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SPATIAL ADAPTIVE SETTLEMENT SYSTEMS IN ARCHAEOLOGY. MODELLING LONG-TERM SETTLEMENT FORMATION FROM SPATIAL MICRO INTERACTIONS

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Spatial adaptive settlement systems in archaeology. Modelling long-term settlement formation from spatial micro interactions.

Kaarel Sikk

Abstract

Despite research history spanning more than a century, settlement patterns still hold a promise to contribute to the theories of large-scale processes in human history. Mostly they have been presented as passive imprints of past human activities and spatial interactions they shape have not been studied as the driving force of historical processes. While archaeological knowledge has been used to construct geographical theories of evolution of settlement there still exist gaps in this knowledge. Currently no theoretical framework has been adopted to explore them as spatial systems emerging from micro-choices of small population units.

The goal of this thesis is to propose a conceptual model of adaptive settlement systems based on complex adaptive systems framework. The model frames settlement system formation processes as an adaptive system containing spatial features, information flows, decision making population units (agents) and forming cross scale feedback loops between location choices of individuals and space modified by their aggregated choices. The goal of the model is to find new ways of interpretation of archaeological locational data as well as closer theoretical integration of micro-level choices and meso-level settlement structures.

The thesis is divided into five chapters, the first chapter is dedicated to conceptualisation of the general model based on existing literature and shows that settlement systems are inherently complex adaptive systems and therefore require tools of complexity science for causal explanations. The following chapters explore both empirical and theoretical simulated settlement patterns based dedicated to studying selected information flows and feedbacks in the context of the whole system.

Second and third chapters explore the case study of the Stone Age settlement in Estonia comparing residential location choice principles of different periods. In chapter 2 the relation between environmental conditions and residential choice is explored statistically. The results confirm that the relation is significant but varies between different archaeological phenomena. In the third chapter hunter-fisher-gatherer and early agrarian Corded Ware settlement systems were compared spatially using inductive models. The results indicated a large difference in their perception of landscape regarding suitability for habitation. It led to conclusions that early agrarian land use significantly extended land use potential and provided a competitive spatial benefit. In addition to spatial differences, model performance was compared and the difference was discussed in the context of proposed adaptive settlement system model.

Last two chapters present theoretical agent-based simulation experiments intended to study effects discussed in relation to environmental model performance and environmental determinism in general. In the fourth chapter the central place foraging

model was embedded in the proposed model and resource depletion, as an environmental modification mechanism, was explored. The study excluded the possibility that mobility itself would lead to modelling effects discussed in the previous chapter.

The purpose of the last chapter is the disentanglement of the complex relations between social versus human-environment interactions. The study exposed non-linear spatial effects expected population density can have on the system and the general robustness of environmental inductive models in archaeology to randomness and social effect. The model indicates that social interactions between individuals lead to formation of a group agency which is determined by the environment even if individual cognitions consider the environment insignificant. It also indicates that spatial configuration of the environment has a certain influence towards population clustering therefore providing a potential pathway to population aggregation.

Those empirical and theoretical results showed the new insights provided by the complex adaptive systems framework. Some of the results, including the explanation of empirical results, required the conceptual model to provide a framework of interpretation.

Contents

Introduction

Settlement patterns and landscape perspectives have always had an important place in archaeology. Maps displaying settlement locations are a standard part of excavation and field survey reports and related publications for more than a century. Large-scale settlement patterns became explicitly incorporated into research starting with the 1950s Willey's Viru Valley archaeological survey project 1953. Despite extensive documentation throughout at least 70 years of settlement pattern studies there have been recurring calls for the development of new interpretative frameworks coming from different subfields of archaeology. Even relatively recently it has been claimed (Feinman, 2015) that "the potential for theoretical contributions and insights from settlement patterns and landscape approaches … has only scratched the surface". In this thesis we take particular interest into how geographical and complex systems approaches can advance that goal. Geography, in the sense of locational attributes, is key to presenting archaeological evidences, planning field works and provides key operational instruments in the daily life of archaeologists. We argue here that geographical thinking is also a source for further interpretation.

Settlement patterns have mostly been used for delineating various phenomena, for example spatial extents of archaeological cultures (or technocomplexes) and their spatial relations to each other. They have provided an analytical tool that helps to construct historical narratives including methods from geography. Spatial visualisations of settlement patterns help to tell a story in a more precise and captivating way. In addition, archaeological settlement patterns have also provided an invaluable basis for theory on the behaviour of peoples of the past and contributed to general anthropological and geographical knowledge. Behind every observed settlement pattern, as observable in the archaeological record, there existed a settlement system, a systemic entity that existed in the past. Regularities of observed patterns have given indication that those systems, follow certain rules at least to a certain extent. Hence generalisation and theorisation is possible.

Universal rules governing settlement as spatial systems have been of interest for geographers for a long time resulting in a considerable amount of theory (Doxiadis, 1968). During the last decades those theories have also been formulated as computational models (Batty, 2013; Pumain, 2000). Those models have been mostly based on contemporary observations, but several models of long-term processes have also been based on archaeology. A series of models based on archaeological knowledge have been created to study evolution of settlement systems (Pumain, 2000; Pumain, 2012; Lena Sanders et al., 1997) and major transitions in them including Neolithic transition and development of cities (Lena Sanders, 2014).

The first of the agent-based models developed in urban studies (ABM; see next section) was SIMPOP1 (Lena Sanders et al., 1997), which with the following series of SIMPOP models (Pumain, 2012) had a goal to identify conditions of emergence of cities from the initial relatively homogeneous rural settlement systems during the timespan of 2000 years. They included direct modelling on an aggregate level of spatial units, considering settlement themselves as elementary entities (meso level; for levels used in urban studies see: Léna Sanders, 1998 of the model and modelling their interactions (Pumain, 2000) like information exchange and trade migratory flows (Favory et al., 2012). The modelling is based on causal descriptions of general social processes created by archaeologists as opposed to modelling directly based on empirical data.

(Batty, 2008) described the evolution of urban modelling as movement from “macro-static” to “micro-dynamic”. Potential for a similar research direction exists for studying the principles of formation of settlement patterns using archaeological data. Micro-level modelling of small population units like hunter-gatherer bands or households could open a way to similarly identify conditions of emergence of the meso-level phenomena. So far those phenomena have been used for describing settlement system formation and the evolution of urban forms.

Archaeological data is known for its uneven and fragmentary nature which poses challenges for generally describing micro-actions. The same is valid for actions that lead to settlement pattern formation. In this study we argue that for description of micro-actions of population units a step of modelling is required that would create a direct link between archaeological data and the dynamics of settlement pattern formation process. This link could then be used both for discovery of the laws governing settlement systems’ formation processes but also reinterpreting archaeological data itself by its aggregate meso-level characteristics.

We also argue that this kind of link can be formed using locational data of archaeological residential sites. Locational data has been collected through every archaeological field survey and excavations from a variety of contexts ranging from hunter-gatherer sites to houses in agrarian villages to dwelling locations in larger cities. The data on sites’ locations can easily be associated with environmental conditions in the location and its relation to other contemporary population units. This association has allowed the emergence of the field of archaeological locational modelling. Created inductive models have been used to predict site locations and formally describe the principles of location choice in the concerned societies thus providing empirical input about locational micro-behaviours of the population units.

The goal of this thesis is generally to contribute to further connecting empirical data and theory. The more precise goal is to propose a conceptual framework and computational spatial models to bridge archaeological locational data to micro-level behaviours and to link those to the emergence of principles operating on the meso-level as settlement systems. For this a series of spatial approaches to settlement systems are adopted, related models developed and explored with spatial analytic and simulation tools. We start by examining settlement systems from the point of view of spatial complex adaptive systems drawing insights from socio-ecological systems perspective (Chapter 1). It is done through conceptualisation of the settlement system formation process as a dynamic model of (Chapter 1) and then both empirically (Chapter 2 and 3) and theoretically (Chapter 4 and 5) validating and exploring the developed model.

Methodological framework and data

The thesis is built up from the complexity science perspective considering settlement systems as complex systems. Complexity science focuses on explaining phenomena that consist of a multitude of components interacting with each other and the environment. In the current case those components can be either settlements or micro-level population units like individuals or households. Phenomena that can be formally described often exhibit properties of complex adaptive systems like self-organisation, non-linearity, adaptation, spontaneous order and feedback loops, among others. Use of complexity approaches becomes reasonable if the object of research exhibits emergent behaviour, that means that the system in general possesses properties that its individual elements do not have. Although the idea that the whole is more than the sum of its components is very old (for an overview based on experience of this thesis see Sikk, 2022), only recently has the approach become widespread.

Urban systems and settlement systems in general have been shown to be complex adaptive systems (Batty, 2005; Batty, 2013; Pumain, 2000) and self-organised (Allen, 1997) even while constrained by political or economic control mechanisms (Pumain, 2012). It is possible to apply evolutionary theory for exploration of the transitions (Sanders 2014) of settlement systems between different steady forms (Pumain, 2000). For example, a combination of archaeological knowledge and geographical theories have been conducted to explore the emergence of urban forms from rural settlement systems (Favory et al., 2012; Lena Sanders, 2014). Those explorations have often been using agent-based modelling (ABM), considering aggregate spatial units of settlements as central units in the system.

ABM is a computational simulation method developed for exploring complex systems with combining different levels of analysis. It lets us explore how relatively simple behaviours of system components lead to emergence of complex phenomena. Building on the classical definition of models from Clarke (1972), "a model is a mechanism which connects theory to data". ABM then is a mechanism that enables us to connect theory on one level of analysis to data on another level (Sikk, 2022). In this thesis our goal is to model the formation of aggregate spatial forms from micro-scale population units, for this task ABM is the perfectly suitable tool.

ABMs other special value for archaeology and historical sciences is its simulation capabilities. It enables us to explore scenarios that can not be observed in empirical reality (McGlade, 2005) thus involving experimental method in disciplines usually limited to descriptions and comparative method. ABM can be used to build and test theories of individual behaviours by projecting them to different social and spatial scales (Kohler, Gumerman, and R. G. Reynolds, 2005). Those scales constitute different levels of observation and analysis. For example written sources describe individuals' perceptions, while archaeological observation could provide an aggregate understanding of dynamic phenomena in general (Sikk, 2022).

ABM modelling process is accomplished in several key steps (from (Sikk, 2022)): (1) defining the characteristics of an environment and the rules governing individual agents (ontology), which are then (2) formalised as algorithms and their configurations so that they can be executed as a computer program. (3) The created models are calibrated to fit available observations and (4) validated to behave as expected (face validation). (5) Further steps include running simulation of scenarios which can be compared to empirical observations or theories; and model exploration for explaining phenomena and building theories.

ABM has previously been used for micro-level spatial simulations in archaeology. Examples include studies of foraging behaviour of hunter-gatherers (Janssen and K. Hill, 2016; Lake, 2000), agriculture and economy of neolithic village communities (Kohler, C. D. Johnson, et al., 2007) and also for settlement system formations (Griffin and Stanish, 2007; Kohler, Van West, et al., 1996). Those studies include evaluation of potential conditions for historical processes of specific settlement systems observed in archaeological material. The focus of this thesis is to theoretically explore the abstract rules governing the formation of settlement systems in general which could then be theoretically applied to all known forms of settlement systems. Despite the different purposes, the key mechanism we use is the same as has been used for other micro-level settlement pattern formation studies: residential location choice. By the term we mean decisions made by individuals and groups on where to live and when to move there.

Residential location choice has extensively been used to describe contemporary urban systems (Benenson, 2004; Holm et al., 2004; Huang et al., 2014) see Chapter 1 for details). In archaeology it has been subject of discussion from the earliest settlement system studies in archaeology (Vogt, 1956, p. 174–175; Wood, 1978; Crumley, 1979; Bevan and Conolly, 2006). It presents a rare case in archaeology where micro-level choices have a strong empirical backing, provided by archaeological locational data of residences and settlements.

Originally anecdotal descriptions of find locations were used for describing the principles of residential location choice. Geologist and archaeologist Constantin Grewingk, for example, who was working on the Stone Age in Estonia claimed C. C. A. Grewingk (1865, p. 110), before any of the sites had actually been discovered in the region, that during the period people lived by the sea and rivers (see Chapter 1). This knowledge was probably communicated in the scientists communities at the time and is still perfectly valid for hunter-fisher-gatherers of the region as evidence to support the claim accumulated over time. A real breakthrough to understand location choice in finer detail was introduced with the adoption of geographic information systems in archaeology. It gave birth to inductive locational modelling based on empirical data. This led to the emergence of the field of archaeological predictive modelling, where site locations are predicted through their environmental correlates (e.g. Judge and Sebastian, 1988; Mehrer and Wescott, 2005; Verhagen and Whitley, 2012). These predictive models have been mostly used to conduct surveys aimed at finding sites and cultural resource management practices which are set to prevent site damage. But they have also been used to explain principles of location choice of the people of the past (see Judge and Sebastian, 1988; Mehrer and Wescott, 2005; Verhagen and Whitley, 2012) based on environmental conditions. Entirely environment based modelling has drawn criticism as there exist significant cultural, and social features which influence settlement patterns (e.g. see Grøn, 2018; Verhagen and Whitley, 2012). Barth (2010) has emphasized already in the 60s that a viewpoint is required to separate environmental factors and non-ecological social and cultural components.

Existing approaches let settlement patterns to be considered as passive imprints of accumulated past human activities. One of the goals of the thesis is reinterpretation of these models including space as an active entity in the formation of settlement patterns and considering predictive models as empirical representations of information fields of attractions to the environment (see Chapter 1). During the modelling process empirical data is interpreted and transformed into spatial dimensions which conveys additional potential for interpretation of the past societies while helping to isolate environmental factors from socio-cultural ones (Chapter 3; 5) as proposed by Barth (2010).

Through using tools of complexity science the ultimate goal is then to link archaeological locational data to micro-level choices and meso-level emergence of spatial forms. The latter can then be used to give new interpretations to empirical data and through identification of micro-conditions that lead to certain spatial regularities build new spatial theories of settlement.

Thesis structure and key issues explored

The thesis contains an introduction, five chapters [1] and a conclusion. A general overview of the structure of the thesis is presented in Fig 1. and a description of how each section contributes to the thesis topic follows.

Chapter 1. Framing settlement systems as spatial adaptive systems: a conceptual model

The first chapter provides conceptualisation of settlement systems as socio-ecological systems in the framework of complex adaptive systems. It offers methodological and conceptual backgrounds of socio-ecological systems and complex adaptive systems and gives a general overview of settlement pattern studies in archaeology.

The conceptual framework of adaptive settlement systems is proposed with a systems map laying out its components and links between them. The system is described based on perceived spaces by members of past societies and the mechanism of its formation is based on consecutive residential choice actions by members of the population. Building upon previous studies in archaeology we show that the settlement system formation process can indeed be described as a socio-ecological system and predict several relations between system entities. We describe the information flows needed to make residential decisions and predict the feedback loops these choices create when aggregated by the population.

Being a complex adaptive system implies that particular isolated facets of settlement system formation can not be used for explaining the system. We propose empirical connections and potential theoretical research directions to open up more systemic ways to approach settlement taking into account existence of unobservable entities. The following chapters in the thesis study selected information flows and feedbacks described in this system: the influence of perceived environment on residential choice; modification of the environment by population; and the influence of populations on perceived social attractions in space. Two chapters present a case study based on the Stone Age settlement patterns in Estonia and two chapters present theoretical simulation studies based on the proposed system.

[1] The chapters have been written for publication in scholarly journals and there is therefore some repetition of their contents, especially in descriptions of the methodological background of the research. For the same reason there are minor differences in the overall style of the chapters.

