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Framing settlement systems as spatial adaptive systems

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ABSTRACT

Theoretical developments are needed to interpret the increasing amount of large-scale spatial data about past settlements. So far, settlement patterns have mostly been considered as passive imprints of past human activities and most theories are limited to ecological processes. Locational and spatial interactions have scarcely been included as long-term driving forces of settlement systems but hold promise to explain large-scale patterns. This paper proposes a conceptual model for long-term spatial adaptive settlement systems based on the complex adaptive systems framework and both spatial and cross-scale interactions. The goal of the model is to find new ways of interpreting archaeological location data and understand settlement systems as emerging from micro-choices of population units interacting in space. The conceptualisation is carried out on a level that it can be used to bridge hunter-gatherer and urban theories.

We first describe settlement patterns based on concepts from archaeological locational studies and social-ecological systems. Second, we identify the abstract spatial and aspatial entities of the system and describe the potential relations between them. Using knowledge from previous research, we then map both empirically observable and abstract system entities and predict links between them in order to come up with an overarching conceptual framework. The system is based on residential choice mechanisms and exposes several cross-scale feedback loops between the micro-level choices and the settlement system emerging at the meso-level. We finally argue that the proposed adaptive settlement system framework has the potential to bring new insights into long-term processes, especially through dynamic spatial simulation, and at the same time, provides an interpretational framework for archaeological records and empirical spatial analysis. Examples of its applications in archaeological research are introduced.

0. Introduction

The diachronic interplay between population, environment, and human socio-economic formations is currently considered as one of the great challenges of contemporary archaeology (Altschul et al., 2017). Settlement patterns[1] as spatiotemporal projections of large-scale processes provide essential insights into the topic. The primary means of understanding the dynamics of settlement systems is formalised spatial analysis (Verhagen, 2018, p. 21). In recent decades the advancement of geographical information systems has completely revolutionised the field and led to an abundance of empirical data and methodology for analysis.

In particular, locational models, which are in the focus of this paper, have yielded considerable success in providing quantitative descriptions of environmental conditions (see Judge and Sebastian, 1988; Mehrer and Wescott, 2005; Verhagen and Whitley, 2012) and recently also spaces (e.g. Banks et al., 2006; Whitford, 2019; Vernon et al., 2020; Sikk et al., 2022) suitable for human activities. Although these models have good predictive power, there have been calls for the development of a theoretical framework to add new depth to explanations that can be achieved with the rapidly increasing quality of archaeological data (Whitley et al., 2010; Verhagen, 2018, p. 14).

There has been a lack of theory building between data exploration and extrapolation in the process of predictive modelling. Theory has been assumed to be existing or reduced to simplistic ecological cause effect relationships (Verhagen and Whitley, 2012, p. 57). Verhagen and Whitley (2012, p. 71) have stated that the purely empirical, predictive approach lacks by nature two key elements: causality and cognition. While predictive models provide some methods for exploring results,

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[1] For clarity, we distinguish between settlement patterns as observable in the archaeological record and settlement systems as systemic entities that existed in the past

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they are often considered to be a "black box" (Verhagen and Whitley, 2012, p. 71). This leads to a simplification of causal explanations for ecological constraints with spatial effects being completely neglected.

Although settlement patterns are considered as one of the most important conceptual developments in 20th-century archaeology, they have been usually observed as a passive footprint of human activities. Theoretical approaches have been divided into different disciplinary silos and this has prevented developing a framework that could connect knowledge of hunter-gatherer and urban settlement. It has been said that despite the great potential for theoretical contributions and the wealth of collected data, settlement pattern studies have only scratched the surface of what is possible (Feinman, 2015; Vogt, 1956; Parsons, 1972; Crumley, 1979; Judge and Sebastian, 1988).

To contribute to the theory and broaden the scope of interpretation we propose a conceptual model of settlement system formation by integrating knowledge from locational and social-ecological system (SES) modelling. While locational modelling traditionally provides insights into the locations of settlements, SES provides a framework to work with the social and ecological processes involved in settlement system formation. It considers systems with bio-geo-physical features interacting with social actors (Berkes et al., 1998; Anderies et al., 2004; Ostrom, 2009; Schoon and Leeuw, 2015; Fitzhugh et al., 2019) in the general framework of complex adaptive systems (CAS). We particularly base our approach to SES as proposed by Anderies et al. (2004).

The CAS approach makes it possible to describe settlements as evolving dynamic systems (Pumain, 2000) using tools of complexity science including complex interactions and emergence and cross-scale feedback loops (Verburg et al., 2016). One essential aspect is the inclusion of space as one of the active drivers (Favory et al., 2012) of settlement systems which reach steady states in the process of morphogenesis.

Based on CAS principles we approach a settlement system as a populations spatial adaptation to the environment. The central adaptation mechanisms which also bridge the locational modelling and SES are residential choices carried out by population members who follow a specific socio-economic strategy.

The model is based on multiple levels which include individual choices (micro level) and emerging spatial patterns (meso level) and is intended to more closely integrate those levels. To do so we create a systems map containing spatial and non-spatial entities connected by information flows and feedbacks. By identifying the entities constituting such a spatial system, their relations, as well as feedback loops across scales we construct a general conceptual framework. Possible empirical sources of exploring specific settlement systems are discussed. The higher level purpose of the framework is to create a basis for further simulation modelling based on theory building and exploration of particular settlement systems.

It is intuitive that individual residential choices lead to spatial reorganisation and form spatial patterns which in turn influence new choices. We argue that choices and patterns are joined through similar cross-scale feedback loops, leading to non-linear relationships. Therefore the inherent complex and adaptive nature of settlement systems (Allen, 1997; Pumain, 2012; Sanders, 2021) is linked to micro-scale interactions. Explaining even isolated aspects of complex systems, like the effects of environment and social organisation, requires a general overview of complete systems.

The remainder of this paper is organised as follows: in the two following sections a brief overview of settlement pattern studies is provided and the theory of social-ecological systems is discussed. In the next section the conceptual model is constructed and the theoretical and empirical background of its components is considered. In the "Discussion and perspectives" section, model implications, future research and limitations are discussed with an emphasis on empirical interpretation of locational models.

