverse sources/archives, including written texts; difficulties distinguishing causation from correlation; and mismatched spatial and temporal scales between social and ecological processes, as well as between the different sources/archives used to reconstruct them. Such scale and resolution mismatches complicate the integration of archaeological, palaeoenvironmental, and historical evidence (Table 1) within a single study. In addition, methodological transparency remains limited, particularly regarding how written sources are incorporated into ABMs ('Existing ABMs on Human–Environment Interactions in the Mediterranean, 1000 BCE–1000 CE'). Although ABM has been used to study human–environment interactions in Mediterranean contexts (Table 2), applications remain relatively few (Fig. 1), and the full potential of this approach to integrate existing evidence, bridge conceptual gaps, and move beyond single-scale analyses has not yet been fully explored (Dearing, 2006; Le Page et al., 2017; Miyasaka et al., 2017; Silva et al., 2022).

What Can ABM Offer to Studies of Human–Environment Interactions?

ABM is not universally suitable for all aspects of human–environment interactions. Its limitations have been widely discussed, particularly with regard to the necessary simplification of complex human behaviours into programmable decision rules, the substantial computational demands for large-scale or high-resolution simulations, and the difficulty of managing models with many variables (Cegielski & Rogers, 2016; Le Page et al., 2017; Manson et al., 2020). Methodological developments (*e.g.* for calibration and optimisation) have been proposed to mitigate aspects of these limitations (Canessa & Chaigneau, 2015; Robertson et al., 2025). Nevertheless, ABM offers unique advantages for addressing several persistent problems in studying human–environment dynamics: specifically issues of incomplete evidence, identification of causal links and appropriate scales.

One of the challenges is the uneven visibility of archaeological evidence across regions and periods due to differential preservation, detectability, and survey intensity (*e.g.* Witcher, 2006b, 2016). For example, wine and oil production is often disproportionately represented because amphorae survive better than traces of cereal cultivation (Witcher, 2016). Rather than relying exclusively on such incomplete records, ABM allows us to simulate plausible socio-environmental scenarios beyond what is preserved, generate virtual datasets, and test the robustness of archaeological and historical interpretations in the context of biased or incomplete data (*e.g.* Carney & Davies, 2020; Cortell-Nicolau et al., 2025; Romanowska et al., 2019).

A key strength of ABM is its ability to run controlled experiments to reproduce empirical patterns (*e.g.* proxy-based land-cover reconstructions or distributions of archaeological sites) while isolating the effects of specific processes that impact these patterns within complex systems (Cegielski & Rogers, 2016; Dearing, 2006). Several archaeological ABM applications have already demonstrated this potential (*e.g.* Barton et al., 2021; Carney & Davies, 2020; Nikulina et al., 2024, 2025). In Mediterranean contexts, Vidal-Cordasco and Nuevo-Lopez (2021) and Bernigaud et al. (2024) explicitly evaluate modelling outcomes by using sensitivity analysis to isolate the influence of various factors on past socio-environmental dynamics. The simulated results for trade of wine in the transition period from Bronze to Iron Age in the Languedoc-Roussillon region are compared with empirical evidence (Crabtree, 2016).

Other ABM studies on human–environment interactions in the Mediterranean during the study period (Boogers & Daems, 2022; Gauthier, 2019) rely more on scenario exploration, theoretical dynamics, or internal system feedbacks than on direct empirical comparison. These approaches are entirely valid given the model's scope and the available data. However, they may leave underexplored one of the key strengths of ABM: the possibility of investigating causal mechanisms, for example through sensitivity analysis which helps to identify how different factors impact modelled outcomes (Nikulina et al., 2024; Romanowska et al., 2021). Where appropriate, methods such as ABC or genetic algorithm may also help to explore an ABM and its parameter space more systematically (Carrignon et al., 2020; Nikulina et al., 2025; Romanowska et al., 2021).

A persistent challenge is how empirical evidence is incorporated into ABMs. Currently, there is no standardised framework for incorporating empirical evidence into ABMs of past human–environment interactions. This flexibility is one of ABM's strengths, as it allows researchers to adapt models to different questions, datasets, and scales. At the same time, it can lead to highly variable practices. Rather than standardising exactly how each type of evidence should be incorporated, more attention should be paid to greater transparency in how evidence is selected, transformed into parameters and assumptions, justified, combined and included in studies, especially when historical written evidence is involved (Foxhall Forbes et al., 2026).