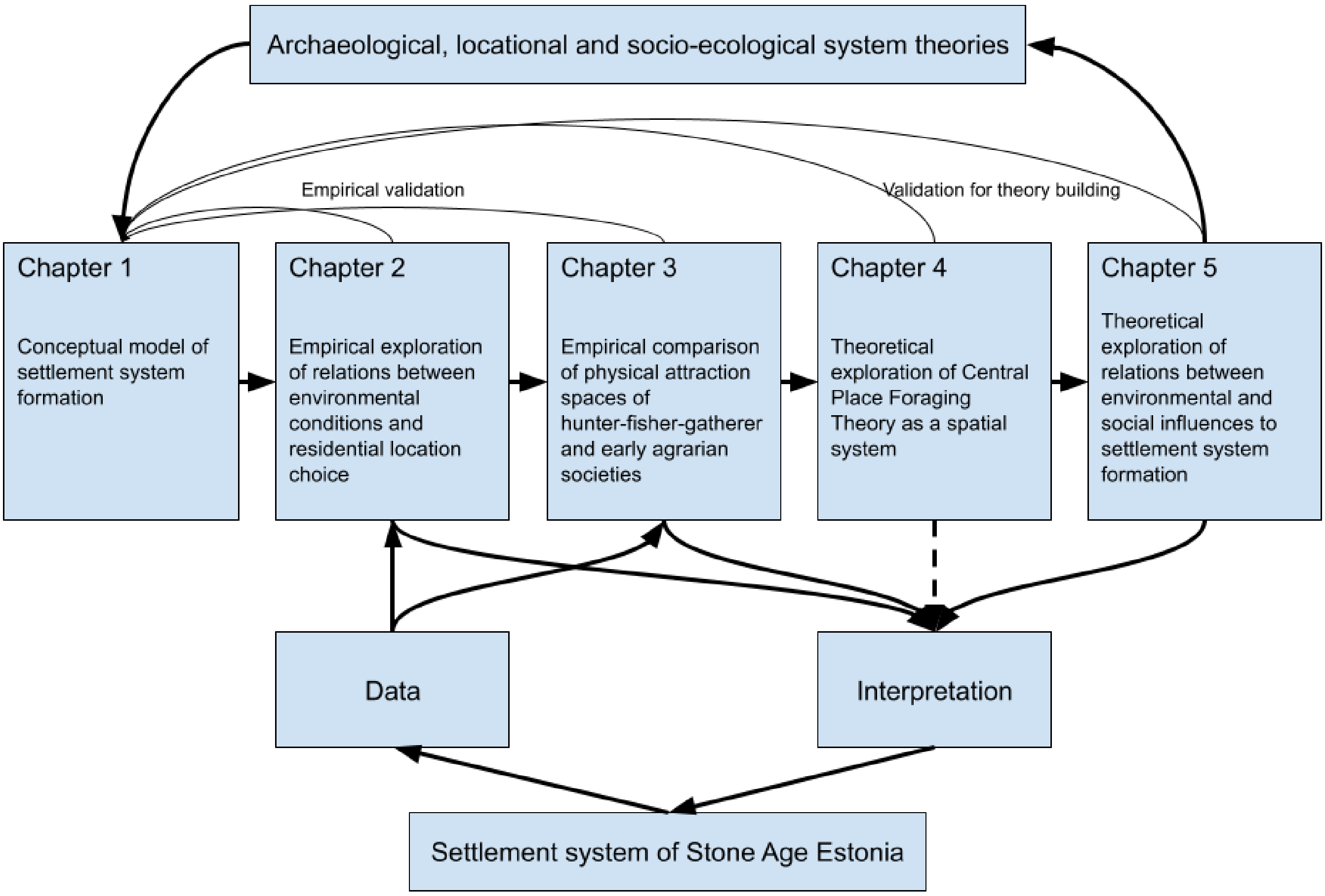

Figure 1: Thesis overview as an information flow diagram

Chapter 2. Exploration and statistical validation of relations between site locations and environmental conditions, case study of Stone Age Estonia

The first empirical chapter serves mostly as a validation of the relation between environment and residential location choice based on data concerning hunter-fisher-gatherers and early agrarian societies in Estonia. Although this relation was expected based on previous research, the study provides a quantitative assessment of it and a proof of concept for simple empirical studies based on the relationship. Pre-pottery Mesolithic site locations were shown to have considerable variation in comparison with hunter-fisher-gatherer sites with pottery, which had very well-defined site location choice principles. The sites of early agrarian Corded Ware stage society had quite different environmental conditions, being less dependent on water bodies and having different preference for soils. The reasons behind the patterns revealed are discussed in the chapter and a descriptive interpretation of some of the effects is given. The revealed difference between the hunter-fisher-gatherer and early agrarian settlement systems led to the starting point of the following chapter.

The paper is published as:

Sikk, K., Kriiska, A., Johanson, K., Sander, K. and Vindi, A., 2020. Environment and settlement location choice in Stone Age Estonia. Estonian Journal of Archaeology, 24(2), pp.89-140.

Data used for the statistical analysis is available online at: https://zenodo.org/record/3775415

Chapter 3. Comparing contemporaneous hunter-gatherer and early agrarian settlement systems with spatial point process models: case study of the Estonian Stone Age

Chapter 3 provides another empirical study based on the dataset introduced in Chapter 2. The chapter focuses on using inductive modelling as empirical evidence of physical attraction space as perceived space as proposed in Chapter 1. The purpose is to study the statistical differences revealed in Chapter 2. We formulate an environmental effect model as a point process model and implement it using the MaxEnt tool, which provides spatial attraction rasters of the two phenomena.

A comparative exploration of the rasters of the corresponding areas shows significant differences and provides reasoning that allows an explanation for previously hypothesised tolerated immigration by early agrarian societies. It also indicates certain areas of potential competition over space. In addition to spatial differences there is a significant difference in model performance, which is then discussed in the context of the general settlement system formation model. From the literature several hypotheses to explain the difference are proposed, including different social organisation and complexity or different spatial perspectives on land because of land use strategy/technology.

The hypotheses are also considered in the following chapters using theoretical simulations.

The chapter is published as: - Sikk, K.; Caruso, G; Rosentau, A; Kriiska, A. (2022) 'Comparing contemporaneous hunter-gatherer and early agrarian settlement systems with spatial point process models: Case study of the Estonian Stone Age', Journal of Archaeological Science: Reports, 41, p. 103330. doi:10.1016/j.jasrep.2021.103330.

The code and the dataset used for analysis are published as supplementary materials with the article for reproducibility of spatially non-explicit models.

Chapter 4. A apatially explicit ABM of central place foraging theory and its explanatory power for hunter-gatherers settlement patterns formation processes

In Chapter 4 we implement a well-known central place foraging model as a spatial settlement pattern formation model to explore its potential effects on settlement patterns. We develop it as an agent-based model built upon the generative principles of resource depletion and residential and logistic mobility. A fast feedback loop between physical environment and residential location choice is emerging in this system.

Although environmental configuration influences mobility, as demonstrated by the work on the original model, it does not significantly change residential location choice principles by itself. But the model provides an illustration of significant changes to perceived physical attraction space even after relatively small changes to the physical environment itself.

Published as: Sikk, K., Caruso, G., 2020. A spatially explicit ABM of central place foraging theory and its explanatory power for hunter-gatherer settlement patterns formation processes. Adaptive Behavior, Evolution of Cultural Complexity.

The scripts reported in this article have been deposited in the Zenodo repository, (https://doi.org/10.5281/zenodo.3709457). Model is published in Github public repository as a work in progress (https://github.com/vinnetu/OFTpatterns/).

Chapter 5. Disentangling the emergence of environmental determinism and population agglomeration with an ABM

The last chapter in the thesis provides a theoretical simulation study on the relation between social and environmental impacts on residential location choices including the related feedback loops proposed in Chapter 1.

We study which properties of individual (micro-level) motivations lead to variations in the population density and dispersal leading to a system of settlements and the emergence of meso-level effects. The topic of environmental determinism is in the centre of the study and is tackled using a socio-ecological systems approach. It has been an important point of discussion in archaeology and geography, particularly in relation to environmental models. It was first discussed in the thesis in Chapter 3, which led to the question in Chapter 5.

To test environmental determinism we create an agent-based system where agents' choices are made based on perceptions of environment and social context. The exploration also includes unobservable, random effects that make it possible to study robustness of the general model and the effect of diversity of individual models. The model exploration with sensitivity analysis reveals several significant results on how both the homogeneousness of the environment and a preference for population density influences population clustering and reduces environmental determinism. It proposes a way to measure environmental determinism that potentially provides methods to isolate social and spatial effects from empirical data.

The robustness of environmental determinism and thus also environmental predictive models is shown through the formation of group agency by spatial interactions, which leads to overall selection of environmentally suitable locations. It also demonstrated that cognitive explanations like affordances can be only used to explain residential choice in exceptional cases of small human groups or specialised activities such as hunting camps, but not for more complex societies.

The chapter is an example of a theoretical simulation study in which an agent-based model is used to build theory based on the principles of socio-ecological systems using the model proposed in Chapter 1. The results strengthen the hypothesis put forward in the empirical studies that the reduced environmental determinism of early agrarian societies in the Estonian Stone Age is caused by more homogeneous spatial patterns introduced by agriculture.

The agent-based model code in NetLogo scripting language and Jupyter notebook scripts used for model exploration have been deposited in the Zenodo repository, (https://zenodo.org/record/6533834).

Acknowledgements

This research started and achieved its final form thanks to a series of fortuitous events and surprising coincidences. I started this project equipped with experience from the software development industry and studies in archaeology. As a result I had developed interest towards systemic understanding of long-term processes of human societies and some intuition on how humanistic understanding of those processes could be approached in a quantitative way. This work with settlement systems was based on ideas from fields like archaeology, history, quantitative geography, economy, computer science and complex systems modelling. It required a very specific setting, hard to fit to established interdisciplinary frameworks. It made me embrace a certain amount of randomness, which worked well in the research environment close to people who provided valuable exchanges and assistance during the project.

I was lucky enough to find Luxembourg Centre for Contemporary and Digital History (C^2DH) and more particularly the DHH project which provided an environment with academic freedom and plenty of opportunity to carry out such exploration. The playful thinkering approach of C2DH made it possible to delve into my long-developed curiosity and to freely explore disciplinary boundaries. I would like to thank Andreas Fickers for leading the centre and others behind the C2DH and DHH teams for creating the environment with the creative, playful, stochastic component at the core of it. I would also like to thank Brigitte Melchior-Dolenc for finding solutions to issues that arose during the project and other members of the team for enriching exchanges and good company.

Central fortuitous coincidence was the involvement of prof. Geoffrey Caruso in the DHH team and his agreement to become the supervisor of my work. His knowledge on the spatial issues involved was essential to the project and his research interests provided a perfect match to the intuitive direction I was heading towards. I am especially grateful for the fruitful cooperation.

I want to thank prof. Aivar Kriiska for opening up data about the Estonian Stone Age for me and working with archaeological materials but as importantly for encouraging me with experimentation of new, sometimes very abstract approaches to archaeological data.

I also thank Andrea Binsfeld for valuable feedback during the research project and defence committee members prof. Philip Verhagen and Dr. Arnaud Banos for very encouraging reviews and valuable comments on the manuscript.

I had an opportunity to visit several research events during my stay in Luxembourg, from which one event certainly stands out in changing the direction of my research. I want to thank the team behind organising eX Modelo (https://exmodelo.org/) summer school of the year 2019 for the event and their research and presentation of model exploration techniques.

Most importantly, I want to thank my wife Kätrin and daughter Iida who came with me to this unexpected adventure in Luxembourg and enthusiastically enjoyed it together with me; and son Theo who joined our team during the adventure!

Chapter 1

Framing settlement systems as spatial adaptive systems: a conceptual model

This chapter is in submission process to the Journal of Archaeological Method and Theory

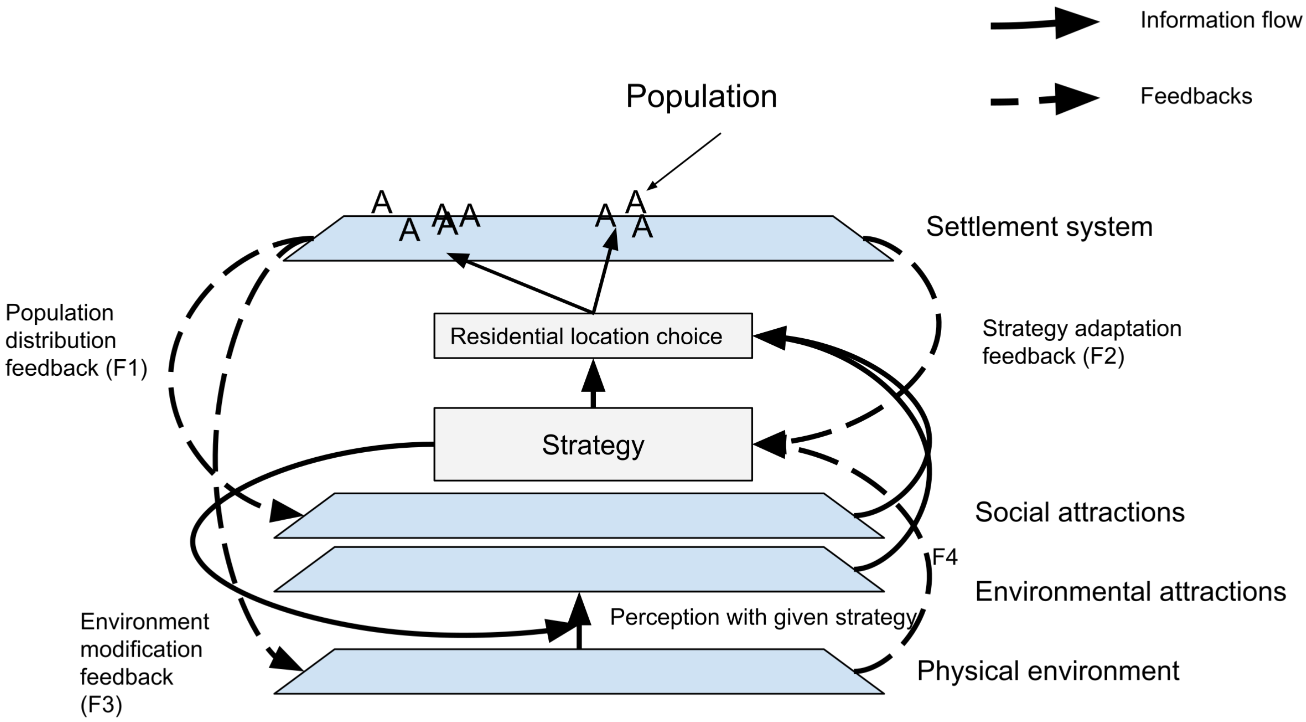

Figure 1.1: General model of adaptive settlement system developed in this chapter

Introduction

The diachronic interplay between population, environment, and human socio-economic formations is currently considered as one of the great challenges of contemporary archaeology (Jeffrey H. Altschul et al., 2017). Settlement patterns [2] 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; Sikk, Caruso, et al., 2022; Vernon et al., 2020; Whitford, 2019) 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, 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. 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 (Crumley, 1979; Feinman, 2015; Judge and Sebastian, 1988; Parsons, 1972; Vogt, 1956).

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 socio-ecological system (SES) modelling. While locational modelling

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

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, Folke, et al., 1998; Fitzhugh, Butler, et al., 2019; Schoon and Leeuw, 2015) in the general framework of complex adaptive systems (CAS).

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; Lena Sanders, 2014) 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 socio-ecological systems is discussed. In the next chapter 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.

1.1 Theoretical background

1.1.1 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 (Parsons, 1972, p. 1972), which indicate past human activities and their distribution in space. 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. Trigger, 1967; Willey, 1953) was gradually developed 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 (Garmy, 2021; Lena Sanders, 2014). 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 (Lena 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 duration of ca. 2,000 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 (Pumain et al., 2009; Lena Sanders et al., 1997).

Most of these models are based on archaeological knowledge as opposed to direct data-based modeling. 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; Pumain, 2006). Rank-size hierarchies (e.g. Bevan and Wilson, 2013; Crema, 2014; Davies et al., 2014) and settlement scaling (Hamilton, Milne, 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;

Aivar Kriiska, 2003; Nakoinz, 2010).

1.1.2 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, 2018; Verhagen and Whitley, 2012). Central to the reasoning of these models was spatial decision making. Behavioural ecological methods (for an overview see Kelly, 2013; Kennett and Bruce 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 (Bettinger, 1980; Jochim, 1976). 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 Kamermans, 2007; Wheatley, 2004, 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 (J. 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; Fitzhugh, Butler, et al., 2019; Kirch, 2005). 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 (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, 2017; Banks et al., 2006; Vernon et al., 2020; Whitford, 2019), 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; Chliaoutakis and Chalkiadakis, 2016; Kohler, C. D. Johnson, et al., 2007; Wilkinson et al., 2007) 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, C. D. Johnson, et al., 2007, p. 373), with resource availability being modified by depletion processes (e.g. Kohler, C. D. Johnson, et al., 2007, p. 373). 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).

1.1.3 Socio-ecological systems

To overcome the divide between social and environmental influences, we propose using concepts from the socio-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. 1.2); they are used to bridge social and environmental dimensions (Berkes, Colding, et al., 2001; Berkes, Folke, et al., 1998). 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.

The SES approach 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, Colding, et al., 2001; Berkes, Folke, et al., 1998; Schoon and Leeuw, 2015).

The original goal of that research programme was to help develop contemporary

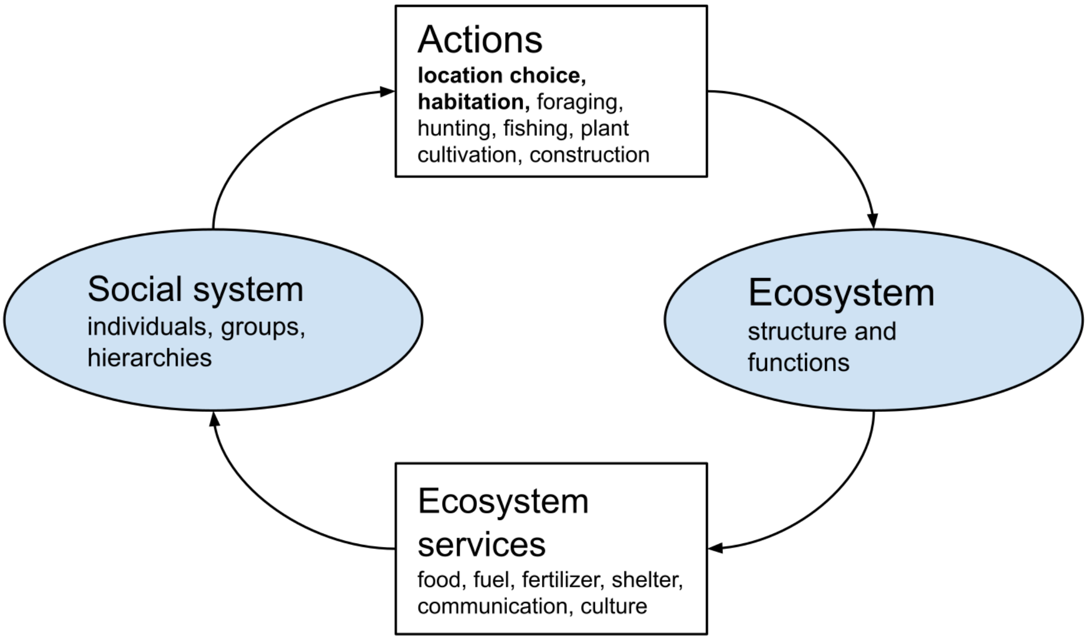

Figure 1.2: General socio-ecological services diagram adapted for residential choice from Alliance (2007). "Assessing and managing resilience in socio-ecological systems: supplementary notes to the practitioners workbook".

ecosystem management practises. SES links hierarchically nested ecosystems with similarly nested social systems through management actions and the reception of ecosystem services based on ecological knowledge and understanding (Berkes, Folke, et al., 1998).