1. Theoretical background

1.1. Modelling settlement system formation

Archaeological settlement patterns are reconstructed using observations from archaeological excavations, surveys or remote sensing. The central units in these patterns are typically settlement sites, which indicate past human activities and their distribution in space (Parsons, 1972). Here we briefly discuss the existing formal geographical research in archaeology that may serve as a basis for developing a theoretical model of settlement system formation.

The theoretical background for formal approaches to settlement patterns was developed within the processualist movement in archaeology (e.g. Clarke, 1977). An initial implicit understanding that settlement patterns can be considered as a mapping of social organisation in space (e.g. Willey, 1953; Trigger, 1967) was gradually developed, with Winters referring to the functional relationships between groups of contemporary sites and starting to distinguish between settlement systems and settlement patterns (Winters, 1969). Approaches to settlement studies further evolved into more explicit models using geographical theories (e.g. Crumley, 1979).

More recently, in cooperation between geographers and archaeologists, archaeological knowledge has been used to develop geographical theories of evolution of settlement patterns to various urban forms (Favory et al., 2012; Garmy, 2021; Sanders, 2021). For this complex system models have been typically designed on meso-level using settlements as central units of the systems. Examples of such models include the first multi-agent model used in geography, SIMPOP1 (Sanders et al., 1997) and the following series of SIMPOP models where the objective was to identify conditions of emergence of cities from the initial relatively homogeneous rural settlement system over the duration of ca. 2000 years (Pumain, 2012). The growth or decline of a city in the system is modelled through trade interactions with the surrounding villages and other cities (Sanders et al., 1997; Pumain et al., 2009).

Most of these models are based on archaeological knowledge as opposed to direct data-based modelling. Several empirical models have been created to explore specific aspects of settlement systems. For example relations between settlements and regularities of rank–size are well-known universal principles and included in theories of urban systems and their evolution (Batty, 2001; Bretagnolle et al., 2007; Pumain, 1997, 2006). Rank–size hierarchies (e.g. Bevan and Wilson, 2013; Crema, 2014; Davies et al., 2014) and settlement scaling (Hamilton et al., 2007; Ortman et al., 2015) models have been mostly applied to study settlement size. Both of these approaches develop social reasoning behind spatial population structuring. In addition, formal methods have been used to explore different spatial aspects of settlement including relationships between residential core and related territories and settlement size and scaling. Territorial studies have used both environmental reasoning (e.g. catchment analysis) and social reasoning and often apply geographical techniques like Thiessen polygons to settlement distribution data (e.g. Clarke, 1977; Kriiska, 2003; Nakoinz, 2010).

1.2. Locational modelling of settlement in archaeology

As in this paper we focus on residential location choice as the generative principle of settlement patterns we focus on locational models as the main source of knowledge. Locational models started to be built with the general purpose of describing and predicting site locations (for a thorough overview of locational models see Mehrer and Wescott, 2005; Verhagen and Whitley, 2012; Verhagen, 2018). Central to the reasoning of these models was spatial decision making. Behavioural ecological methods (for an overview see Kelly, 2013; Kennett and Winterhalder, 2006) derived from biological and economic modelling e.g. optimal foraging theory (overview: Martin, 1983, central place foraging (Kelly, 2013, p. 96–101) and diet breadth model (Kelly, 2013, p. 46–52), were used to explain spatial behavioural phenomena including location and mobility decisions. These decisions were mostly considered to be based on access to food resources, sometimes abstracted as energy, and their spatial distribution (Wood, 1978). At the same time a range of models started to consider the dependence of these choices on existing populations using geographical theories like central place theory (King, 1985; Nakoinz, 2010). Gravity models were introduced in theoretical studies of hunter-gatherer locational choice (Jochim, 1976; Bettinger, 1980). The work by Limp and Carr (1985) introduced decision making as an interpretative topic in archaeology in a more general context.

In the 1980s there was a radical shift in theoretical direction. The adoption of post-processual theory principally downplayed both environmental and social organisation-based determinism and rejected the study of explanations based on regularities. It instead promoted the role of individuals as the driving force in archaeological patterning and focused on their multiperspective exploration (for an overview see Verhagen and Whitley, 2012, p. 60.

The second change can be linked with the rise of GIS applications. Empirical analyses based on the physical environment started to be used in cultural resource management (CRM). Paradoxically, although successful, their quantitative results were hard to connect to theoretical frameworks, and this created a split of practises between CRM and academic research. These studies produced well-performing predictive models that in themselves provide a strong validation of environmental effect on settlement location choices Verhagen and Whitley, 2012).

Debates about the limitations of the explanatory power of these models followed Wheatley, 2004; Kamermans, 2007, p. 60. It is generally accepted that location choices are determined by two groups of factors: local environmental conditions and social factors, which depend on relations with the existing population (Vogt, 1956, p. 174–175; Wood, 1978; Crumley, 1979; Bevan and Conolly, 2006). Ultimately the limitations of empirical models arise from the distinction between environmental and social factors, with only the environment being relatively well observable in archaeological material. Kohler (1988, p. 19–21) argues that the reasons for this are "subtleties and especially the fluidity of the socio-political environment", which refers to rarely observable dynamic change.

Awareness of these limitations was apparent while developing the models, and several valuable insights and hypotheses were expressed in the seminal book edited by Judge and Sebastian (1988). The predictive power of the models was questioned from a systemic perspective. Ebert and Kohler (1988, p. 106) considered the following question to be essential: "What proportion of human behaviour is immediate and can be explained by proximity arguments and what proportion is systematically organised within a given society?"

This question establishes the potential of given locations for habitation as being dependent on their position in the context of the existing population, which in turn is dependent on social organisation. It was hypothesised that as social complexity grows, the proportion of social factors in settlement choice also increases (Altschul, 1988, p. 81; Kvamme, 2005, p. 18, 19), leading to a decrease in the effect of the natural environment.

Location choice was considered to be influenced by economic intensification (Ebert and Kohler, 1988, p. 141) and the spatial configuration of the natural environment (Ebert and Kohler, 1988, p. 138–142). From a predictive point of view these influences reduce the model function as they introduce spatial autocorrelation into model results. But these spatial effects also offer the potential of extracting new, indirect information from environmental models and thus gaining new insights into past societies.