Clear reporting of data inclusion is essential not only for interpretability but also for addressing a key methodological concern: the risk of circular reasoning, in which the same data are used both to construct the model and to evaluate its outcomes. This is especially important when historical written sources are involved. Given the challenges associated with historical written evidence ('Sources/Archives of Evidence That Can Be Used to Study Human–Environment Interactions in the Mediterranean, 1000 BCE–1000 CE') and the difficulty of incorporating such evidence into ABMs, this risk is particularly important. Therefore, it is essential to state clearly which evidence is used at different stages of the model development sequence (Romanowska, 2015) and to ensure that this is transparent to both readers and potential model users. ODD protocol and open-source ABM libraries (*e.g.* www.comses.net) already offer important steps towards this, but their application remains largely limited among reviewed ABMs (Table 2).

In some contexts, model-derived datasets from other frameworks can be used. For example, raw pollen counts are difficult to interpret due to taxon-specific differences in productivity, dispersal, and preservation (Serge et al., 2023). As a result, approaches such as Multiple Scenario Approach (MSA) and Regional Estimates of VEgetation Abundance from Large Sites (REVEALS) were developed to generate corrected vegetation reconstructions (Bunting & Middleton, 2009; Bunting et al., 2018; Fyfe et al., 2025; Sugita, 2007a). In particular, REVEALS produces corrected vegetation estimates at regional scale (*e.g.* Hellman et al., 2008; Mazier et al., 2012;

Serge et al., 2023; Sugita, 2007a). The LOcal VEgetation Estimates (LOVE) model provides pollen-based reconstructions at a local scale (*e.g.* Katrantsiotis et al., 2025; Pearce et al., 2025; Sugita, 2007b). Both REVEALS and LOVE are components of the broader Landscape Reconstruction Algorithm (LRA) framework, which contributes to multi-scalar integration via transitions between broad regional patterns (REVEALS) and local vegetation reconstructions (LOVE). These models bridge scales and support integration across them. In addition, these datasets are best suited for long-term trends and require coordination and standardisation.

While such datasets help to mitigate some of the limitations in datasets used in ABMs, it is important to recognise that they are themselves modelling outcomes. As such, they come with their own sets of assumptions, uncertainties, and potential biases, all of which must be carefully evaluated when integrating their outputs into other models (Nikulina et al., 2024, 2025). In the Mediterranean context, outputs from other models have already been incorporated into ABMs. For example, Dermody et al. (2022) use HYDE population estimates to model grain demand, while outputs from the hydrological model PCR-GLOBWB are used to estimate grain yields and water use. While this study has its methodological advances, the authors acknowledged that using HYDE estimates produced outcomes suggesting grain deficits in some Roman provinces, contrary to historical evidence. Similarly, Welton et al. (2025), in a study that also partially covers the Mediterranean, found that for the mid-Holocene, HYDE and KK10 show land use patterns that differ from reconstructions based on archaeological evidence. Thus, there is need for caution when relying on model-derived inputs in ABMs for studies on past socio-environmental systems.

Historical written sources raise additional challenges. Their inclusion should not be treated as automatically beneficial, since they may increase model complexity without improving the model. Where the written record is sparse there is also a risk of extrapolating too broadly from limited information. The relationship between complexity and performance is often discussed in terms of the Keep It Simple Stupid (KISS) and Keep it Descriptive Stupid (KIDS) trade-offs: whether models should remain as simple as possible to aid understanding (KISS) or instead incorporate more complexity and details to better approximate a reality (KIDS) (Axelrod, 1997; Edmonds & Moss, 2005). KISS is considered as one of the best practices in ABM (Romanowska et al., 2021).

However, for the Mediterranean between 1000 BCE and 1000 CE, written sources often preserve information about institutions, decision-making, economic practices, and social responses and perceptions that cannot be recovered from archaeological or environmental data alone. The value of historical written evidence, therefore, lies in enabling ABMs to address a different set of research questions. Two of the reviewed models, Bernigaud et al. (2024) and Dermody et al. (2022), illustrate this potential, even if they also reveal ongoing problems of transparency and contextualisation. The priority, then, is not simply to include more historical evidence but to develop clearer and more reproducible ways of deciding when it is useful, how it is translated into model assumptions, and how its contribution can be evaluated (see 'Towards a Methodological Framework for Integrating Written Sources into ABMs on Human–Environment Interactions').