Extending ecological concepts to SES has become increasingly popular in recent decades (Schoon and Leeuw, 2015) and has increasingly shifted to the social field. For example it has given rise to the concept of "social resilience", defined as "the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change" (Adger, 2000, p.347).

SES systems are considered to be universally complex and adaptive. The social and ecological systems within them are linked through feedback mechanisms (Berkes, Colding, et al., 2001). 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 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).

SES has therefore 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, Butler, et al., 2019). The term SES has only recently been adopted in archaeology (e.g. Barton et al., 2012; Daems, 2021; Kohler, Bocinsky, et al., 2012; Solich and Bradtmöller, 2017) 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.

1.2 Combined: Adaptive Settlement Systems

1.2.1 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 figure 1.3) as outlined in this section. In the map we include both spatial and aspatial entities 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 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 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, C. D. Johnson, et al., 2007), households are typically considered (Kohler, C. D. Johnson, et al., 2007; Léna 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. 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 Figure 1.3 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).

1.2.2 Decomposing residential location choice into social and physical attraction spaces

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, Caruso, 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. Tu et al., 2016; Van Herzele and Wiedemann, 2003) indicating that regardless of the chain of causality of the settlement formation process, there are clearly strong relations between physical environment and residential location choice.

Residential choice has been thoroughly studied both theoretically and empirically in urban economy and explored with modelling approaches (e.g. Holm et al., 2004; Waddell, 2002) 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 (Schindler, Le Texier, et al., 2018; Sener et al., 2011) while air pollution (Schindler, Wang, 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 direct access to ecosystem services ((Program), 2005). We adopt the concept because it is naturally coupled with SES (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 (Klassen et al., 2021; Ortman et al., 2015) and risk minimization (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.

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.

1.2.3 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 1.1 and become tangible spatialised layers in our conceptual diagram (Fig. 1.3, in blue).

The first tangible concept in the proposed model is population, which consists of

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

Table 1.1: Entities used in the conceptual model

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. 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.

1.2.4 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 and Daly, 1999) and technological means of exploiting ecosystem services, such as tools for hunting, agriculture, construction and transportation. It 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 (Lewis R. 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 Lewis R. 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 socio-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

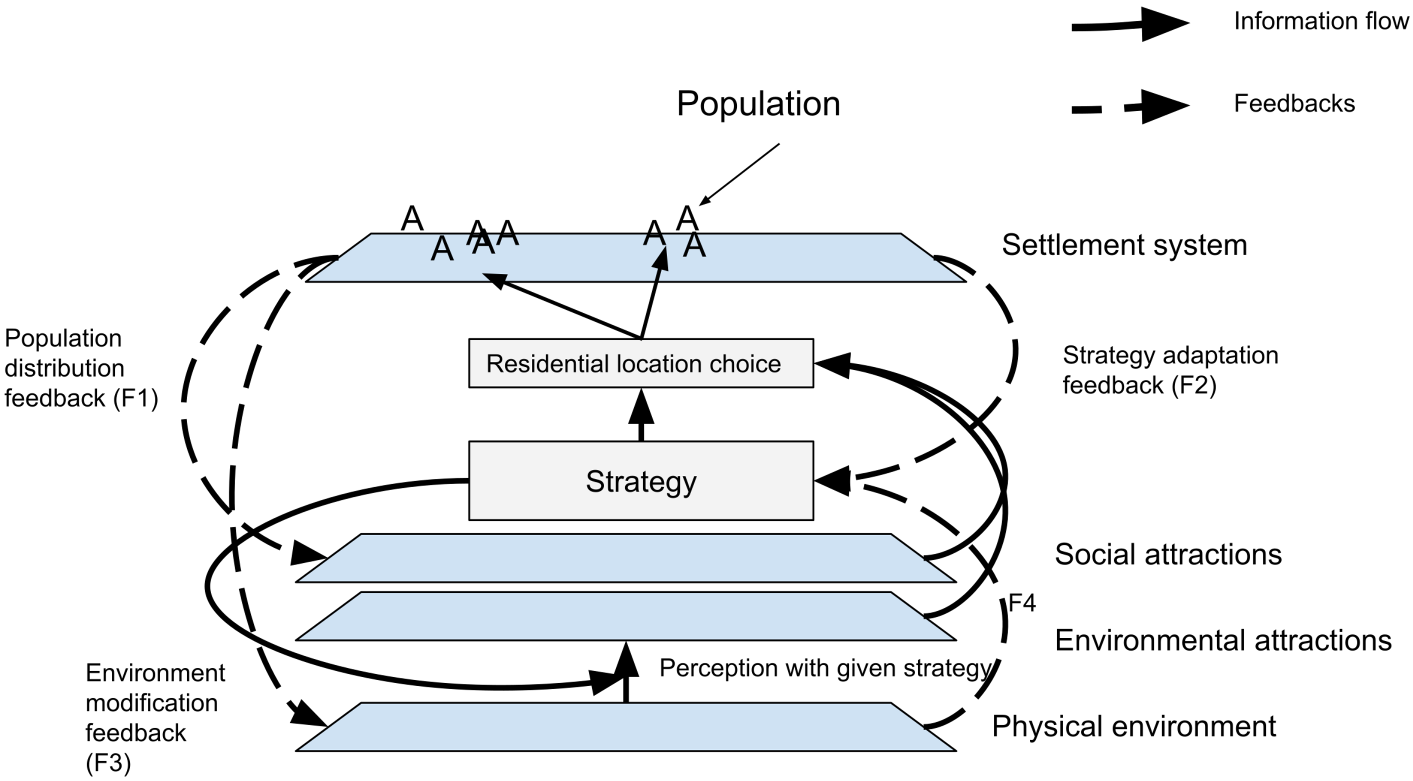

Figure 1.3: System map of the proposed model of formation of spatial adaptive settlement systems. Blue layers are spatial entities and grey boxes are decision forming entities of the system. Arrows signify information flows and feedbacks.

and consider strategy as an exogenous entity and a separate subject of enquiry. Our goal is to isolate spatial effects and focus on adaptation as a spatial process. We therefore 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.

1.2.5 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 changes, leading to new local perceptions of the social space (Fig. 1.3, feedback F1). 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 lands we can assume that residential choices are made based on a strategy developed in the original location of the population. The settlement system is then formed through the feedback loop adjusting environmental and social attractions.

In the event of a population increase which 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 see Chapter 5.

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. Lewis R. Binford, 1980; Kelly, 2013) but also among city dwellers. It can therefore be assumed that this feedback loop leads to relatively fast spatial processes.

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, R. S. Walker, 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. 1.3; 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. 1.3, 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 access to 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. 1.3; 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 (Grove, 2009; Kelly, 2013). It has been noted that the variability of climatic conditions is likely to initiate changes in technological knowledge and related subsistence strategies (Lewis R. Binford, 1980; Kelly, 2013).

But more significant long timescale environmental changes have also been studied. Significant amount of research on environmental change has been focused on critical situations like extreme weather events (J. 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 (Gronenborn, 2016; Gronenborn et al., 2014; Schmidt et al., 2012). 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. Kirch, 1997; Spriggs, 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.

1.3 Discussion and perspectives

In the previous sections we conceptualised settlement systems using the rapidly evolving theoretical framework of SES, which brings 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 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.

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. We propose that inductive locational modelling with its well developed methods can be focused to represent 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, Caruso, et al., 2022). But so far relatively few studies have applied the results of the approach quantitatively or comparatively (Daumantas et al., 2020; Sikk, Caruso, et al., 2022; Whitford, 2019).

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 size of settlement provides proxies about population size (Drennan et al., 2015), distances between sites are an indication of density and 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.

1.4 Conclusion

In this paper we proposed framing settlement system formation as a complex adaptive system integrating knowledge from the fields of archaeological locational modelling and socio-ecological systems. Settlement structure in the model 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, creating a dynamic system with feedback loops.

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 CAS approaches and methods like ABM. We propose that inductive locational models can be used as a source representing abstract 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 model with its internal relations can provide ways to reinterpret empirical data, particularly inductive models that use environmental variables to describe settlement choice principles. They can pave the way for case studies of specific settlement systems and 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 CAS methodology.

Chapter 2

Environment and settlement location choice in the Stone Age Estonia

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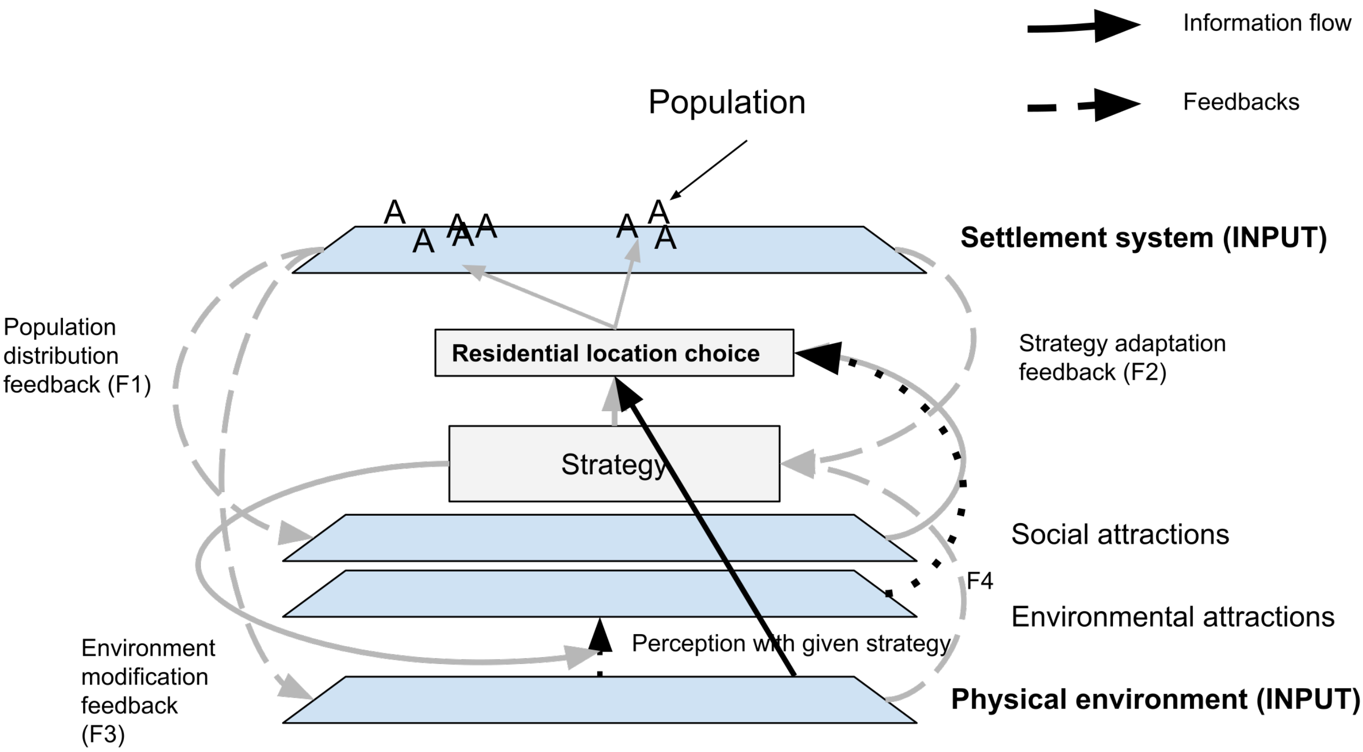

Figure 2.1: The chapter explores the relation between environment and settlement location choice

Introduction

It has long been assumed that locations of Stone Age settlements are to a large extent determined by environmental conditions. Already in the mid-19th century, geologist and archaeologist Constantin Grewingk 1865, p. 110 claimed that in Stone Age Estonia people lived by the sea and rivers, before any of the sites from the period had actually been discovered in the area. Over time archaeological finds confirmed this idea and it has become so convincing that archaeological sites are used as proxy data for geological shoreline reconstructions (e.g. Rosentau, Muru, et al., 2013; Veski et al., 2005). Proximity to shoreline (e.g. Jochim, 1976, p. 55) is not the only environmental characteristic of a suitable site location; sandy soil (e.g. A. Kriiska and Tvauri, 2002, p. 56; Huurre, 1983, p. 41 and the position in the local landscape (e.g. Jochim, 1976; Kvamme and Jochim, 1990; Plog and J. Hill, 1971) are also considered important. Those environmental features are also present in an implicit mind model, often described as a "gut feeling" that guides archaeologists during the search for sites in the landscape.

Currently no statistical analysis has been made to quantitatively assess the influence of environmental features on Stone Age settlement site locations in Estonia. In this paper we undertake this task, analysing the features of site locations and exploring regularities appearing at the level of the whole settlement pattern.

Environmental statistical (locational) analysis of archaeological sites has been a common practice for decades, involving research on several periods and regions (e.g. Hahn, 1983; Jochim, 1976; Kvamme, 2005; Kvamme and Jochim, 1990) including the studies of Bronze Age and Iron Age sites in regions of Estonia (Haav, 2014; Kimber, 2016). The purpose of most of these studies has been to develop inductive models for predicting the archaeological potential of certain regions and finding new sites. As results have shown, predicting variables vary depending on both area and research period, although the most significant tend to be proximity to water, soil type and geomorphological features (e.g. Kvamme and Jochim, 1990).

In this study we analyse Stone Age settlement site locations in Estonia and their environmental conditions. Recent research has significantly widened our knowledge with the addition of new site locations and datings. We statistically describe the accumulated data and study the relationship between currently observable geological variables and past settlement choice. By comparing statistics for different stages of the Stone Age we explore how the site selection principle changed over time and re-evaluate existing qualitative explanations for settlement location choice in a quantitative context. The methodological goal of the paper is to study the usefulness of environmental variables for describing Stone Age settlement choice. Exploring the relationships between variables is outside the scope of this paper.

To achieve our aim we collect available data about the geological characteristics of the environment, including soil type, approximate distance to shoreline and geomorphological variables derived from the digital elevation model (DEM). We perform univariate statistical analyses of the environmental variables of site locations and compare them for the different stages of the Stone Age. We group the variables of sites by their stages of the Stone Age and compare the statistical distribution of environmental variables of the groups and assess how they differ from environmental data and each other. For variables with a significant impact on settlement choice we provide descriptive statistics and use them in archaeological interpretations.

2.1 Materials and methods

2.1.1 The history of the discovery of Estonian Stone Age settlements

The first Stone Age site was found in Estonia in the year 1867. The discovery of the Kunda Lammasmäe settlement by Grewingk was methodologically effective even in the modern sense. Finds collected over more than a decade, the palaeogeographic reconstruction of the ancient lake, landscape analysis and skilled fieldwork all played a role in the discovery (C. Grewingk, 1882; C. Grewingk, 1884; C. Grewingk, 1887). After that, no Stone Age settlements were found for half a century. This was due to the fact that the study of the Stone Age declined after Grewink's death, and work focused on the Iron Age. The only place where attempts were made to find settlements in the concentration area of Stone Age finds was the lower reaches of the Pärnu River, but the fieldwork did not yield results (Frank et al., 1906;Glück, 1906; see also A. Kriiska and Saluäär, 2000b).

In the early 1920s, the first new discovery of a Stone Age settlement was made during the excavation of a Metal Age site (Spreckelsen, 1925). Several Stone Age settlements have been found while studying settlements from other periods, including a significant number for the Corded Ware stage in particular. The number of settlements found began to grow gradually only in the 1930s and 1940s, when Richard Indreko began to study locations with many stray finds (Indreko, 1932; Indreko, 1948a). The sites he methodically discovered, together with others found accidentally in construction and excavation works since the 1950s (e.g. L. Jaanits, 1979; Гурина, 1967) or in other searches (L. Jaanits and K. Jaanits, 1975), became the main focus of research for decades. Long-term and large-scale excavations of the sites found were carried out (mainly by Lembit and then also by Kaarel Jaanits) but settlements were not systematically searched (with a few exceptions), not even those in the immediate vicinity of excavated settlements (for a more detailed discussion of Estonian Stone Age history, see A. Kriiska, 2006). The lack of surveys for finding new sites seems to have been rooted in the belief that Stone Age settlements are very scarce. L. Jaanits justified the lack of Mesolithic settlements in Estonia in the book "Prehistory of Estonia" (Lembit Jaanits et al., 1982, p. 48), saying "If this can be partly explained by the fact that the cultural layers of settlements have not been discovered, the main reason must be the sparseness of the settlement at that time." The work reflected the state of the late 1970s and presented all the known Stone Age settlements, including 10 Mesolithic (pre-pottery), 7 Narva, 16 Comb Ware and 19 Corded Ware stage settlements.