Recently it has become widespread practice in archaeology to integrate human activities and environment into one system (Edwards and Sadler, 1999; Kirch, 2005; Fitzhugh et al., 2019). In modelling studies, attempts have been made to overcome the distinction between environmental and social factors by using first and second order point process modelling (Bevan and Conolly, 2006; Davis et al., 2020; Vernon et al., 2020) and network techniques (Knappett et al., 2008; Bevan and Wilson, 2013) which provide theoretical static corrections to predictive models.

Two important frameworks that have recently been introduced to the field can help explain settlement system formation based on locational data. The first major innovation is the development and widespread adoption of eco-cultural niche modelling (Banks et al., 2006; Banks, 2017; Whitford, 2019; Vernon et al., 2020), which is based on the ecological concept of human niche (Hudson, 1969; Kvamme, 1985). It provides a mature framework for isolating the niche of various human cultures, but as it is focused on human–environment interactions it does not provide a toolkit to isolate the population-dependent effects that lead to pattern formation within that niche.

A new level of explicit formulation of individual decisions was introduced with the second methodological framework, known as agent-based modelling (ABM). In archaeology the methodology provides a way to connect processual and post-processual visions of research, with the first focusing on emergent patterns and the second on individual actions. ABM forces researchers to adopt a rigorous approach for the formal description of individual behaviours, which in itself contributes to theory building. Several models using location choice and settlement pattern formation (Axtell et al., 2002; Kohler et al., 2007; Wilkinson et al., 2007; Chliaoutakis and Chalkiadakis, 2016) have been created. In most cases, location choice is based on proximity to specific resources, e.g. soil fertility, game, water and fuel (e.g. Kohler et al., 2007, p. 63), with resource availability being modified by depletion processes (e.g. Kohler et al., 2007, p. 63). But social and political concerns have also been addressed (Griffin and Stanish, 2007; Heckbert, 2013).

To broaden understanding of settlement systems (Judge and Sebastian, 1988; Kvamme, 2005; Verhagen and Whitley, 2012) in an empirical and methodologically rigorous way, integrating previous research to create an overarching inferential framework is still needed. This enables researchers to keep pace with the fast development of data acquisition and processing techniques and provides tools to study the long-term dynamics (Verhagen, 2018, p. 14) of human–environment interactions (Saqalli et al., 2014; Silva et al., 2022).

1.3. Social-ecological systems

To overcome the divide between social and environmental influences, we propose using concepts from the social-ecological system (SES) approach, which is increasingly used to tackle contemporary issues related to environmental change and its relationship with human activities. SESs are generally defined as coherent systems with interacting biophysical and social factors (see Fig. 1); they are used to bridge social and environmental dimensions (Berkes et al., 1998, 2001; Ostrom, 2009) and more recently also technological dimension (Depietri and McPhearson, 2017; McPhearson et al., 2022). This approach has become particularly relevant with the acknowledgement of global change; sustainable development is seen as being too limited a concept, and longer-term objectives including adaptation and resilience therefore need to be considered (Silva et al., 2022).

The SES approaches started to be developed both from the ecological and social fields. The ecological strand originally grew out of resilience thinking and theories about the co-evolutionary nature of human and biophysical systems (Norgaard, 1994). The first studies of interactions between ecosystems and society were carried out in cooperation between social and natural scientists (Gunderson et al., 1995), and these were followed by an explicitly defined research programme coupling social and ecological systems (Berkes et al., 1998, 2001; Ostrom, 2009; Schoon and Leeuw, 2015).

The original goal of that research programme was to help develop contemporary ecosystem management practices. SES links hierarchically nested ecosystems with similarly nested social systems through

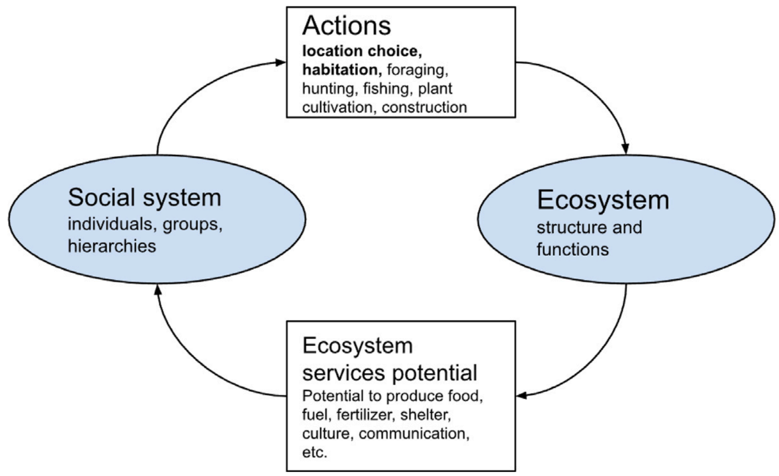

Fig. 1. Social-ecological system diagram adapted for residential choice from Resilience Alliance (2007). "Assessing and managing resilience in social-ecological systems: supplementary notes to the practitioners workbook".

management actions and the reception of ecosystem services based on ecological knowledge and understanding (Berkes et al., 1998).

Alongside the progress in the ecological domain, SES also developed along the work initiated by political economist Elinor Ostrom on common-pool resources, challenging their centralised control (Ostrom, 1990). Her initial Institutional Analysis and Development (IAD) framework highlighted how various actors interact in different social, ecological, or social-ecological situations, enabling her to structure her research on small-scale SESs. Problems with general system dynamics and gradual exogeneous influences prompted the development of her Social-ecological systems framework and the exploration of conditions for self-organising sustainable communities (Ostrom, 2019, 2009). This approach highlighted the need to study how institutions, communities and the environment interact and led to a classification of external factors into biophysical conditions, community's attributes and the rules-in-use. Empirical studies of these contextual variables got increasingly intertwined with a coupled systems perspective, and results highlighted the importance of both environmental and organisational components (Ostrom, 2009).

Ostrom's contributions significantly advanced the understanding of social-ecological systems by integrating institutional perspectives and cooperative behaviours. In turn, this underscored the importance of considering multi-level analysis, from individual behaviours to organisational and population-level dynamics and explicitly differentiating individual actors (users), governance systems, resource units, resource systems and ecosystems (Ostrom, 2009; del Mar Delgado-Serrano and Ramos, 2015).