The incorporation of quantitative historical data (*e.g.* prices, household sizes, or tax records) might in some cases seem to be relatively straightforward. Qualitative evidence (*e.g.* perceptions of the environment or societal responses to climatic events) is harder to formalise and is, therefore, often excluded. Yet historical texts can inform agent behaviour, provide parameter values, define testable scenarios, or help evaluate model outcomes. Approaches for translating qualitative information into model assumptions remain underdeveloped. Some suggestions already exist, such as linguistic and statistical tools (Franzosi, 1998), ABMs based on expert knowledge (Oetker et al., 2023). An important consideration is to avoid circular reasoning mentioned above and clarify how evaluation should proceed: whether through qualitative historical contextualisation, quantitative assessment (requiring conversion of qualitative data), or a hybrid approach supported by close collaboration between different fields. In relation to that, one persistent concern is the perceived lack of transparency in how models are constructed, parameterised, and interpreted.

As noted above, there is unlikely to be a single optimal scale for studies on human–environment interactions given their multi-scalar nature. While scale-crossing approaches are well established in environmental sciences, their integration into social studies remains relatively scarce (Elsawah et al., 2020). As a bottom-up approach, ABM presents an opportunity for multi-scalar analysis since it allows for the explicit representation of individual agents and their interactions at the local (micro) level and at intermediate (meso) scales when agents are organised into groups or networks (*e.g.* households or neighbourhoods). These interactions can lead to emergent macro-level patterns at the system level, thus facilitating the exploration of how social organisation and decision-making processes operate across scales within human–environment systems.

Thus, ABMs can be powerful tools for identifying causal mechanisms across scales and exploring socio-environmental scenarios even when evidence is incomplete, uneven, or highly fragmented. The value of these models, however, depends on the quality and transparency of the underlying data, their use and assumptions. ABMs and formal models more broadly function not only as heuristic tools but also as frameworks for making assumptions explicit, improving transparency, and strengthening reproducibility, areas in which substantial progress is still needed despite ongoing efforts across disciplines (Istrate, 2021; Le Page et al., 2017; Lee et al., 2015) even in relatively data-rich regions such as the Mediterranean.

Towards a Methodological Framework for Integrating Written Sources into ABMs on Human–Environment Interactions

One of the key challenges identified in the current review is the absence of clear methodological pathways for the systematic integration of the information from historical written sources together with other evidence listed in Table 1. While a fully developed framework is beyond the scope of this paper, here we outline a conceptual approach to illustrate how such integration might take place in practice based on our ongoing work in the SSE1K project (https://pric.unive.it/projects/sse1k/home).

At its core, our approach treats written sources not as contextual background but as structured evidence that can inform models. The process begins with the extraction of statements from historical written sources that relate to decision-making, practices, or constraints (*e.g.* agricultural choices, use of natural resources, or environmental perceptions). These statements are then critically evaluated by professional historians in order to determine their temporal and spatial applicability (*i.e.* for which period(s) and area(s) can this information reasonably be used), as well as their degree of reliability, acknowledging the fragmentary and context-dependent nature of historical evidence. The extracted statements should be treated as a dataset used for the model development or for evaluation of results and should accompany the ABM and/or associated publication in a structured format. This will allow readers to trace the origin of modelling assumptions which were based on historical written sources.

As noted in 'Sources/Archives of Evidence That Can Be Used to Study Human–Environment Interactions in the Mediterranean, 1000 BCE–1000 CE', historical written sources provide heterogeneous, partial, and sometimes contradictory evidence. Nevertheless, specific evidence can still be extracted and used for modelling exercises. For instance, studies by Goodchild (2007) and Goodchild and Witcher (2010) show how information related to agriculture (*e.g.* agricultural yields derived from textual sources) can be combined, quantified, and integrated into spatial models of production. However, the integration of qualitative historical evidence into models is more difficult. Therefore, it is necessary to translate qualitative statements into forms that can be used for modelling.

Depending on the available data and the research question, this may involve linking described conditions (*e.g.* characterised as 'dry' or 'warm') to numerical ranges derived from independent datasets (*e.g.* climatic or environmental reconstructions), while taking into account the temporal and spatial applicability established in the previous step for the extracted statements. For example, if a source refers to 'dry' conditions in a specific region and period, it is necessary to determine what 'dry' corresponds to in that particular context, based on available environmental data. Importantly, such translations make the link between environmental conditions and agricultural decision-making (*e.g.* crop choice, sowing and harvesting schedules) or expectations of yield explicit and traceable to its source of information.

The translation step results in numerical ranges that can be used to define ABM parameter thresholds or agent decision-making. Thus, historical information does not simply supplement the model but rather actively shapes the model development. In addition, such an approach allows for the coexistence of different types of evidence within the model, including historically informed practices and environmental conditions, making it possible to explore how their interaction influences system dynamics.