The situation changed only in the mid-1990s as a result of contacts with Finnish archaeology. Participating in and studying archaeological fieldwork in Finland provided both the methodological skills necessary for organising fieldwork and, above all, the knowledge that the current source base in Estonia is not sufficient for further research. From 1994 the systematic identification of settlements began in Hiiumaa and the Narva region (e.g. A. Kriiska, 1995b; Aivar Kriiska and Lembi Lõugas, 1999) and then continued in many other places in Estonia (Vedru, 1996; Vedru, 1997; Vedru, 1998). The main basis for this was simple (often unwritten) palaeoreconstructions based on already known settlements on the ancient shores of the Baltic Sea and Lake Võrtsjärv. Intensive landscape surveys were carried out, during which open land sites (fields, forest roads, etc.) were inspected and test pits were dug either at selected locations or en masse on prehistoric coastal and shore formations. Exploration trips often took place in parallel with excavations (e.g. A. Kriiska, 1998; A. Kriiska and Saluäär, 2000a; Aivar Kriiska and Lembi Lõugas, 1999), but special expeditions of different lengths were also organised (e.g. Aivar Kriiska, A. Haak, et al., 2003). Most settlements were discovered during such expeditions, including the sites found in ploughed fields in central and southern Estonia as a result of surface clearing. A number of settlements were also found through the examination of excavated material from previously excavated antiquities (e.g. Aivar Kriiska, A. Haak, et al., 2003, p. 36; T. Jussila and A. Kriiska, 2006, p. 44).

In addition to sites found close to large bodies of water, Mesolithic settlements gradually began to be found on the banks of small rivers and lakes (for a discussion, see A. Kriiska and Kihno, 2006, p. 46, and a few settlements with no relation to water bodies at all were also found (T. Jussila and A. Kriiska, 2006).

Altogether the sites have been found using different sources and methodologies: reports from the public, archaeological research of later Prehistoric periods, surveys based on stray finds and surveys based on former shorelines using both fieldwalking and bulk digging of test-pits in prospective areas.

In all thoroughly studies regions (Estonian islands, northern and north-eastern coastal area and former shorelines of Lake Võrtsjärv) a large amount of locations with different environmental conditions have also been surveyed. Usually only some of the surveyed areas include finds from the Stone Age. During archaeological fieldworks of the last two decades it has been a standard practice to survey region surrounding the area of research including locations outside the observable pattern of sites. This all provides a confirmation that observed pattern is not only the result of search pattern but is grounded in empirical reality.

In addition to the "negative sample" other types of sites like Iron Age sites and burials have been systematically surveyed (results of the surveys have been regularly published since 1996 in the Archaeological Fieldwork in Estonia). Recently large-scale surveys of natural flint stone have provided comparative reference material to the Stone Age archaeological site distribution (A. Kriiska, Khrustaleva, et al., 2018).

2.1.2 Dataset

The dataset presented here is based on previously described Stone Age research and includes data (Appendix 1) from recent systematic surveys conducted until 2017 (some sites discovered later were included as well). The sites are classified into four stages of the Stone Age: pre-pottery Mesolithic (9000–5200 cal. BC), Narva (5200–3900 cal. BC), Comb Ware (3900–1800 cal. BC) and Corded Ware (2800–2000 cal. BC). The classification of the sites is based on finds and related typo-chronology using existing radiocarbon and other dating methods, if possible. The last two stages have significant overlap in time and are distinguished by pottery types. The number of sites included is 410, with 244 pre-pottery Mesolithic sites, 39 sites with Narva pottery, 60 sites with Comb Ware and 67 sites with Corded Ware.

Only the sites with known exact locations were incorporated into the database. The locational data was then used to retrieve environmental information corresponding to each site forming an environmental database of the Stone Age settlement. As sources we used available spatial environmental data sets including soil and current waterbodies data as vector layers and DEM as rasters layers, all of which have been made available by Board (2019). Because of the large area covered we used raster layers with the resolution of 5m.

2.1.3 Proximity to water

We preprocessed all of the data sources for the purposes of our research. Because of the significant change in water levels during the long period from the Stone Age to the present, site distances to water could not be directly derived from contemporary maps. The area under study has been affected by the changing water level in the Baltic Sea and the post-glacial land uplift, which has "tilted" it. Erosion and local hydrological changes have modified the environmental conditions as compared to the period of habitation, especially for sites from the oldest Mesolithic period.

The shoreline configurations of water bodies have changed over time for various reasons. They have individual histories and require individual approaches to assess the placement of sites related to each body of water. The Baltic Sea, whose shoreline has changed significantly and which is closely linked to past settlements, has been thoroughly researched in Estonia (e.g. T. Jussila and A. Kriiska, 2006), mostly focusing on local areas like Pärnu bay (Habicht et al., 2017; Nirgi et al., 2020; Rosentau, Veski, et al., 2011; Veski et al., 2005), Tallinn bay (Muru, Rosentau, Aivar Kriiska, et al., 2017), Narva bay (Rosentau, Muru, et al., 2013; Ryabchuk et al., 2019), Hiiumaa (L.Kriiska Lõugas et al., 1996; A. Kriiska, 2004, p. 107–115 and Ruhnu Island (Muru, Rosentau, Preusser, et al., 2018).

The lakeshores of bigger lakes have also shifted because of the water level change and land uplift. While the Holocene history of Lake Võrtsjärv (e.g. T. Moora and Raukas, 2003; T. Moora, Raukas, and Tavast, 2002) has been studied relatively thoroughly from the perspective of the Stone Age settlement (e.g. Tallgren, 1922, p. 31–34, fig. 2.5,2.6, Indreko, 1934; A. Kriiska and Johanson, 2003; T. Moora, 1990), less research has been conducted on the hydrological history in relation to human habitation by Lake Peipsi (e.g Л. Ю. Янитс, 1959a, p. 18-25; Roio et al., 2016, p. 225). Although rivers are contained in riverbeds and are thus easier to trace, their courses often change and their banks are often dynamic. In several cases they flow in valleys created by much older (glacial) geological conditions.

For this reason we estimated the distance to past shorelines using data from the current shoreline, palaeoshoreline reconstructions, DEMs and also archaeological interpretation of the sites, employing different strategies for different contexts. For rivers we were able to measure the distance to the current riverbank or a historical riverbank in the event of an existing palaeoreconstruction of a connected lake or coastal region. For lakes we measured the distance to the current shoreline or a clearly observable palaeoshoreline. For sites connected to the Baltic Sea and Lake Võrtsjärv we measured site distances using palaeoreconstruction of their shorelines.

Because settlement locations are defined by just one point and we do not know the size of the site, we rounded the distances to the closest 50m. The resulting estimation is of limited accuracy but is sufficient to assess shoreline connectedness in general. We were only able to include larger bodies of water, and small streams were excluded as no reliant information on their past hydrological conditions could be found. This means that sites distant from the shoreline did not necessarily lack natural drinking water sources, but they did not have close access to water providing aquatic resources and the possibility of boat use.

2.1.4 Geomorphological variables

Available DEMs of settlement areas open up opportunities for further exploration of settlement choice in relation to the geomorphology of site locations. This can be studied through geomorphometry – the measurement and mathematical analysis of the configuration of the earth's surface. The analysis is then based on quantified geomorphological characteristics of site locations and comparisons with overall environmental characteristics.

We used a set of variables that have been already tested in archaeological research (Kvamme, 2005; Kvamme and Jochim, 1990, e.g.) to describe settlement locations in relation to the environment. We also included a set of variables used in ecological models (Amatulli et al., 2018). Those variables include simple local DEM derivatives describing the morphology of a location such as slope, aspect and various measures of surface curvature.

We also included several more complex DEM derivatives that are linked with the elements (water, wind, earth, sunshine) of the environment. The Topographic Wetness Index (TWI) is used to describe topographical control of hydrological processes and is calculated as a function of the slope and the upstream catchment area (Sörensen et al., 2006). Wetness has been shown to be related to many natural processes such as soil formation (I. Moore et al., 1993), and it has also been used in archaeological research to assess historical agricultural land use (Andresen, 2008).

The Convergence Index (Kiss, 2004; R. and F, 1993) describes the hydrological convergence of a location, often used in hydrological calculations. A lower location in comparison to surrounding areas draws in flows, while a location with a higher Convergence Index is a starting point for flows and a Convergence Index of 0 describes locations where flows pass through.

Although the Convergence Index is mostly useful for hydrological research, the variable might describe influences on human perception of the location. A similar measure, the Topographic Position Index (TPI; Guisan et al., 1999, describes the prominence of a location in the surrounding area and is thus often used in landform classification algorithms. A higher TPI indicates a higher elevation in relation to the surrounding environment, and vice versa. The measure has been used in archaeological research to show the prominent locations of Bronze Age graves (De Reu et al., 2011), among other research. As TPI measures prominence within a certain radius, we experimented with different radiuses of 50, 250, 500 and 1500m. The statistical effect size measures of the TPI with different radiuses can give us information about the range in which topographic prominence was most important for settlement location choice.

The Morphometric Protection Index (MPI), also termed positive openness, expresses the degree of dominance or enclosure of a location in the surrounding landscape. It is an angular measure of the relationship between relief and horizontal distance and incorporates the viewshed concept. It is calculated from multiple zenith and nadir angles – here along eight azimuths (Yokoyama et al., 2002). Higher locations with better views have a higher MPI, while locations hidden in the valleys have a lower MPI.

To explore the terrain ruggedness of the site locations we experimented with three measures: the Vector Ruggedness Measure (VRM; Hobson, 1972), the Terrain Ruggedness Index (TRI) and the Surface Roughness Index (LSRI; Beasom et al., 1983).

The wind exposition index (Böhner and Antonić, 2009; Gerlitz et al., 2015) expresses how open a location is to wind, taking into account all directions cumulatively using angular steps. Potential incoming solar radiation (Insolation Index; Böhner and Antonić, 2009) describes the yearly solar radiation to which a location is exposed. The index could give an indication of past preferences: did Stone Age people prefer settlement locations in direct sunshine or in the shade?

It must be kept in mind that these variables are not statistically independent since they are derived from the same data source. To derive the geomorphological variables from the DEM we used SAGA GIS 7 (Conrad et al., 2015). Appendix 2 contains a full list of variables used with further details.

2.1.5 Variables describing soil

Suitable soils are essential for an agrarian economy, but soil also determines the local vegetation and habitat of other organisms influencing hunter-gatherer subsistence. Soil is also closely related to the water regime of the location: sandier soils drain away water but soils with a high clay consistency collect water. To acquire data about the soil characteristics in settlement locations we used contemporary soil data provided by the Board (2019). The data covering the whole country contains classifications and information about soil texture. Although the data resolution is uneven, it provides enough information to give meaningful insights into the relationship between soil characteristics and site selection. For this research the distribution of soil types from archaeological sites was compared to the overall distribution of soil types in the whole country.

Because of the large number of soil classes in the available soil classification it was generalised using a classification developed to reflect soil genesis, structure and fertility (Astover, 2005). It has been argued that a contemporary soil classification might not have a good overlay with concepts of soil as seen in the past (Kvamme, 2005 Verhagen and Whitley, 2012, p. 57, so quantifiable variables and more abstract categories are preferable. To overcome this problem we extracted information on the soil texture of each settlement location available in the existing dataset. Using soil texture standards (Astover et al., 2017) we quantified the measures of soil rustiness and clayness, respectively the share of large fractions in the soil and the percentage of clay present in the soil. These new variables enabled us to move from commonly used soil categories to a quantitative approach that was better suited to statistical analysis.

2.1.6 Statistical method

To evaluate the relationship of each variable with settlement choice we analysed the distributions of the variables. The distributions were compiled using the location of the sites, grouped together according to the stage of the Stone Age in which each site was inhabited. We compared them with each other and with samples taken from the environment.

The goal of the comparison is to check whether the variable values are just random environmental characteristics or whether they contain regularities, implying that they are related to a location choice made by past inhabitants.

To test the existence of non-random differences between the site and environmental samples we used the Kolmogorov–Smirnov (K–S) test. The K–S test measures the divergence between known Stone Age sites and expected cumulative frequency distributions of environmental characteristics (Siegel and Castellan, 1956, p. 47–52; Shennan, 1988, p. 53–61). The test is an established methodology in archaeology because of its ability to compare distributions with very different sizes (Wheatley and Gillings, 2003, p. 136-142) and its suitability for continuously distributed geo-environmental data (Kvamme, 1990). The K–S test indicates the statistical significance of the difference between variable distributions, thereby proving the reliability of the result. But to gain insights into causal processes of settlement choice we also needed to evaluate the effect size, especially since the variables used in the current study are not statistically independent.

The effect size was assessed using Vargha and Delaney's A measure (Vargha and Delaney, 2000). The A measure estimates the difference between two samples using the probability that a random variable pulled from the first (settlement) distribution is larger than a random variable pulled from the control (environment) distribution. The value of A ranges from 0 to 1, with 0 indicating that all the site values have higher scores than the environmental values, 0.5 that they are the same, and 1 that all the site values have lower scores. The A statistic has been recommended for cases when parametric tests cannot be applied (J.C.-H, 2016). It has also recently been applied to geomorphological data in archaeology (Weaverdyck, 2019).

For the variables which demonstrated statistically significant (p value < 0.05) differences, with A more than 0.647 or less than 0.353, descriptive statistics were calculated and interpreted. The A statistic together with descriptive statistics of variable distributions gave us indications about the size and direction of the effect and was used to interpret the relationships between site selection and environmental preferences during different archaeological periods.

The sample of environmental data was generated by randomly picking 10,000 points from all areas in the raster data used. All of Estonia was not used because of limited computational resources, so overall distributions might have a bias towards the topography of regions with known archaeological sites. We do not consider this to be a problem because the differences discovered between the site and environmental distributions would be even more significant if using data from the whole country.

2.2 Environmental variables and site selection

2.2.1 Proximity to water

The statistical analysis of the distribution of the sites' proximity to water confirmed current knowledge about water connectedness in the Stone Age. The majority of the sites were situated close to water, with a mean distance of 260m from the centre of the site to the respective shoreline. As compared to the random sample pulled from the environment, the effect size of the closeness to water is significantly large (A statistic = 0.08; K–S p value = 1.35e-187), reflecting the major influence of closeness to water on settlement choice.

There were also significant differences in distance distributions of sites grouped by different typo-chronological classes. The mean distances of the classes are fairly similar (pre-pottery Mesolithic 141m; Narva stage 51m; Comb Ware stage 53m), with the exception of the Corded Ware stage sites (779m). On Fig. 1 the distances to water are visualised as a box plot. The Narva and Comb Ware stage sites exhibit a very similar tendency towards closeness to water, with almost all sites being less than 100m from the shoreline and even the outliers being situated less than 250m from the shoreline.

The pre-pottery Mesolithic sites are also close to water, with 75% of the sites at a distance of less than 100m. The site distance distribution includes a lot of outliers which could be an indication of higher mobility and varied site functions, e.g. temporary hunting camps (e.g Lembit Jaanits et al., 1982, p. 40; A. Kriiska, 2004, p. 21; T. Jussila and A. Kriiska, 2006, p. 47).

The sites with Corded Ware pottery show a different relationship with water bodies. The effect of closeness to water is still large but an A statistic of 0.25 expressed a significantly smaller effect than the values of 0.03 for other periods. Although most of the sites are on the river bank and lake shores (37 shore sites and 8 shore-connected sites), with a median distance of only 85m, a new habitation mode

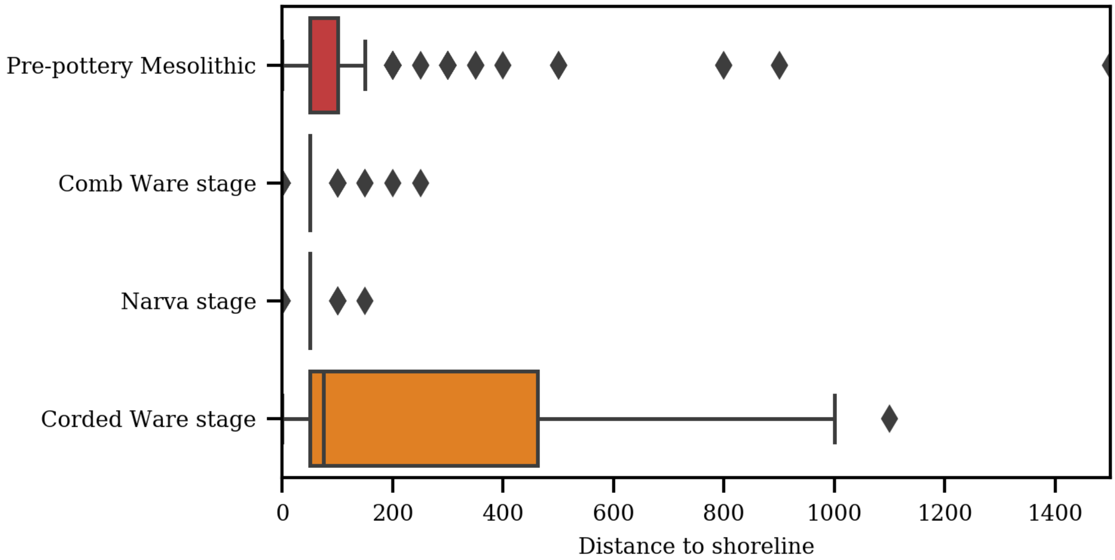

Figure 2.2: Distribution of sites' proximity to waterfront visualized as a boxplot.

which does not seem to be constrained by bodies of water is observable.