SES systems are considered to be universally complex and adaptive. The social and ecological systems within them are linked through feedback mechanisms (Berkes et al., 2001; Ostrom, 2009). SESs can therefore be considered as complex adaptive systems (CAS) displaying properties such as non-linearity, emergence, self-organisation, hierarchies and dynamic stability with multiple steady states (Holling, 1973) and chaotic and catastrophic behaviour (e.g. Petrosillo et al., 2015). These properties can be explored as emergences ranging from relatively simple behaviours of the individual elements of the system to complexity approaches such as ABM (see Filatova et al., 2013; Gotts et al., 2019).

As the structure of interactions is lost in the previously mentioned Ostroms social-ecological systems framework, the "Robustness of SES Framework" was developed (Anderies et al., 2004). This framework explicitly displays the interactions and feedbacks between the system's elements as derived from empirical data. The framework has been used for developing and interpreting SESs in various case studies including foragers land use (Freeman et al., 2019) and provides several core elements of the framework developed in this paper.

In recent years, the Social-Ecological-Technological Systems (SETS) approach emerged as a further extension (particularly in urban contexts Depietri and McPhearson, 2017; McPhearson et al., 2022). It acknowledges the critical role of technology in shaping and mediating human–environment interactions, distinguishing the technological sphere as a distinct entity, akin to social and ecological systems. Beyond contemporary technological innovations, SETS can support the analysis of technology effects within any human–environmental interaction system. It provides additional tools to structure and map empirical data on system entities and feedbacks.

SES approaches have been used to study contemporary land use (e.g. Dearing et al., 2010; Rounsevell et al., 2012), including an exploration of system feedback loops (Meyfroidt, 2013), and to frame a theory of land use (Turner et al., 2020). SES has been also used for traditional land use systems like resource management for farmers in Tanzania (Tengö and Hammer, 2003), indigenous knowledge of the environment (Fairhead and Leach, 1996), and human ecodynamics using archaeological data (Fitzhugh et al., 2019). The term SES has only recently been adopted in archaeology (e.g. Barton et al., 2012; Kohler et al., 2012; Solich and Bradtmöller, 2017; Daems, 2021) but applying agent-based models to generally explore integrated social and environmental dimensions has been already practised for decades (see Section 2.1).

Applying an SES perspective to settlement systems introduces the possibility of considering settlement as a fully coupled system without artificial isolation of various facets (Cote and Nightingale, 2012). SES also enables us to describe settlement as a dynamic system with multiple steady states (Holling, 1973) and paves the way for the inclusion of generative principles like networks, cost-benefit and information to study concepts like resilience and investigate the long-term dynamics of human impact on nature and vice versa.

2. Combined: Adaptive settlement systems

2.1. Settlement system

The general purpose of the proposed conceptual model is to map both empirically observable and abstract system entities and predict links between them using knowledge from previous research. For this we develop a systems map (see Fig. 2) as outlined in this section. In the map we include both spatial and aspatial entities and argue about their connections using information flows guiding decisions and physical processes leading to feedbacks. This system map then serves as a backbone for a conceptual framework with a high-level goal to gain insights into the long-term dynamics of settlement systems in the context of environmental history and human ecodynamics. We

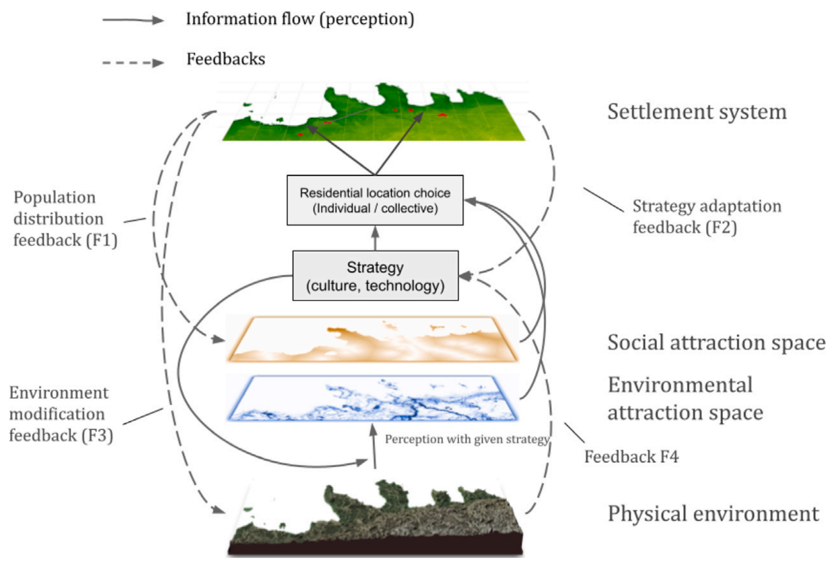

Fig. 2. System map of the proposed model of formation of spatial adaptive settlement systems of a hypothetical case. Layers are spatial entities, from top to up: real physical environment, perceived environmental attractions in the space (blue), perceived social attractions in the space (golden) and settlement system. Grey boxes are entities leading to decision making of the system, those decision can be either individual or collective. Arrows signify information flows and feedbacks.

therefore discuss the archaeological record as an empirical source for formalising model entities so that they can be used to develop dynamic models of specific systems.

For the purpose of unequivocal abstraction we do not use the concept of settlement in isolation but instead define settlement systems similarly to Gordon Willey's 1953 original definition: "the way in which man disposed himself over the landscape on which he lived". We define a settlement system as a spatial arrangement of a population in space as related to the environment. This arrangement is dynamic and we consider it to be populations' spatial adaptation to the environment, e.g. a coherent spatial structure satisfying the needs of the inhabitants (Doxiadis, 1968).

From a spatial system perspective we consider the mechanism of adaptation to be composed of optimal residential moves made by inhabitants. These locational choices are made from their individual perspectives, which as a whole lead to the emergence of properties of the system. The majority of the evidence we see in material culture in general is the result of group rather than individual decisions (Verhagen and Whitley, 2012, p. 86, 87), and the same can be assumed for residential choices. The exact nature of the agency (Sikk, 2023) taking residential decisions is beyond the scope of this paper but in general we can consider human groups living and moving together as having agency. In contemporary urban geography (Huang et al., 2014) and some archaeological cases (Kohler et al., 2007), households are typically considered (Kohler et al., 2007; Sanders, 1998). It is also possible that movements are made in larger groups and might not be subject to free will. We do not consider this as a contradiction as both coercive and non-coercive cooperation has been considered in social systems (DiMaggio and Powell, 2000). Managed complex adaptive systems can provide a conceptual extension for the model formalising them, with some agents having more power and taking non-local decisions that influence global strategies (Gotts et al., 2019).