Importantly, this proposed workflow is not intended as a fixed protocol but as a flexible and iterative strategy that can be adapted to different research questions, regions, and datasets. Its purpose is to make explicit the intermediate steps between different evidence and formal modelling, thereby increasing transparency and reproducibility. More broadly, it highlights the potential of ABM to serve as a bridge between different types of evidence, enabling the exploration of how decisions and perceptions recorded in historical sources may have shaped long-term human–environment interactions.

Such studies depend on close collaboration between historians, archaeologists, geoscientists, and modellers. Each type of evidence requires specific expertise and must be analysed according to the methodological standards of the discipline from which it derives (Foxhall Forbes et al., 2026). One of the major challenges is that different fields often work with different concepts, standards of evidence, temporal and spatial resolutions, publication practices, and availability of funds, which can make sustained collaboration difficult. At the same time, ABM can provide a useful platform for interdisciplinary dialogue, since it requires assumptions, uncertainties, and causal relationships to be made explicit and openly discussed. In this sense, the development of ABMs for past human–environment interactions should be seen not only as a modelling exercise but also as a collaborative process of knowledge integration.

Conclusion

Studies of past human–environment interactions in the Mediterranean throughout 1000 BCE–1000 CE are based on different written, archaeological, and palaeoenvironmental sources. They vary in spatio-temporal resolution, posing challenges for integrating diverse types of evidence within a single analytical framework and complicating efforts to identify the causal mechanisms in the functioning of past socio-ecological systems. As a result, there is a risk that palaeoenvironmental fluctuations that correlate with socio-economic changes are misinterpreted as causal drivers of those changes.

Our review of ABMs developed to study human–environment interactions in the Mediterranean between 1000 BCE and 1000 CE reveals that relatively few models explicitly focus on these relationships, despite the region's extensive research history and the availability of evidence. The limited number of models, together with uneven documentation and the small number of publicly available ODD protocols, makes it difficult to identify meaningful trends in model development.

The reviewed ABMs utilise a wide range of evidence to define research context, inform models, and assess outputs. In most studies historical written evidence is used in a more general or contextual way, and fewer models use such evidence more directly in model development. Methodological transparency in relation to the use of this type of evidence remains limited, particularly regarding how written evidence is selected, evaluated, translated into formal rules or parameters, and assessed in terms of spatial and temporal applicability. Likewise, the evaluation of model outputs is uneven: only some studies compare outputs directly with empirical evidence, and only a few apply sensitivity analysis. At the same time, some degree of variability is to be expected, given the flexibility of ABM, differences in research questions, uneven research histories, and major differences in data availability across Mediterranean regions. Nevertheless, it remains essential that ABM studies specify clearly which data are included, and how they are used at different stages of model development, in order to avoid circular reasoning and to address concerns in the wider historical and archaeological communities about the value of the approach.

ABM's capacity to simulate interactions across multiple spatial and temporal scales (even when empirical data are uneven, biased, or incomplete) makes it particularly valuable for studying socio-ecological systems in historically complex regions such as the Mediterranean. By integrating heterogeneous evidence, including archaeological, palaeoenvironmental, and historical data, ABM allows us to move beyond identifying correlations and instead test explicit causal mechanisms under controlled, reproducible experiments. Importantly, ABM can quantify how diverse environmental and social processes operating at different scales interact to produce emergent system-level outcomes.

Building on this review, we identify several priorities for future work. First, greater standardisation and transparency in model description and data use are crucial for reproducibility, including the consistent application of protocols such as ODD (+ 2D), open sharing of code, and explicit reporting of how data are transformed and incorporated into models. Second, where the research question allows and data are available, historical written sources need to be more systematically and critically integrated into studies of human–environment interactions. It is important especially in studies that develop ABMs, where historical written sources should be used not merely as contextual background but as substantial inputs to models with careful consideration of spatial and temporal constraints of historical written evidence. Third, scale-crossing research designs should be applied. ABM can help link local decision-making with emergent patterns at regional and supra-regional scales and vice versa, thereby revealing causal mechanisms.

When combined with such methodological advances and genuinely interdisciplinary collaboration, ABMs and other formal approaches can make assumptions explicit and support the testing of hypotheses about long-term socio-ecological dynamics. In doing so, they can help to bridge persistent gaps between datasets, scales of analysis, and theoretical frameworks; improve our understanding of how human–environment relationships evolved in the Mediterranean over the long term; and clarify how their historical legacies continue to shape contemporary sustainability challenges.

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Declarations

Competing interests The authors declare no competing interests.

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