2.2.2 Variables describing soil

The Estonian Stone Age settlement sites have been described as predominantly situated on sandy soils. This can be explained by the fact that sandy soils drain water, thus providing dry and pleasant locations (e.g A. Kriiska, 2004, p. 56). To test the hypothesis with empirical data and analyse the sandiness of the Stone Age sites we used the soil formulas of the site locations from the Estonian Land Board database. We grouped the sites by period and compared their clayness distribution to that of the whole environment.

The results confirm previous observations that the Stone Age sites are situated on more sandy soils (e.g. A. Kriiska and Tvauri, 2002, p. 56; Huurre, 1983, p. 41). As the soil sandiness effect varied for different stages we considered them separately. Surprisingly the pre-pottery Mesolithic sites were not significantly different from the environment while the Corded Ware stage sites had a small tendency towards sandiness (A statistic = 0.253, p value = 0.0002). Narva stage sites (A statistic = 0.195, p value = 3.651e-10) and Comb Ware sites (A statistic = 0.238, p value=2.014e-11) showed a large effect.

Figure 1.3 illustrates the comparison of site soil clayness with expected clayness. A tendency to select sandy soils is visible, as soils with a clayness of 10% or less are

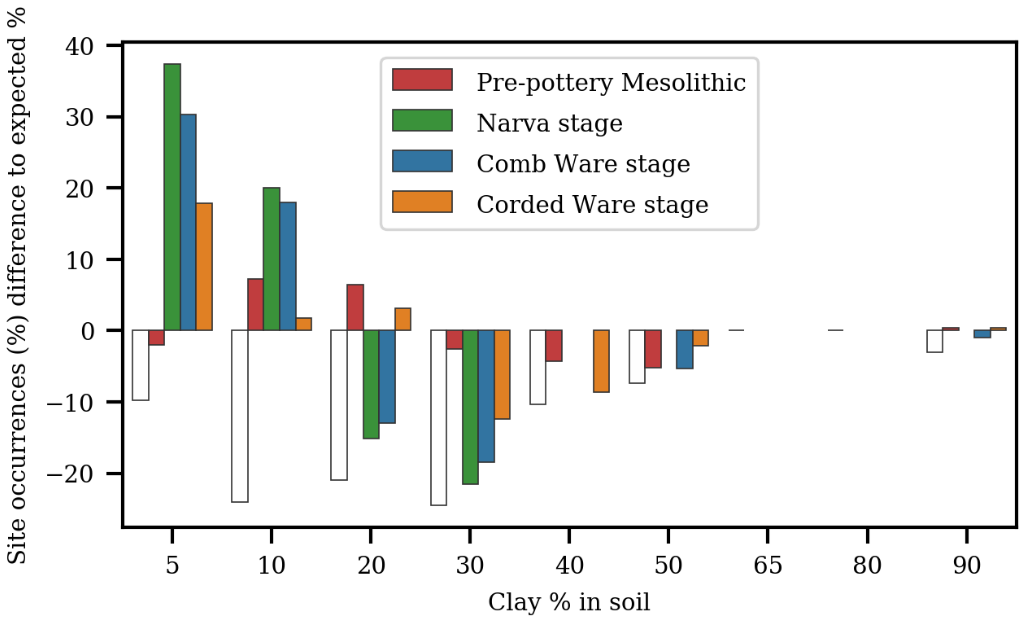

Figure 2.3: Clayness of soil as a percentage of sites situated on soils with a given clayness. The plot is visualised as a comparison with the number of soils with the same clayness in the environment, thus showing the difference with the expected distribution. The white bars are included to show the percentage of soils of corresponding type in the environment

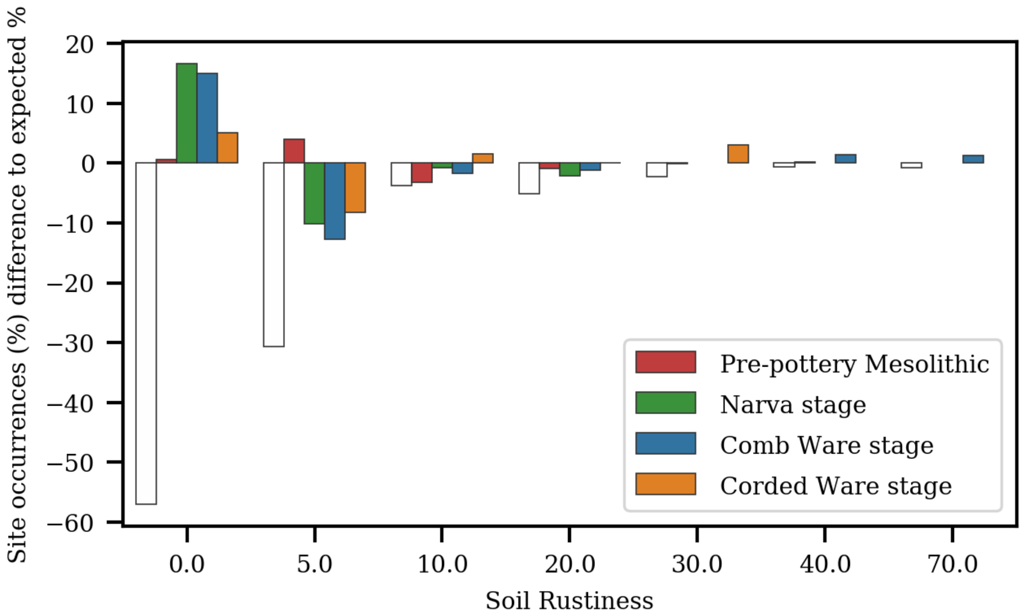

Figure 2.4: Soil rustiness as a percentage of sites located on soils with a given rustiness. The plot is visualised as a comparison with the number of soils with the same rustiness in the environment, showing the difference with the expected distribution. The white bars are included to show the percentage of soils of corresponding type in the environment.

used significantly more than would be expected by random settlement choice. The preference is especially clear for sites from periods with pottery, with almost all Narva stage sites being situated on soils with clayness of less than 20%. Corded Ware stage sites were also found on soils with higher clayness; the tendency towards placement on sandy soils for these sites is less significant than for Narva and Comb Ware stage sites.

For pre-pottery Mesolithic sites, despite the general effect of higher than average clayness, we can still see the importance of sandy soils. Soils with higher than 30% clayness were found in only some instances. For some reason, fewer sites than expected were situated on fine sands, and there are several outliers on soils with high clayness. The sites with Narva and Comb Ware also tend to be situated on soils with lower soil rustiness (Fig. 2.4), with significant numbers of sites on soils with no stones in them.

The soil types in sites grouped by soil classification (Fig. 2.5) reveal that Stone Age people preferred locations with albeluvisols and for sites with pottery also podzols. Almost no sites are present on gley soils. The Stone Age stages with pottery differ remarkably from the pre-pottery Mesolithic, for which the effects are less pronounced or even opposite, e.g. high presence of sites on brown soils. Although the aforementioned regularities are significant, site selection principles are in general more effectively described by the clayness of the soil than by the soil classification.

It must be taken into account that the soils might have changed after the period of the settlement which could possibly make the use of current soil categorisation inaccurate but would have lesser effect on quantitative measures of clayness and soil rustiness.

2.2.3 Geomorphological variables

The relationship of 19 geographical variables to settlement choice was assessed and most of them were found to be significant (Table 2.2.3). The variables with a significant effect on settlement choice are described and interpreted below.

Variable	Description	A statistic	K-S test p value
D_WATER	Distance to water	0.089; large	1.356e-187
CLAYNESS	Soil texture as % of clay content	0.398; small	8.295e-10
RUSTINESS	Soil rustiness	0.527; negligible	0.021
SLOPe	Slope	0.671; medium	2.936e-29
C_PROF	Profile curvature	0.55; negligible	7.455e-05
C_TANG	Tangential curvature	0.515; negligible	0.354
C_MAXI	Maximum curvature	0.562; small	9.247e-05
C_MINI	Minimal curvature	0.503; negligible	0.489
EAST	Eastness; part of ASPECT	0.625; small	1.151e-20
NORTH	Northness; part of ASPECT	0.665; medium	2.072e-27
VRM	Vector Ruggedness Measure	0.707; medium	7.249e-33
ROU	Terrain Roughness	0.682; medium	2.318e-33
TRI	Terrain Ruggedness index	0.752; large	8.378e-51
C_INDEX	Convergence index	0.52; negligible	1.676e-05
WEXPO	Wind exposition	0.603; small	2.238e-12
SOLAR	Solar radiation	0.466; negligible	0.004

TWI	Topographic wetness index	0.321; medium	3.76e-25
MPI	Morphometric protection index	0.617; small	1.842e-10
TPI10	Topographic position index (50 m)	0.692; medium	6.255e-37
TPI50	Topographic position index(250 m)	0.676; medium	8.52e-36
TPI100	Topographic position index(500 m)	0.718; medium	1.539e-50
TPI300	Topographic position index(1500 m)	0.691; medium	3.482e-44

Table 2.2: Used environmental variables

The slope of the ground is one of the most easily perceivable geomorphological characteristics for a person at the location. As expected, inhabitants preferred settlement locations on slight slopes. The distribution of slope values at site locations (Fig. 2.6) shows a significant influence toward a bigger slope (A statistic = 0.671, p value = 1.43e-37) in comparison to the environment, reflecting a clear preference in settlement choice. Some differences between slope distributions in different Stone Age stages can also be observed. Sites with Narva-type pottery were situated on the steepest slopes (mean 0.056 radians), and pre-pottery Mesolithic sites were mostly on flatter ground (mean 0.046 radians), but the latter had also more outliers.

Since settlement choice is related to the slope of the environment we also analysed the directionality of the slopes. The east-west direction has a small effect (A statistic = 0.625; p value = 1.151e-20) towards the east, and the south-north direction has a medium effect (A statistic = 0.665; p value = 2.072e-27) towards the north. To explore the directionality we visualised the variable ASPECT as a radial plot (Fig. 2.7). For the visualisation we only selected sites with a slope greater than 0.07 rad.

For the pre-pottery Mesolithic sites no general preference towards any slope direction is observable but for Narva and Comb Ware stage sites there is a preference towards sites on slopes directed to the south and south-west. Southward and south-east facing slopes can be optimal for more sunshine, but the solar insolation analysis (variable SOLAR) indicates a small negative effect for sites with pottery and a small positive effect for the pre-pottery Mesolithic. The directionality might be influenced by the general topography of the region, e.g. the direction of the water from the site location if the settlement was situated close to the waterfront. A certain skewness

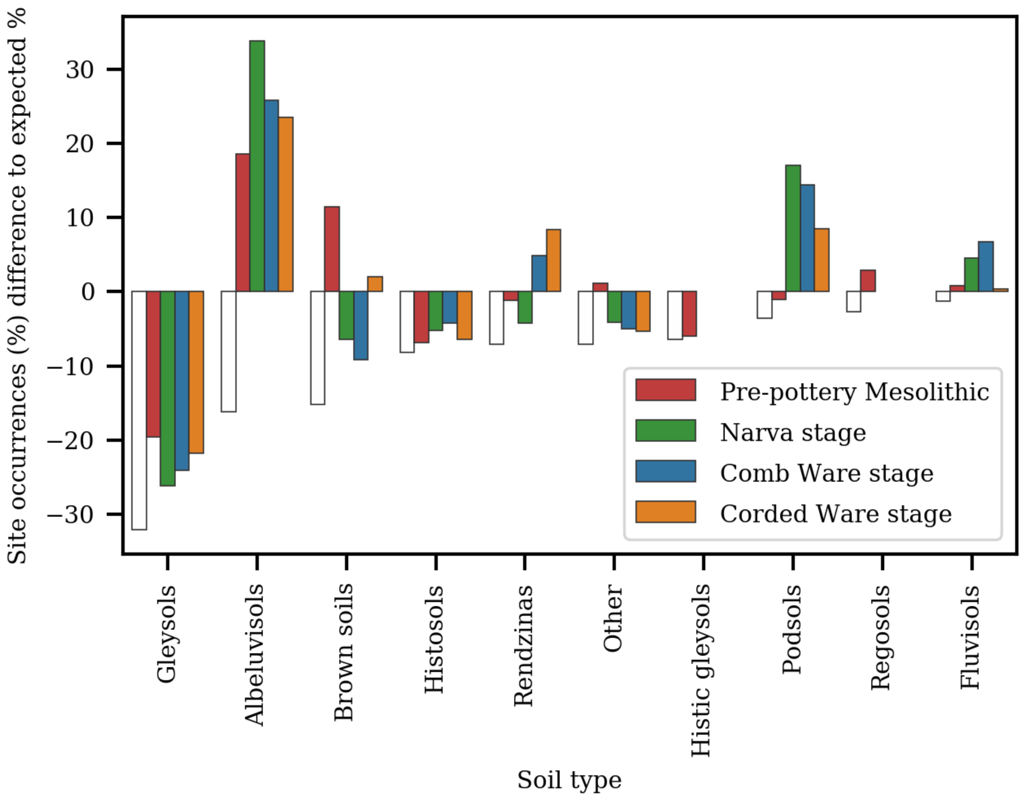

Figure 2.5: Distribution of soil types compared to distribution of soil types in the environment. The white bars are included to show the percentage of soils of corresponding type in the environment.

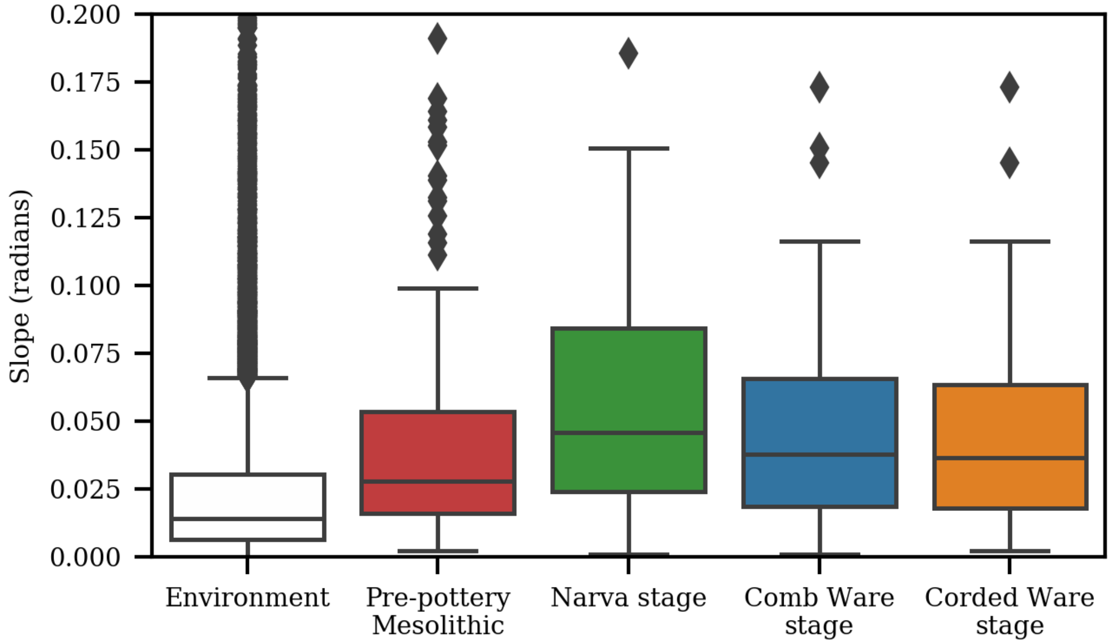

Figure 2.6: Boxplot illustrating the distribution of slope (in radians) in settlement site locations in comparison with the environmental sample.