The system can achieve various steady states, some of which have typically been distinguished on a general level, including mobile foragers, hunter-fisher-gatherers with central camps, agricultural villages and urban forms with different levels of agglomeration. These states primarily associated with subsistence modes and spatial distribution have mostly been considered as a resulting pattern. In this study, we isolate the spatial system according to the laws of geography but consider it coupled with social and subsistence systems through residential location choice based on cost-benefit principles.

The settlement system is illustrated in Fig. 2 as a spatial layer resulting from interactions in the system. We outline the sources and processes below, starting from the components of the system and then moving to information processes including feedbacks and formed loops (Verburg et al., 2016).

2.2. Decomposing residential location choice into social and physical attraction spaces

Barth (2010) has emphasised already in the 60s that a viewpoint is required to separate environmental factors and non-ecological social and cultural components. This viewpoint is crucial for modelling purposes as discussed in this section, for its empirical implications see "Discussion and perspectives" section.

Empirical locational studies in archaeology have gathered evidence of significant environmental influence on settlement choices. In some cases environmental determinism has been shown to be especially clear-cut with hunter-fisher-gatherer societies (Sikk et al., 2022) consisting of small population units. It can also be observed with larger, sedentary settlement (e.g. Whitley et al., 2010) and within urban contexts mostly observed in relation to green spaces (e.g. Van Herzele and Wiedemann, 2003; Tu et al., 2016) indicating that regardless of the chain of causality of the settlement formation process, there are clearly strong relations between physical environment (we include both natural and anthropic features under the term) and residential location choice.

Residential choice has been thoroughly studied both theoretically and empirically in urban economy and explored with modelling approaches (e.g. Waddell, 2002; Holm et al., 2004) where it forms an important part of transport and land use models. The theory and modelling is based on accessibility or distance to locations providing composite goods (e.g. Papageorgiou and Pines, 2012, p. 130.131). The goods and amenities known from case studies are shopping opportunities, cultural facilities, public transport, education facilities (Hunt, 2010; Sener et al., 2011), distance of working place (Vega and Reynolds-Feighan, 2009) and also green spaces (Sener et al., 2011; Schindler et al., 2018) while air pollution (Schindler et al., 2021) and traffic restrictions (Sener et al., 2011) make locations less attractive. Most factors in the urban context are not in relation to physical features but based on access to services based on urban infrastructure emerging from social context and people who work in it. Even air and noise pollution and urban spaces are direct results of human activities. This social effect coming from relations to the population is intuitively understandable. Indeed, if one plans to move to a specific location, knowledge of who already lives in the vicinity and especially which services they provide is essential.

Based on the distinction of environmental and social effects we decompose residential choice into two abstract groups of influences: one coming from the physical environment and another coming from the population. Typically archaeological models tend to specify attractions in the physical environment rather explicitly as suitable soil, hunting grounds or a specific biotope. In more abstract studies the term "resources" is often used (Wood, 1978, e.g.). This approach has been criticised as being too economic (Crumley, 1979) and ignoring a variety of potential influences on the choice process. It is also counterproductive for resilience thinking, the aim of which is to focus less on resource quantities and more on response options (Cote and Nightingale, 2012, p. 478).

We therefore describe the attractions of the physical environment through logistically direct access to ecosystem services (Millennium Ecosystem Assessment, 2005). We adopt the concept because it is naturally coupled with SES (Resilience Alliance, 2007). It offers a useful abstraction that encompasses all services provided by the natural environment to humankind and gives us an existing conceptual framework to work with. The concept also broadens the criticised utilitarian economic approach. Ecosystem services are classified into regulating services, provisioning services, cultural services and supporting services. Of these only provisioning services are typically considered in archaeological models. The concept was developed with contemporary decision making in mind and we assume that it can also be used as a guideline to inform us about past decision making processes.

In another group of influences we bring together social attractions. Those attractions can be commonly described as the accessibility of social services — everything society provides for an individual. Its in-depth discussion is beyond the scope of this paper but some examples include security, mating and marriage networks, cultural attractions and also access provided to ecosystem services through trade and specialisation. It is known that at least some of these services are population-dependent and that they provide economic benefits like subsistence diversification and result in increased return rates (Ortman et al., 2015; Klassen et al., 2021) and risk minimisation (Solich and Bradtmöller, 2017).

As well as considering social benefits, this approach also includes push factors making a location less attractive. For example if the population density exceeds the carrying capacity, competition might add a repulsion force to the region. Similar effects would result from competition imposed by cultural or political boundaries, creating negative social attractions.

Both ecosystem and social services might be accessible directly, for example bringing water from a stream or talking to a group of people, but in most cases they are mediated through technological means as described in SETS framework (McPhearson et al., 2022). Accessing water might only require containers for transportation, but can also be reached through built infrastructure of pumps and cleaning stations, depending on the existing technology.

The final choice of habitation is then made based on evaluation of these attractions. Ebert and Kohler (1988, p. 106) asked from an empirical viewpoint "what proportion of human behaviour is immediate and can be explained by proximity arguments and what proportion is systematically organised within a given society?". It is theorised that within any given society there are regularities regarding this proportion that can be related to social or cultural complexity (Kvamme, 1985), which we consider to be an important abstraction for modelling purposes.

While considering the location selection process we must also take into account decision making processes used in past societies. Bounded rationality (Wood, 1978) is a universal principle coming from details of human information processing, for example from variations in personal knowledge of the environment, social structures and personal beliefs. Potential variations in residential choice preferences may also arise from social heterarchy and economic specialisation. For example traders can be expected to prefer higher social connectivity, while farmers in the same society are likely to favour better access to fertile grounds.

Table 1
Entities used in the conceptual model.

Concept	Description	Observability
Population	The population consisting of past inhabitants	Estimates by analogy
Physical environment	The natural and constructed/technogenic environment during habitation	Contemporary environment
Physical attraction space	Abstract layer of physical attractions as perceived by past inhabitants	Inductive locational models
Social attraction space	Abstract layer of social attractions as perceived by past inhabitants	Proxies from social archaeology
Settlement system	Population dispersed in space in relation to the physical environment	Archaeological record; partial evidence

2.3. System entities

The description of settlement pattern formation through a residential choice process implies a systematic linkage of the described entities. The entities in the system are listed in Table 1 and become tangible spatialised layers in our conceptual diagram (Fig. 2, in blue).

The first tangible concept in the proposed model is population, which consists of inhabitants observed in the system and varies in its size and demographic characteristics. The population uses an economic and socio-cultural strategy and consists of population units making residential choices based on their perceptions of space, which we have divided here into physical and social space.

The second tangible component is the physical environment existing in space which contains the considered system. As local access to ecosystem services can be provided by the human-modified environment, e.g. agricultural systems, or even the constructed environment of cityscapes, we do not distinguish between "natural" and human-modified environments.

The next concepts are abstract entities, described in the previous section as parts of the residential choice process, that reflect information and indicate the spatial relationship between population and physical and social environments. Physical attraction space spatially represents the way the past population perceived any location in the physical environment as suitable for living and social attraction space represents the same for social factors (including relationships, cultural norms and community needs). These relational concepts can be modelled as a space of relevant attractions for all locations in the system.

Settlement system in our model represents a tangible spatial distribution of the human population. It is formed by consecutive residential choice events carried out by members of the population, which are determined by other components of the system. This results in spatial morphogenesis of population dispersal. The resulting spatial arrangements start influencing other components of the system, leading to cross-scale feedback loops unfolding in different timescales.

2.4. Location choice and strategy

The way environmental and social spaces are perceived by the population depends on the economic and socio-cultural strategy of the given society. This includes the aspects explored by behavioural economics (e.g. Smith et al., 1983), including the subsistence system (Kelly, 2013; Lee et al., 1999) and technological means of exploiting ecosystem services, such as tools for hunting, agriculture, construction and transportation. A technology of significant importance is for example storage (Freeman and Anderies, 2015). Strategy also includes the way in which society is organised, its hierarchies, specialisation and policies.

Selected strategy determines residential choices by defining how people see value in a location. For example, proximity to water could be evaluated as an ecosystem service within a given strategy. It could have value in relation to regulating services, for cleaning, waste removal, agriculture and transportation; in relation to provisioning services, for fishing or food and tool production; or in relation to cultural services, for communication and ritual. The meaning of water could vary significantly for hunter-fisher-gatherers and early agrarian villages. Similarly, agrarian strategy involves access to fertile soils, which might not be required by hunter-fisher-gatherer society.

Subsistence strategy also determines the carrying capacity of the land, thereby influencing the preferred population density. But the latter is also influenced by requirements of security and access to specialised services in accordance with the complexity of the social organisation. Strategy can determine the temporality of settlement choice events; residential mobility has often been related to resource depletion in the environment (Binford, 1980; Kelly, 2013).

As seen from these examples, strategy encompasses a large domain of questions, which involve several aspects of anthropological and archaeological research. Strategy also changes over time and itself follows an economic and social adaptation process that helps the system work in a coherent and resilient manner. Based on Binford (1980) and Bettinger and Baumhoff (1982) we can deduce that residential choice introduces constraints on subsistence and subsistence in turn introduces constraints on settlement placement. This is an example of how residential choice (spatial adaptation) and ecological strategy form a coupled system of adaptation with individual groups having to choose a balance between them.

Often whole societies are considered as social-ecological systems but typically the research focuses on aspects we classify here under strategy. Solich and Bradtmöller (2017), while exploring such a system, came to the conclusion that connectedness was the most crucial central concept of their model, signalling the importance of geography. As this study focuses on settlement systems we have taken a different approach and consider strategy as an exogenous entity and a separate subject of enquiry. We focus on adaptation as a spatial process and primarily isolate spatial effects, therefore we discuss strategy only in relation to spatial processes. As strategy can also change according to the environment (see below) we can consider it as a coupled system going through co-adaptation with settlement system formation.

2.5. Feedback loops

The feedback loop of social attractions (LOOP 1) is theoretically implied by the concept of social attraction space. If there are any spatial changes in the system, resulting from population increase or decrease, migrations or other demographic dynamics, the spatial structure of the settlement system and therefore relations between population units change, leading to new local perceptions of the social space (Fig. 2, feedback F1). The same loop can also start through political or institutional change, which first modifies the information (perceptions) in the social space or choices of residence (coercive or not). Consequently changes in information lead to changes in the spatial arrangement. This starts a systemic adaptation process with aggregated individual choices based on new attractions, which drives the whole system to a new steady state. The way in which changes to the settlement system influence residential decisions needs to be studied, but some assumptions can be made. In the case of inhabiting empty land we can assume that residential choices are made based on a strategy that had evolved in the population's original environment. The settlement system is then formed through the feedback loop adjusting environmental and social attractions.

In the event of a population increase that exceeds the carrying capacity of the land, population pressure is created, which forces the settlement to be restructured. If the population strategy aims to maximise population density, increasing agglomeration can be expected until economic limits are reached; otherwise expansion of the system is expected.

Feedback F1 can lead to a positive feedback loop and result in an agglomeration process in which increasing population density attracts new inhabitants, which in turn increases the attraction of the region. The loop is dependent on residential mobility, which is known to be frequent among mobile forager societies (e.g. Binford, 1980; Kelly, 2013) but also among city dwellers. It can therefore be assumed that this feedback loop leads to relatively fast spatial processes in cases it is influential.

The following feedback relationships between system entities and their proposed causal mechanisms are based on anthropological and (ethno-)archaeological research. The spatial structure of the population can create feedback loops changing socio-cultural and subsistence strategies (LOOP 2). The relationship between population connectedness and size has long been related to the development of social complexity (Carneiro, 1967). Recently it has been shown that social complexity increases with the connectedness of the population of food-producing societies (Fogarty and Creanza, 2017) but only occasionally for hunter-fisher-gatherers (Kline and Boyd, 2010). Urban systems exhibit the same principles, which has led to cities being studied as "social reactors" (e.g Bettencourt et al., 2007; Ortman et al., 2015). Increased social organisation leads to hierarchies (Hamilton et al., 2020), economies of scale (Ortman et al., 2015) and technological innovation (Crema and Lake, 2015), which change the strategy of the system (Fig. 2; feedback F2). The change of strategy leads to a new principles guiding residential choices.