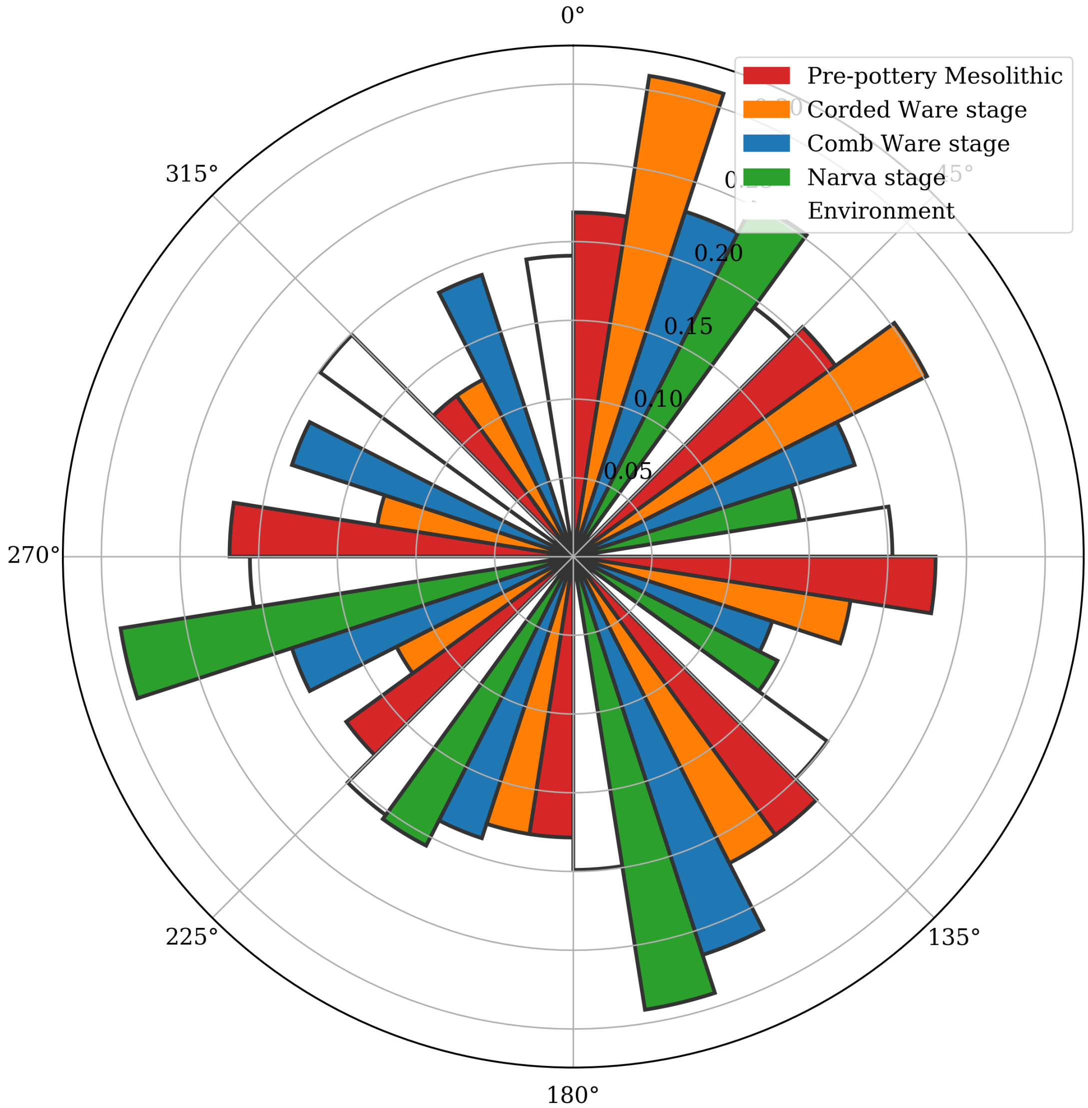

Figure 2.7: Radial histogram visualising slope direction (aspect) for sites with a slope of more than 0.07 rad compared to that of the environment.

of the data is especially clear for the Narva stage sites, because of the small sample of which 28% (11 sites) are from the same Riigiküla microregion facing the former lagoon in the south.

Surprisingly the sites with Corded Ware have a slight tendency to have slopes towards the north and north-west. This might be caused by the fact that the Corded Ware stage site distribution is dominated by inland sites on the Klint plateau of northern Estonia, which slope towards the north.

Variables describing local surface curvature (profile curvature, tangential curvature, minimal and maximal curvature) of the site locations did not express any significant effects.

In contrast with the local surface curvature, the general ruggedness of the environment was found to be strongly related to site location. All of the tested measures give significantly different statistical distributions for sites in comparison to the general environment (VRM: A statistic = 0.707, medium; p-value = 7.249e-33; TRI: A statistic = 0.752, large; p-value = 8.378e-51; LSRI: A statistic = 0.682; medium, p-value = 2.318e-33). All measures clearly indicate that the settlement sites are situated on a more rugged landscape than the environment in general, with TRI (Fig. 2.8) expressing the strongest effect. The sites with pottery tend to be situated in a more rugged environment than the pre-pottery Mesolithic sites, probably as a result of the different nature of the observable sites.

Wind exposure (Fig. 2.9) was calculated with the Wind Exposition Index tool and it showed that Stone Age sites are more exposed to the wind than the overall environment (A statistic= 0.603; small; p value = 2.238e-12). Pre-pottery Mesolithic sites are more sheltered than sites with pottery. Corded Ware stage sites were found to be in significantly windier locations (A statistic = 0.682, medium; p value = 4.88e-07). It is possible that these results do not reflect the effect of wind on settlement location choice but rather the fact that sites were situated on shorelines which are more exposed to wind. The pre-pottery Mesolithic sites have less wind exposure because past water bodies have retreated and they are no longer directly on the shoreline.

A similar tendency appeared when analysing the topographic openness of the location. The variable was calculated using the Morphometric Protection Index Model in SAGA GIS. Again, the distribution of settlement site locations showed a tendency towards openness as compared with the surrounding environment (A statistic = 0.617, small; p value = 1.842e-10), with sites with Narva-type pottery being in the most open places and pre-pottery Mesolithic sites being in the least open places. As with WEXPO, the variable is probably related to the closeness to water, but the relationship between both variables has yet to be statistically proven.

One of the reasons that has been used to explain the choice of sandy areas for settlements is their dry nature, since the water drains away through the sand. To

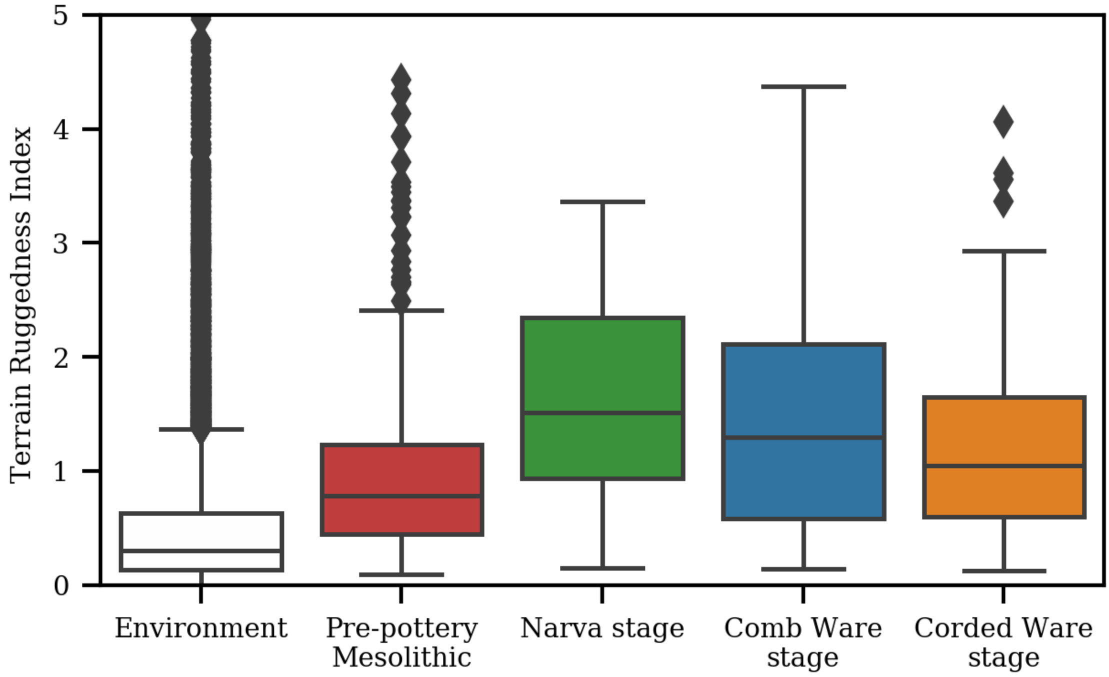

Figure 2.8: Box plot of Terrain Ruggedness Index (TRI) values of the site locations grouped by period and compared to the environment.

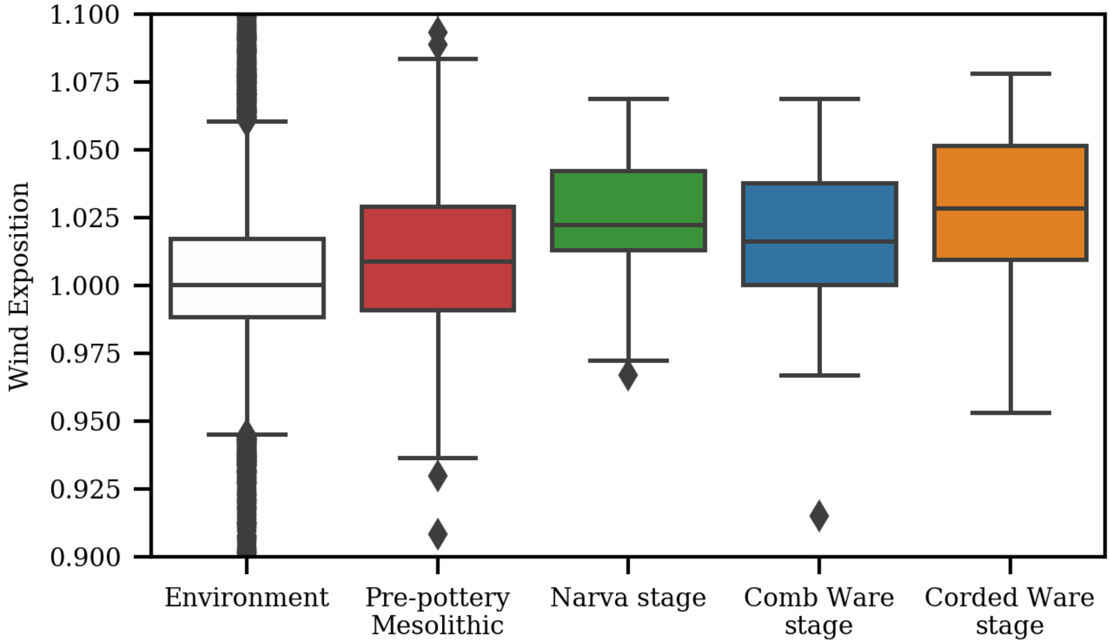

Figure 2.9: Box plot of Wind Exposition Index (WEXPO) values of the site locations grouped by period and compared to the environment.

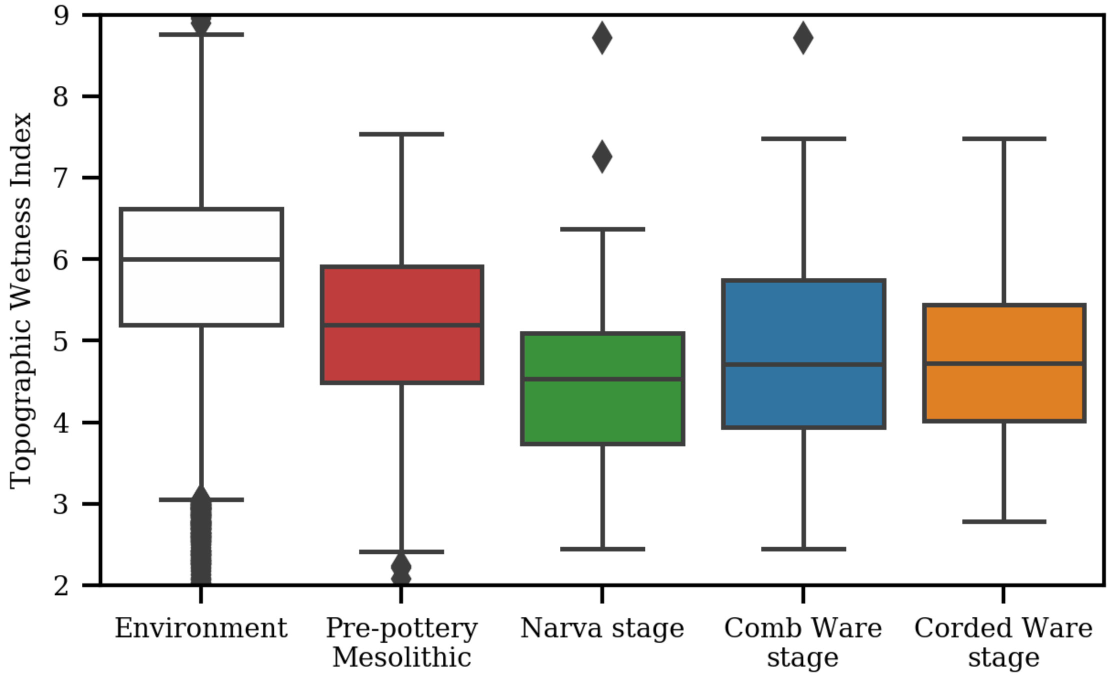

Figure 2.10: Box plot of the distribution of Topographic Wetness Index (TWI) values in site locations in comparison to the environmental sample.

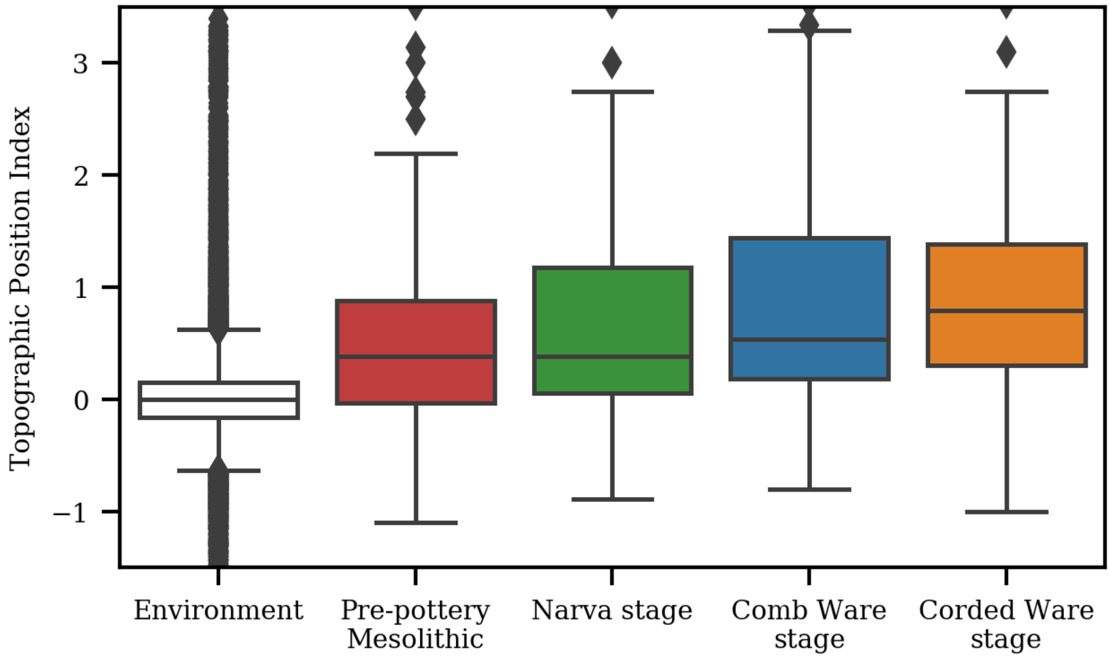

Figure 2.11: Box plot of the distribution of Topographic Position Index (TPI) values using a context range of 500m. The box plot visualises the comparison between values in site locations and the environmental sample.

check the importance of the dryness of the location we used the Topographic Wetness Index (TWI; Fig. 9). The TWI of locations chosen for settlement sites appears to be considerably lower than the environmental location sample (A statistic = 0.321; medium; p-value=3.76e-25), confirming the importance of dryness for location choice. The result is especially meaningful given that most of the sites are close to water bodies or wetlands. It clearly shows the principle of choosing a settlement close to water but in a dry place, avoiding any water flowing to the site from surrounding higher areas.

To analyse regularities in the prominence of site locations in the landscape we calculated the Topographic Position Index (TPI) with Saga GIS. The TPI is an algorithm used to measure the topographic slope positions of locations in relation to their surrounding environments. The TPI is a zonal statistic and operates in the context of the surrounding environment. As experimental tests showed that the TPI had a considerable effect on settlement choice we experimented with different ranges to identify the spatial context in which the variable had the greatest effect. We calculated the TPI with 50m, 250m, 500m and 1500m surrounding ranges. The biggest difference between sites and environment was seen in the 500m range (Fig. 2.11; A statistic = 0.718; medium, p-value=1.539e-50), showing the importance of higher location in relation to quite a large area. The greatest tendency towards selecting higher locations was observed for Comb Ware and Corded Ware stage sites. But the meaning of the tendency still needs to be studied because for some shore-bound sites it might be also influenced by the closeness to water, as the water level is always lower than the site on the land.

Overall geomorphological statistics informed us that Stone Age sites were situated in rugged environments and in high, dry positions on a slight slope. The distributions of geomorphometric variables might also be influenced by the locations' proximity to shorelines, which might cause certain regularities in the geomorphology of the locations, but this effect has not yet been studied.

2.3 Changing settlement choice

2.3.1 General observations

It has long been assumed that water bodies were the main determining factor in the location choice of Stone Age settlements. By the beginning of the 21st century, there was enough reference material in Estonia for empirical conclusions to be drawn. Although the tendency of settlements to be located close to shorelines had been mentioned before, the only paper focusing on the issue is by T. Jussila and A. Kriiska (2006). The study explores hunter-fisher-gatherer sites in Estonia and Finland and focuses on exceptional sites situated further away from shorelines. In the paper, T. Jussila and A. Kriiska (2006, p. 46) propose a site classification based on distances to water (D): shore-bound sites ($D < 150$m), shore-facing sites ($D < 300$m), inland forest sites ($D < 1$km) and inland "deep forest" sites ($D > 1$km). According to this classification, 333 of the sites in the dataset used in our study are shore-bound sites, 40 are shore-facing sites, 21 are inland forest sites and 17 are inland "deep forest" sites. But it should be borne in mind that the categories were developed for hunter-fisher-gatherer sites and are not optimal for Neolithic (semi-)agrarian sites.

According to the classification, most of the sites are very closely connected to water, with only rare cases being qualified as inland sites. The majority of the inland sites belong to the Corded Ware stage, where hunting, fishing and gathering might have not been the main subsistence mode.

The results indicate very strong water connectedness for the pre-pottery Mesolithic, Narva and Comb Ware stages. This does not necessarily imply a lack of land use away from the water; it may simply be that we lack information on these sites. Shore sites are often found while prospecting past shorelines, but there is no methodology to find inland Stone Age sites and they are usually found while exploring sites from later periods. Still, the lack of data does not refute the general tendency of settling close to water. During archaeological surveys, areas close to the shoreline are also routinely checked and the findings cease when surveying further away from the past shoreline.

Another very clear indication is that Stone Age sites tend to be on high, dry and sandy locations, as seen in the soil type, higher TPI and lower TWI of the site locations. These environmental influences were expected and are intuitive when observing landscape; they generate a certain gut feeling as to suitable locations for settling or camping. Nevertheless, the magnitude of the influence when expressed quantitatively was even clearer than expected.

2.3.2 Pre-pottery Mesolithic

Pre-pottery Mesolithic sites followed aforementioned tendencies but compared to later periods had greater variation. The difference in variation was observable for all significant measures including distance to water, TWI, TPI and most surprisingly clayness, as several sites were situated on soil with high clayness.

The reasons for the variation in general are manifold and relate to the nature of available data about the oldest period of habitation. As the find material is the oldest there has been the most significant environmental change, including hydrological regime change, during the period. So the information about the distance to water is less accurate, and also soils might have been modified by changing water levels and flows.

The time period is multiple times longer than the later Stone Age stages, with no significant markers that recognise relevant sub-periods. In most cases the functions of the sites have not been distinguished from each other because of a lack of required markers.

Apart from explanations based on data, the variation can also partly be explained by the nature of the settlement choice for the period. Requirements for environmental conditions might be influenced by a lower selectivity regarding settlement locations. The lack of selectivity may in turn be caused by lower requirements and effort put into site investment, which can be considered as an indication of the short-term use of settlements (Sahlins, 1972, p. 11–12). The temporary nature of sites is typical for hunter-fisher-gatherers who moved around a lot. It is probable that a lot of sites were temporary sites for highly mobile hunter-gatherers, while those from later periods used their camps for longer.

The hypothesis of higher mobility is backed up by the number of sites situated on flat land and soil of high clayness, which do not usually provide good conditions for long-term habitation, especially with wet weather. Those sites might be used by groups seeking temporary shelter and not planning for significant site investment at the location.

Given the nature of the dataset we can safely assume that it contains information about site selection for multiple settlement modes used in accordance with varying subsistence systems, site functions and mobility modes. The settlement choice behind this dataset might contain both mobile temporary habitation and permanent settlement sites. The sample probably also includes later Mesolithic periods with a habitation mode similar or identical to the Final Mesolithic Narva and Neolithic Comb Ware stage modes. Isolating those modes is not in the scope of the current research.

2.3.3 Narva and Comb Ware stage

Known Narva and Comb Ware stage sites are situated in environmentally very similar settings, with Narva stage sites having more pronounced environmental influences on settlement choice. The difference between them is not statistically significant because of the small sample of Narva stage sites. The sample from the Narva period is also skewed towards characteristics of a certain region as nearly 28% of the sites are from the same microregion on the shores of one palaeo lagoon. For this reason we decided to consider Narva and Comb Ware stage sites together.

The vast majority of the sites are situated close to the shoreline on sandy, dry, high, open areas on rugged terrain. The site locations imply careful selection that might indicate a greater emphasis on site investment. Find material contains pottery, which is considered to be an indication of more permanent settlement (Marshall, 2006). In comparison with pre-pottery Mesolithic periods, a clearly defined method of permanent settlement choice is observable in archaeological records.

We assume that there were also temporary sites which have not been found or might be hard to distinguish from the pre-pottery Mesolithic period. The data might be skewed because most of the sites were found during archaeological field surveys using methodology targeted for such sites.

2.3.4 Corded Ware stage

The statistical analysis showed that, although partly contemporaneous with Comb Ware stage habitation, a completely different settlement location choice system emerged during the Corded Ware stage. Corded Ware stage settlement location choice can be divided into two different models.The environmental conditions of the first are similar to the Comb Ware stage and in several cases the sites have both Comb Ware and Corded Ware pottery, either the latter replacing the former or the two existing together. However, their coexistence has not been proven in any case, while metachronic habitation is visible in radiocarbon dates in several Estonian settlement sites.

As best seen in the box plot (Fig. 2.2), the placement logic of the second model of Corded Ware stage sites differs significantly from cases where Corded Ware is present on sites with Comb Ware. In several cases Corded Ware stage habitation existed on previously inhabited sites despite the shoreline having receded kilometres away from the time of previous habitation (Aivar Kriiska, 2003, p. 19). Such sites are observable on the islands and also at the shores of Lake Võrtsjärv, while the southern and eastern Estonian settlements seem to remain mostly connected to rivers (Aivar Kriiska, 2000, p. 71; (Aivar Kriiska, 2003, p. 19)).

In northern Estonia new sites emerged in a completely different topographical setting. The sites are situated on the limestone rendzina (Klint) (V. Lang, 1996, Fig.101, 120, V. Lang and Konsa, 1998; Aivar Kriiska, 2003, p. 19; Paavel et al., 2016, p. 56). They have distinct environmental conditions including different soils which often have a higher clay content and higher wetness. TPI values inform us that these sites tend to be situated in more prominent positions in the landscape than previously.

The position of the sites implies that their subsistence was not based on an aquatic economy; instead it might suggest the importance of an agrarian economy. V. Lang (1996, p. 444) and Aivar Kriiska (2000, p. 74) have suggested the introduction of a sedentary lifestyle and single-family households that continued on to the Early Metal Age. Although Bronze Age settlements are not included in the current study, the change in settlement choice method certainly confirms this hypothesis. However, it must be emphasised that later Bronze or Iron Age settlement or burial sites were located on many Corded Ware stage settlement sites (e.g. V. Lang and Konsa, 1998; Ots, Allmäe, et al., 2003; Paavel et al., 2016)).

Dating from the sites indicates that hunter-fisher-gatherer and (semi-)agricultural settlements existed contemporaneously and formed distinct cultures that we can currently distinguish by different pottery, in addition to other parameters (e.g. A. Kriiska, 2019, p. 15, 22)). Therefore it is also possible that some sites classified as Corded Ware stage by fragments of pottery were not the living places of the bearers of this culture, but that the pots were brought to Comb Ware stage settlement sites as a result of exchanges of goods (L. Jaanits, 1955, p. 186).

As with earlier periods with pottery, archaeological material does not inform us about temporary settlements or hunting camps. In earlier periods the main source of information is flint and quartz, but the find material associated with the Corded Ware stage in Estonia contains almost no lithic material (Paavel et al., 2016, p. 53; (e.g. A. Kriiska, 2019, p. 44)), meaning that there is currently no methodology to find traces of temporary Corded Ware stage camps.

2.4 Methodological discussion

2.4.1 Survey bias

As described in the „Materials and methods" the survey methodology might have introduced bias into the statistical analysis and interpretation of settlement choice. While certain bias is inherent for any archaeological research as used samples are influenced both by conditions of preservation and researchers' presumptions, we argue that the existing sample is representative of past settlement choice.

In current study the main problem could be overemphasis of the sites proximity to shorelines. As this is a known issue recently the former shoreline based surveys have included searches in the areas further away from coastal areas. Although often undocumented or documented only in unpublished archaeological reports these results have shown quite clear-cut habitation area as archaeological finds have ceased to be found while moving further away from the shorelines. It shows that there is no continuous habitation spanning towards the inland.

There also exists quite a big sample of non-survey based and negative results coming from research of other periods and large-scale surveys. While several sites of the Corded Ware period found from research of later sites (eg. Jõuga, Soodevahe sites; V. Lõugas and Selirand, 1989, p. 241; Paavel et al., 2016) are further away from the past shorelines, Narva and Comb Ware sites found while studying later sites have been situated close to the former shoreline (eg. Kaseküla site).

The statistical difference between the environmental variables of sites of Corded Ware and other stages which have all been found by identical process is in itself an indication of differing logic behind the settlement placement. Indeed this does not preclude certain statistical bias, studying it further would require quantitative research of negative results of archaeological survey.

As is often the case in archaeological research there also remains a possibility of existence of a currently unobservable mode of habitation, eg. inland base settlements or hunting camps. In this case their settlement choice logic needs to be described based on isolated set of sites as they do not form a spatial continuum with the current water connected settlement pattern. From current research it appeared that similar situation seems to be true for the Corded Ware settlements that can be described as two separate modes of habitation.

2.4.2 Environmental variables and settlement choice

The statistical analysis presented in this paper indicates that settlement locations in Stone Age Estonia were strongly linked to the environmental conditions of the site locations. In the current case the dominant variables are closeness to water and clayness of the soil, but geomorphological variables also have a considerable effect.

It is worth mentioning that simple DEM derivatives like surface curvatures did not show a significant relationship with site selection, as opposed to more complex topographic variables like TPI and TWI. These results might give insights into the settlement choice model from a human perspective, but they require further study.

Although proven to work successfully for predictive models (for a discussion see: Kvamme, 2005), the causality of the effects of individual factors presented by variables still needs to be researched. For example, closeness to water may have been required for direct access to aquatic resources, transportation and communications. Water is also required as a complex ecosystem service providing drinking water, hygiene, water for agricultural use, etc. Geomorphological variables are not statistically independent and several of these factors may be influenced by the nature of landscapes close to water.

Archaeological research looks for causal explanations for different phenomena, and statistical models are expected to provide such explanations. But the relationship between observable variables and a possible choice model explaining the residential decisions of Stone Age people needs study. For example, we can observe that a degree of surface slope is preferred for site location, but does that mean that it was required for the people in the past, or does it just describe the sloping ground near the shoreline? Although the issue could be further explored with a statistical analysis of the relationship between the variables, offering archaeological interpretations for questions like these requires a conceptual model of settlement choice.

The geographical scope of settlement choice needs further clarification. It needs to be assessed to what extent environmental correlates arise from the fact that general regions (e.g. big lakes, lagoons, river estuaries) providing necessary resources have similar topographies, as opposed to the fact that they may meet the requirements of a specific location. In the current study we performed a statistical experiment measuring the range in which the TPI variable has the most effect. We found it to be an area with a 500m radius. Similar statistical experiments of other variables could also be carried out.

Another topic that needs to be researched is the reuse of archaeological sites: were the sites inhabited based on continuous knowledge, were they continuously the "best" locations in the environment, or had previous habitation modified the environment in a favourable way? An interesting example is the Kivisaare site, which was inhabited during all periods despite being situated on an island during the Mesolithic and in an inland forest during the Corded Ware period.

2.5 Conclusion

The goal of the current study was to give a statistical overview of the settlement pattern of the Estonian Stone Age and to analyse the influence of the environment on settlement choice in the period. To this end we compiled a list of the archaeological sites ($n = 410$) that can be categorised as belonging to one of the stages of the Estonian Stone Age. We extracted environmental variables for the settlement site locations and compared their distribution to the distribution of the variables in the environment overall. For distributions with significant differences (K–S p-value < 0.05), we quantified them with Vargha and Delaney's A measure and provided descriptive statistics.

Quantitative assessment confirmed previous observations that proximity to water had the most significant effect on settlement choice, while soil type was also of considerable importance. To measure settlement choice we quantified soil types by the percentage of clay content. There was a clear link between sites' suitability for habitation and higher sandiness (meaning lower clayness).

We assessed several geomorphological variables for their impact on settlement choice and concluded that while simple DEM derivatives have no links with settlement choice, more abstract topographical variables like TPI and TWI have strong effects. For all stages studied, most of the sites are situated close to water, on dry, sandy areas avoiding water flows on a gentle slope in slightly more prominent locations.

There are some differences between settlement patterns for the different stages of the Stone Age. Site locations from the pre-pottery Mesolithic have greater environmental variation. This suggests that archaeological material reflects several different modes of habitation caused by environmental changes during the period, multiple site functions and variable levels of site investment by hunter-fisher-gatherer groups practising differing modes of mobility.

Both the Narva and Comb Ware stage sites followed a very clearly defined pattern, with the majority of the sites being situated close to the shoreline on sandy, dry, high, open areas on rugged terrains. The site locations indicate strong site investment with higher sedentism.

During the Corded Ware stage a new settlement mode emerged; some sites were not situated close to water and were placed on different soils. The sites were situated on higher locations on older shoreline formations or cliffs which were no longer close to the shoreline. Settlements emerged on the Klint in northern Estonia and on old shore formations far from the sea and Lake Võrtsjärv. On the islands and in central Estonia this corresponds closely to Bronze and Iron Age settlement patterns.

New environmental characteristics affecting settlement choice indicate new agrarian or semi-agrarian subsistence and decreasing dependence on aquatic resources. At the same time, several sites were used during both Comb Ware and Corded Ware stages, even though the previously adjacent shorelines had receded by the latter period. Most of the sites still continued to follow the previous placement logic of the partly contemporaneous Comb Ware stage.

Chapter 3

Comparing contemporaneous hunter-gatherer and early agrarian settlement systems with spatial point process models: case study of the Estonian Stone Age

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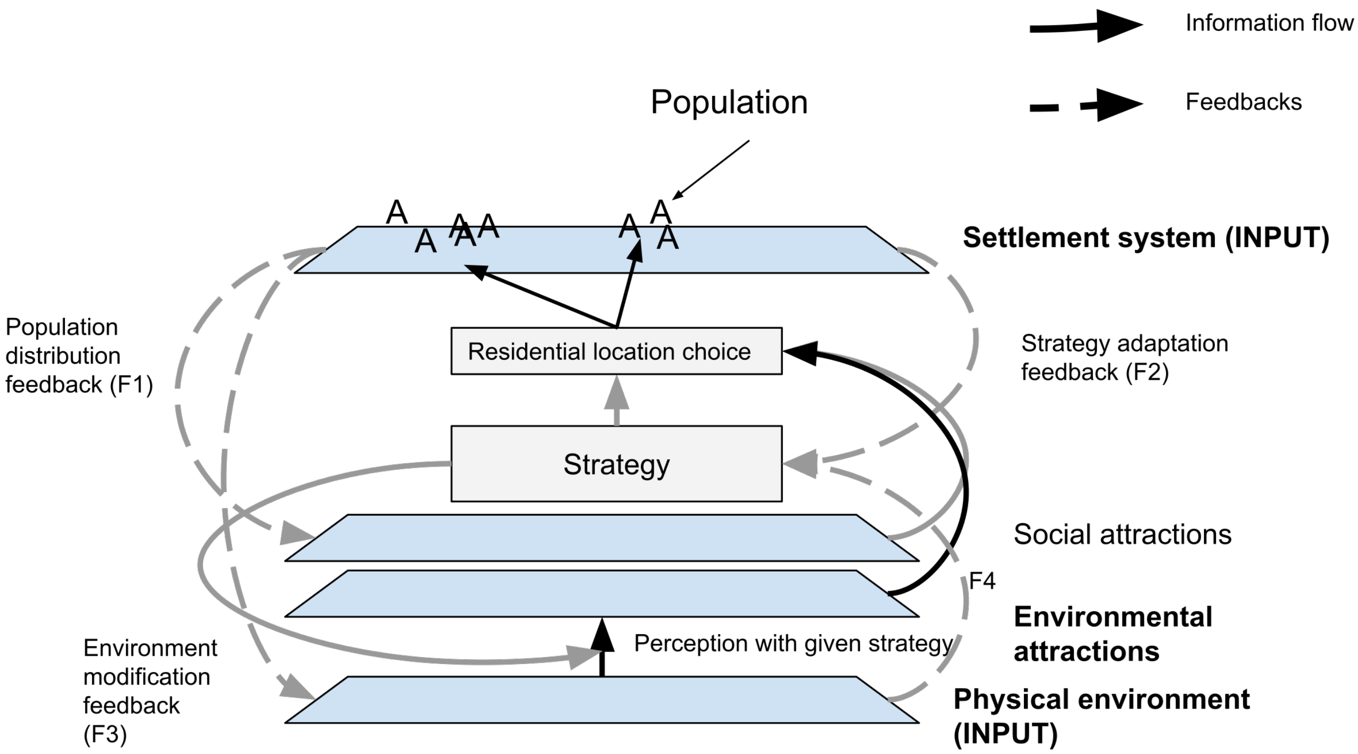

Figure 3.1: The chapter explores the information flow from perceived environment attractions as a spatial entity to settlement location choice

3.1 Introduction

The tradition of creating inductive locational models of archaeological sites spans several decades. These are mostly regression models based on environmental covariates which have been used to search for areas with a high probability of site occurrence (e.g. Kvamme, 2005; Verhagen and Whitley, 2012). The explanatory interpretation of model results tends to be limited to the exploration of individual variables and descriptions of the geographical distribution of model outputs.

The goal of this paper is to present a spatial inductive model exploration, quantitative comparison and comparative interpretation of modelling results. The case study is based on Stone Age Narva culture (NW), Comb Ceramic culture (CWC) and Corded Ware culture (COCW) in the Estonian area. These cultures represent a timespan of c. 1000 years, with early agrarian society migrating and inhabiting a region with existing hunter-gatherer cultural groups. The cultures (e.g. L. Jaanits, 1955; Lembit Jaanits et al., 1982; A. Kriiska, V. Lang, et al., 2020; Aivar Kriiska, 2000; Aivar Kriiska, Oras, et al., 2017; Lembi Lõugas et al., 2007) and their different principles of settlement choice (Sikk, Aivar Kriiska, et al., 2020a; Chapter 2) have been thoroughly studied in the region. So far there has been no comparative spatial research of the two populations.