The spatial structure of the population can lead to various groupings of connected populations with different population densities. Higher population densities with more connectedness in the settlement system can therefore result in increased social and economic organisation, changing the strategy of the system. For example, a technological innovation could be introduced and then lead to more effective ways of harvesting certain ecosystem services, which in turn increases the carrying capacity of the land. This in turn could lead to agglomeration, resulting from the rising preferred population density.

Another well-documented feedback loop is the modification of the environment by the population (LOOP 3; Fig. 2, feedback F3). Everything observable in the archaeological record can be considered as environmental modification, from scatters of past tools to constructions including residential shelters to industrial constructions. Research has shown us that after Homo sapiens entered the stage in any landscape, it changed significantly (Kirch, 2005), at the very least through the niche construction process (for an overview of niche construction theory in archaeology see Laland and O'Brien, 2010). Although mostly related to industrial societies, there is evidence of both local ecosystem control and large-scale environmental modifications by hunter-gatherers. An example of this is land management with fire by native communities in Australia (Widlok, 2008) and in the Central Andes (Contreras, 2010, p. 261). Since the rise of agricultural societies and the associated population expansion, humans have had cumulative impacts on natural landscapes and biotic resources worldwide (Kirsch 2005; for an overview of human impact in the Central Andes see Contreras, 2010).

Most significant environmental modifications (especially in prehistory) have been carried out close to residential areas, thereby imprinting the spatial forms of habitation on natural environments. These changes have implications for the physical environment and by extension for the perceived attractions of the physical environment. Consequently, specific locations can become either more or less attractive either seasonally or in the long term. For example, according to central place foraging theory, foragers deplete food resources below an attractive threshold level (Kelly, 2013) and then move to undepleted regions. This results in a mobile lifestyle but also a patchy and dynamic perceived attraction space (Sikk and Caruso, 2020).

The creation of field systems in early agriculture made sedentary village communities possible. As land conversion for agriculture is costly, it also made locations in the vicinity of fields more attractive for settling. Conversely, in some cases agricultural activities led to long-term or permanent depletion (Goodman-Elgar, 2008) of soils, having a reverse effect. Agriculture introduced major modifications to the environment like deforestation (Kaplan et al., 2009) and water management systems (e.g. Contreras, 2010, p. 262), which have only intensified with industrialisation and growing populations.

Many – probably most – environmental modifications provide infrastructure to access ecosystem services and make locations more attractive. These also include residential buildings, prepared agricultural lands and constructed environments for housing and industry that provide different services. Cities contain very attractive residential areas that are typically completely constructed. These kinds of modifications thus add permanence to the attractiveness of locations and decrease mobility. Changes to the environment as a space of attraction consequently influence residential choices and the whole system. Changes to the environment can also modify strategy (LOOP 4; Fig. 2; F4). Changes in subsistence strategy have mostly been researched as human responses to environmental change. There are known short timescale changes: for forager societies, for example, the subsistence strategy is known to be very dynamic. The seasonal variation of the subsistence mode is anticipated and can be considered as different modes of one strategy, but highly dynamic land-use strategies depending on spatial configuration of resources have also been documented (Kelly, 2013; Grove, 2009). It has been noted that the variability of climatic conditions is likely to initiate changes in technological knowledge and related subsistence strategies (Kelly, 2013; Binford, 1980).

Research has also shown the significance of LOOP 4 as long timescale environmental change. Considerable amount of research on environmental change has been focused on critical situations like extreme weather events (Walker et al., 2020, e.g.) or volcanic eruptions which can lead to population and technology loss (Riede, 2008; Sinensky et al., 2021) and challenge the resilience of human societies. Climatic shifts change ecosystems and as a result have a direct impact on hunter-gatherer lifestyles and settlement patterns (Schmidt et al., 2012; Gronenborn et al., 2014; Gronenborn, 2016). Studied human impact includes the effects of agricultural activities including land degradation (van der Leeuw, 2000; van der Leeuw and The ARCHAEOMEDES research team, 2005) and urban societies influence to adjacent ecosystems (Ernstson et al., 2010). Abrupt catastrophes studied so far mostly include isolated island contexts (e.g. Spriggs, 1997; Kirch, 1997) with several general overviews published on the topic (Redman, 1999; Redman et al., 2004). Fisher and Feinman (2005) argue that the observability of human-induced catastrophes is more dependent on analytical scale than on material evidence.

3. Discussion and perspectives

In the previous sections we conceptualised settlement systems deriving from the rapidly evolving theoretical frameworks about SES, which bring with it concepts like ecosystem services and can be related to generative principles like cost-benefit and information. SES is used to study contemporary society and promises to open up new possibilities for research into long-term processes in human history. The use of complex system models which can be transferable between fields paves the way for the interdisciplinary communication of long-term knowledge.

The conceptual model offers an outline of a dynamic spatial perspective of settlement systems in which spatial patterns emerge from group behaviours and play an active role by providing feedback at the level of individual human choices, technologies and socio-economic strategies. Both empirically documented or theoretically implied, this feedback and the resulting loops have effects in various timescales (Renfrew and Poston, 1979) and can differ significantly from one society to the next. Feedbacks make models sensitive to error propagation in which small changes in initial conditions can lead to significant alternation of system (Verburg et al., 2016), therefore their effect needs to be explored through both theoretical and empirical studies of specific settlement systems.

As discussed, settlement systems are by nature CASs, which implies that exploration of their causal mechanics requires them to be considered as whole systems during research because of their complex inner relations. The same applies to the long-term dynamics of such systems.

Although archaeology has produced an abundance of information shedding light on multiple perspectives of past economies and societies, the main focus has been on describing the chronological development of various social and subsistence strategies. A systemic approach to settlements as spatial CASs could open up several new opportunities for both reinterpreting archaeological data and exploring new hypotheses (see Sanders, 2021).

CAS methodologies, especially spatial ABM, are very useful for exploring settlement systems as they provide a way to model complete systems and then explore relevant aspects of them. Modelling settlement and spatial choice is not new in archaeology (see Section 2.1), but when investigating complete systems, the effects of previously described feedbacks and loops need to be explored. The feedbacks and loops described in this paper are formed between individual choices and higher-scale entities like attraction spaces and aggregate strategies. ABM allows us to describe individual choices as agents' behaviours and higher-scale entities as system environments. When running simulations, emerging patterns then change the environment and lead to feedback loops with individual behaviours, which again lead to higher-scale change. One way to explore the settlement formation process would be to look at links between perceived spaces, the influence of population strategy on individual choices and the emerging spatial structure of settlement patterns. The links and feedback loops then lead to the emergence of dynamics that may have an effect in different time spans.

In addition to theoretical explorations, the models can be used to explore specific systems, but ABM faces similar challenges as archaeological analysis in general, namely complications of connections to empirical data. Numerous frameworks have been devised to conceptualise SES, offering methods and classification strategies for correlating empirical data with system entities and relationships. These particularly focus on ecosystem services and can be adopted for geographical distributions. Among these frameworks is Ostrom's Social-Ecological Systems framework (Ostrom, 2009). However, even more pertinent are the Robustness of SES framework (Anderies et al., 2004) suitable for mapping interactions and feedbacks and SETS (McPhearson et al., 2022), the latter of which adopts a distinctive approach to ecosystem services.

We also propose that inductive locational modelling with its well-developed methods can be focused on representing physical attraction spaces. Some work has been done by conceptualising these spaces through eco-cultural niche modelling (Banks et al., 2006) or direct environmental effect modelling (Sikk et al., 2022). But so far relatively few studies have applied the results of the approach quantitatively or comparatively (Whitford, 2019; Daumantas et al., 2020; Sikk et al., 2022).

During the development phase, our model was applied to multiple case studies (Sikk, 2022; Sikk et al., 2022; Sikk, 2023). One fundamental challenge was discerning the relative contributions of archaeologically observable factors within this largely theoretical model. In a comparative analysis of hunter-gatherer and early agrarian societies in Estonian territory, the model provided ways to separate factors that lead to the emergence of settlement patterns. It offered insights into the distinct characteristics of empirical predictive models for site distributions (Sikk et al., 2022). The conceptualisation of environmental attraction spaces revealed how these two societies inhabited different environmental niches, potentially making a peaceful migration possible. Those niches emerged from the different socio-economic strategies of the two societies. Another study involved an ABM implementation of our model and explored the concept of environmental determinism, demonstrating how individual-level social attractions combined with some randomness in the evaluation of sites lead to patterns that are determined by environmental features (Sikk, 2023). This inherent robustness of social-ecological systems might explain the relative success of predictive models in archaeology. Yet, the model also augmented our theoretical comprehension of location choice processes using simulations. A comprehensive parameter exploration on an ABM, grounded in our conceptual model, highlighted numerous spatial effects and illuminated how group agency can manifest in location choice systems (Sikk, 2022; Chapter 5). We think this perspective can also be applied in very different contexts and periods (e.g. urban systems) and provide a more holistic understanding.

Using empirical locational models to describe abstract attraction spaces can be more effective for exploring *longue durée* processes than trying to reconstruct the entire environment and subsistence strategy. Trying to achieve total reconstructions of past environments and human activities would accumulate additional complexities with the addition of each submodel. For example, reconstructing energy resources through vegetation or exploring specific hunting systems increases model complexity with every additional layer. This can be avoided through more abstract empirical models based on a clear conceptual understanding.

It would then be reasonable to explore the possibilities of calibrating created ABMs to locational models. Calibrating ABMs to inductive models is a developing practice (Carrella et al., 2020), but so far it has not yet been implemented in archaeology. Coupling models could also be used to provide systematic explanations of inductive locational models.

Research based on both empirical and theoretical simulations could be used to tackle questions on the optimality of adaptation and trade-offs developed for adaptation such as the one between mobility (spatial adaptation) and changing strategies. Several CAS-specific topics also need to be explored before using the framework to interpret eco-dynamic processes including possible empirical variables, system sensitivity to them, scales (of time, space, system size and agency), heterogeneity of choice, hierarchy and the effects of spatial configurations.

The spatial characteristics of social domains are, and will likely remain, harder to explore using archaeological material. In addition to using proxies from finds, settlement size and density could give a reasonable theoretical approximation of the social attraction space. While the size of settlement can approximate population size (Drennan et al., 2015), distances between sites are an indication of density and of the underlying connection networks and infrastructure. CAS tools including ABM can provide a way to theoretically explore the relations between these proxies and their possible interpretations.

4. Conclusion

Our paper demonstrates how settlement system formation can be understood as a complex adaptive system, integrating knowledge from the fields of archaeological locational modelling and social-ecological systems. Settlement structure in the model framework emerges from individual micro-level residential location choices which are informed by socio-economic residential strategies and available ecosystem and social services. Aggregated population activities change the spatial structure of both social and ecosystem services, which feed back onto residential strategies. Described processes and feedback loops create a dynamic system with a spatial adaptation mechanism.

We broke down settlement systems into entities representing tangible and abstract components. These components can be used to structure a theoretical and empirical exploration of long-term ecodynamics using SES and generally CAS approaches and methods like ABM. We propose that archaeological inductive locational models can be used to represent the perceived attraction space of past inhabitants while exploring settlement systems through simulation studies.

Based on theory and previous research we identified several cross-scale feedback loops between individual choices and emerging aggregated spatial patterns. We showed that it is useful to consider spatial population dispersal not as a passive pattern but as an active system on its own. When studying the long-term dynamics of settlement systems or their causal mechanics, whole systems have to be considered because of their complex inner relations.

The proposed theoretical modelling framework, with its internal relations, provides ways to reinterpret empirical data, particularly inductive models that use environmental variables to describe settlement choice principles. It can be used for both case studies of specific settlement systems or to advance theoretical knowledge about spatial effects on the long-term evolution of human societies. Identified loops illustrate the dynamic nature of settlement systems and show the benefits of exploring them as dynamic systems using the CAS perspective.

CRediT authorship contribution statement

Kaarel Sikk: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Geoffrey Caruso:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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