We used environmental data from combined Narva culture and Comb Ware culture (NW-CWC) sites and COCW sites. For a region in northern Estonia we created spatial environmental suitability rasters for residence and compared them with each other (Vidal-Cordasco and Nuevo-López, 2021; Whitford, 2019). To provide environmental data for modelling we used available Holocene relative sea-level (Muru, Rosentau, Aivar Kriiska, et al., 2017; Rosentau, Muru, et al., 2013), geomorphological and soil data and built palaeo reconstructions of the region for two different time periods.

Landscape surveys for archaeological sites have led to the observation that locations of sites from certain periods are easier to find than others. In Estonia, NW-CWC settlement sites have been methodically found using landscape-based survey tactics while COCW sites are mostly found "by accident" (e.g. Aivar Kriiska, 2000). We can state that archaeologists' implicit mind models can predict the locations of NW-CWC sites but not COCW sites. This provides a strong basis to assume very different settlement systems that require explanations beyond just the influence of individual environmental variables.

The models were therefore explored statistically for their variable contribution and performance. We compared their spatial outputs and interpreted the differences using existing knowledge of the settlement patterns for the cultures concerned.

3.2 Method

Settlement patterns are formed by subsequent habitation events in different locations. In this paper we generalise these locations as points, as is typical practice for archaeological locational models. This allows us to describe settlement patterns as point patterns and their formation as point processes, mechanisms that produce point patterns. Mathematically a point process is a stochastic generation of points in space; in the case of a homogeneous Poisson point process it is determined by intensity λ and results in complete spatial randomness. It is obvious that settlement locations are chosen not as random locations in space but on the basis of a multitude of conditions perceived by settlers. We can call this a non-homogeneous point process and in this case the constant intensity λ is replaced by a deterministic function $\lambda(s)$, where s is any spatial variable (typically environmental) or a set of variables.

To describe the underlying laws, a point process model (PPM) can be constructed and explored. PPMs can be used to characterise point processes and also to distinguish between the effects of first- and second-order properties. The former refers to externally induced global effects (e.g. environment) on the average intensity of points in certain locations and the second to systemic effects emerging from the relationship between the points, or settlements in our case (Bailey and Gatrell, 1995; Crema, Bevan, et al., 2010). In this study we are interested in how the environment influences settlement choice so we can describe it as a heterogeneous Poisson process that includes only first-order effects. The occurrence of the choice event thus remains independent from other events, taking into account only local environmental conditions.

The empirical data allows us to apply a PPM that describes the hypothetical underlying generating mechanism and makes it possible to give theoretical descriptions of phenomena. In the current case we explore how the environment influenced settlement choice and settlement pattern formation. We define the developed PPM as an archaeological environmental effect model (EEM).

To train our EEM models and output them as habitation suitability rasters we use MaxEnt, a machine-learning tool for model training (Phillips, Dudík, and Schapire, 2017). MaxEnt has been shown (Renner et al., 2015, p. 369) to be effective in training PPM models in general and for archaeological site prediction in particular, with only minor loss of explanatory power (Vernon et al., 2020; Yaworsky et al., 2020). MaxEnt applies the expectancies comparison principle and maximum entropy principle to find distributions of variable values that are predicted as suitable, in the current case, for habitation (for a detailed explanation see: Elith et al., 2011; Wachtel et al., 2020). It estimates the role of environmental covariates in settlement choice, constraining the geographic probability distribution to be as close as possible to absolute entropy, i.e. spatial homogeneity in the case of point patterns.

MaxEnt allows the creation of an empirical density estimate which is converted through a link function (the complementary log-log transform being recommended) into a point process intensity, which is then interpreted as suitability for habitation in a given location (Vernon et al., 2020, p. 7, 8). Probability rasters are then created indicating suitability for settlement choice in the research area and can be used to explore the spatial configuration of the effects of environmental suitability.

The approach for exploring environmental effects using an EEM is almost identical to the practice of archaeological predictive modelling in terms of environmental covariates and methodology. Because of having only contemporary environmental data and very sparse information about links between sites, the most feasible predictive model for prehistoric archaeology is the first-order PPM.

EEM explicitly describes the influence of the environment on the settlement pattern formation process. It also enables the study of spatial characteristics of specific landscapes and environmental determinism as a distinct analytical category for settlement choice. Some methodology (e.g. niche overlap and niche breadth measures) for the study of spatial characteristics has been developed in the field of ecological species distribution modelling (SDM) and imported to the archaeological domain through eco-cultural niche modelling (ECNM; Banks et al., 2006; Banks, 2017; Whitford, 2019). The modelling practices also use similar data and a similar methodology. For example the MaxEnt toolkit was originally developed for SDM. SDM is based on species with lesser complexity in their socio-economic behaviour and technology use, so their outputs are considered to be almost entirely determined by the environment.

The purpose of ECNM is to explore the concept of ecological niches; it enables the identification and analysis of complex relationships between cultural systems and the niches used. The method includes analysis of the characteristics of niches as spatial units, including the use of comparative measures (Vidal-Cordasco and Nuevo-López, 2021; Whitford, 2019). It is mostly applied on a continental scale (for some recent regional studies, see Vidal-Cordasco and Nuevo-López, 2021; Whitford, 2019) including non-local variables like climate and brings with it the more general concept of niche. Niche acts as an ecological container for species or societies activities. It is not intended to explain experiential decisions of individual choices which are influenced by local environmental features like elevated sandy patches but also socio-cultural interactions. Those can lead to patterns within a particular niche. Therefore on a smaller scale, varied socio-economic behaviour may have a more complex impact on the environmental determinism to choices that could not be explained through the niche framework.

We create EEMs of hunter-fisher-gatherer (NW-CWC) and agrarian (COCW) settlement patterns and compare these models (see Section 4 for description). This comparison describes deterministic environmental features that also lead to spatial differences between the settlement systems. We explore statistical measures and

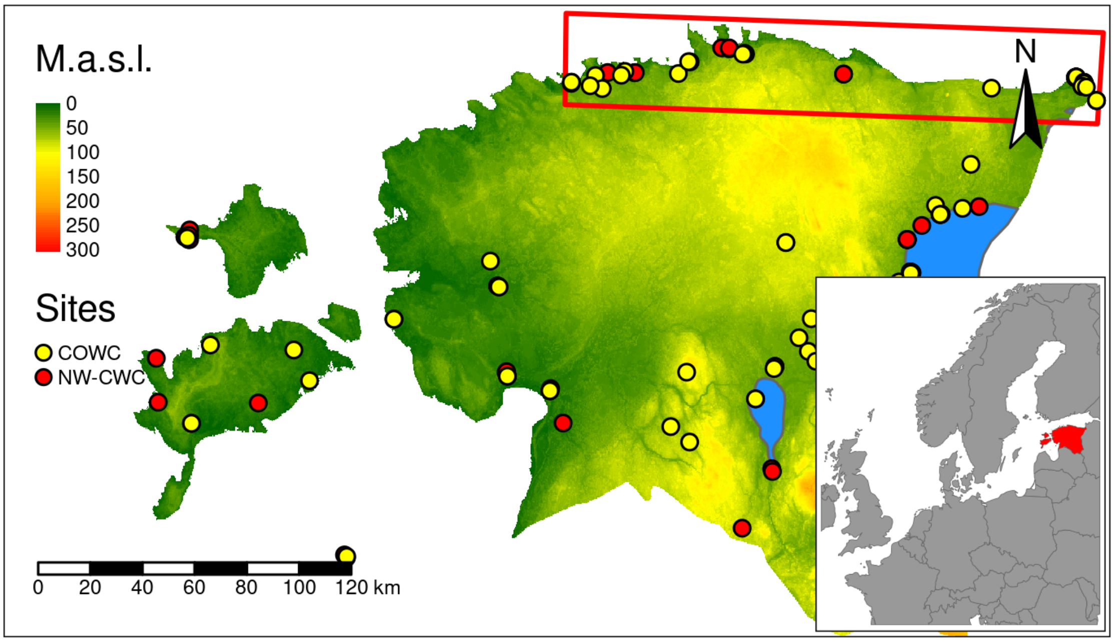

Figure 3.2: Overview of the Stone Age archaeological sites used in this research (for detailed site distribution maps see Sikk, Aivar Kriiska, et al., 2020a). The spatially explicit model was created based on the area in northern Estonia (surrounded by red boundaries).

predictive power of the models, the effect of individual environmental covariates and the spatial configuration of the spatially explicit output of the models (Section 5).

3.3 Archaeological and environmental data

The locational data of this study is based on settlement locations of three archaeological phenomena: Narva culture (5200–3900 BC), Comb Ceramic Culture (3900–1750 BC) and Corded Ware culture (2800-2000 BC) (A. Kriiska, V. Lang, et al., 2020, Fig. 1). The first two groups are hunter-fisher-gatherers with similar subsistence systems. As it has been shown that the environmental characteristics of their settlement sites are virtually indistinguishable (Sikk, Aivar Kriiska, et al., 2020a) they are grouped together as NW-CWC. We study and compare the location choice of two settlement groups: hunter-fisher-gatherer groups (NW-CWC) and agrarian groups (COCW).

The sites of the phenomena can be distinguished by their use of pottery which also helps to filter out temporary work sites that might not indicate habitation. NW, the first in the region to use pottery, was a hunter-fisher-gatherer subsistence culture with a likely dominant aquatic economy (e.g. Aivar Kriiska, Oras, et al., 2017; Oras et al., 2017). There is believed to have been cultural and genetic continuity from the first inhabitants arriving in Estonia about 9000 cal. BC (e.g. L. Jaanits, 1970, p. 86; Mittnik et al., 2018, p. 6; A. Kriiska, V. Lang, et al., 2020, p. 78. The settlements are situated close to water, on islands, lake shores, river deltas and the beaches of marine lagoons (Sikk, Aivar Kriiska, et al., 2020a, and the literature cited therein).

A similar pattern was used by the hunter-fisher-gatherer subsistence CWC peoples who arrived with a migration from the east (e.g. Lembit Jaanits et al., 1982, p. 77; Saag, Varul, et al., 2017, p. 3. Settlement location choice was very similar but the larger area contained several specialised and central sites (A. Kriiska, V. Lang, et al., 2020, p. 109).

COCW developed in Central Europe as a result of immigration from eastern steppe regions of Eastern Europe and also dispersed to Estonia as a result of immigration (Allentoft et al., 2015; W. Haak et al., 2015; Saag, Varul, et al., 2017; Saag, Vasilyev, et al., 2021). The immigration took place at a time when CWC was also present in Estonia, resulting in simultaneous habitation (A. Kriiska, V. Lang, et al., 2020). In considered territory COCW was an agrarian or semi-agrarian society (Aivar Kriiska, 2000; Lembi Lõugas et al., 2007) and despite offering no indication of a new level of social organisation and complexity, it had a very different settlement pattern and settlement choice principles (Sikk, Aivar Kriiska, et al., 2020a). Its inhabitants built their settlements on the north Estonian klint edge, river floodplains, ancient coastal formations in the Baltic Sea region and small drumlins on the lowlands near Võrtsjärv. While hunter-fisher-gatherer sites have been only found in close proximity to water bodies (Sikk, Aivar Kriiska, et al., 2020a), COCW sites are also situated further away. There are several cases of COCW people reusing previous hunter-fisher-gatherer sites if the shorelines had receded from the region.

The empirical data informing us about past settlement choices is derived from environmental conditions in the known settlement sites of the two groups. The previously published dataset of Stone Age settlement sites in Estonia (Sikk, Aivar Kriiska, et al., 2020b) is used as a source of site locations and two groups are selected from the data. There are 99 NW-CWC and 67 COCW settlement locations. The settlements and background environmental locations (n=10000) used for model training were chosen from the whole area of Estonia. The background locations were chosen using spatially structured sampling representing subregions with known archaeological sites to avoid model overfitting (Anderson and Raza, 2010).

Each location (sites and background) was associated with environmental data representing environmental influence on settlement choice. The variables used generally belong to three interrelated categories: distance to water, geomorphology and soil.

Distance to water was divided into distances to sea, lakes and rivers. The second group consists of various variables describing location's position in relation to landforms. Examples include slope, topographic wetness index, which quantifies locations control of hydrological processes; and topographic position index (TPI_100) which quantifies locations relative elevation in comparison to its surroundings. Third group includes various characteristics of soil including its standard classification, wetness, texture and sandiness (for more details see Sikk, Aivar Kriiska, et al., 2020a, Kmoch et al., 2021). Individual variables were chosen based on previous statistical analysis (Sikk, Aivar Kriiska, et al., 2020a) and during the model building process (see 4.3).

Because the goal of the model is to explain the influence of the natural environment on settlement choice, only variables representing abiotic, non-constructed and non-cultural characteristics were used, omitting any possible human-made environmental features like roads or fields. It should be said that soil data could be influenced by agricultural practices, but for this reason we experimented with a large set of soil variables published by Kmoch et al. (2021). Digital elevation rasters (5m resolution) provided by the Board (2019) and soil data were acquired for regions with settlement locations and the area of the spatial model output. The digital elevation models (DEMs) were used to create palaeo reconstructions of two distinct moments in time: 3900 BC, used for NW-CWC settlement reconstruction, and 2500 BC, used for COCW settlement reconstruction.

Based on the current DEMs, palaeo reconstructions of the past topography and shoreline were created and distance to the sea calculated as a separate raster layer. The palaeogeographical reconstructions for the time slices 3900 BC and 2500 BC are based on the GIS approach (Rosentau, Veski, et al., 2011), with the palaeo-sea-level surfaces being subtracted from the 5x5m LiDAR-DTM (Board, 2019). Initial palaeo-sea-level surfaces were interpolated using a point kriging approach from the database of coastal formations (Saarse et al., 2003) for the Litorina Sea (5500 BC) and for the modern Baltic Sea (1892-1991 AD) based on sea-level measurements and geodetic data (Ekman, 1996). These were used as reference surfaces, and two new time slices for 3900 BC and 2500 BC were interpolated between the reference surfaces considering a linear decay in shoreline tilting and average relative sea levels taken from the shore displacement curves for the Tallinn (Muru, Rosentau, Aivar Kriiska, et al., 2017) and Narva-Luga areas (Rosentau, Muru, et al., 2013). For the Tallinn area, the cultural layer thicknesses were also subtracted from the DTM based on data by Arbeiter (1993).

The geomorphological layers of the past were derived from DEMs and known water level changes using SAGA GIS 7 (Conrad et al., 2015). For this two spatially explicit residential potential rasters were created for the coastal region of north-eastern Estonia (Fig. 3.2). The region was chosen because of its general suitability for habitation during both periods as it has several known subregions with existing sites. Most of the study area is unexplored for archaeological sites, potentially raising the possibility of subsequent model validation using landscape surveys.

3.4 Modelling methods

3.4.1 Toolkit for training inductive point process model

We used the MaxEnt program with the "SDMTune" model tuning library (Vignali et al., 2020) written in R. SDMTune was used as it provides all the tools needed to run a complete modelling workflow, which in this case included data management for training, testing and validation, data-driven variable selection, model parameter tuning, validation and generation of raster maps of models (Fig. 3.3).

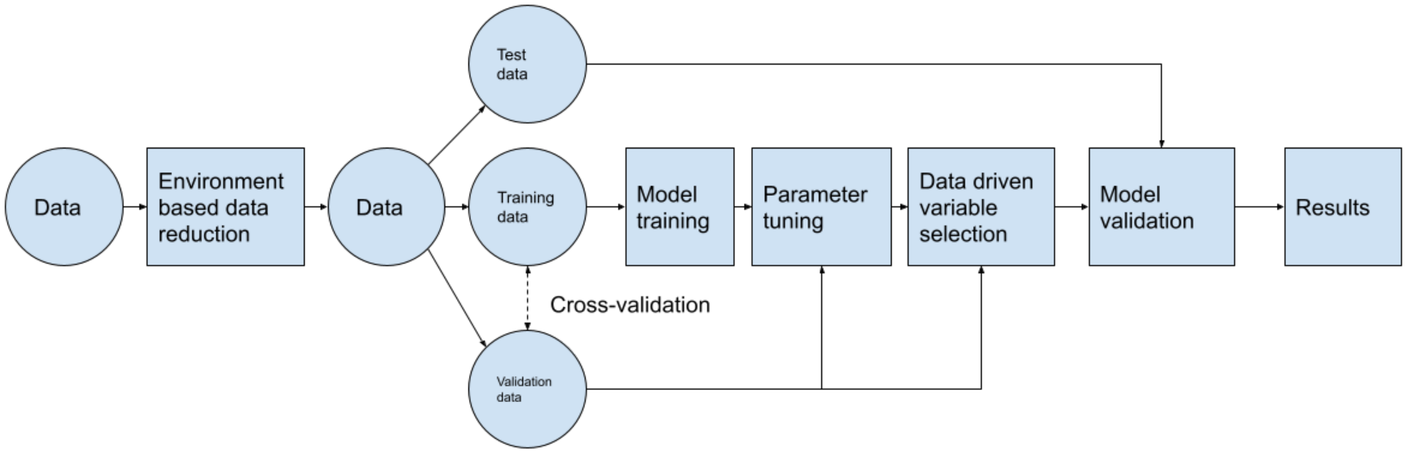

Figure 3.3: Workflow diagram used for the modelling process with SDMTune library, based on (Vignali et al., 2020).

3.4.2 Variable selection

One of the significant statistical problems in combined archaeological and environmental data is the collinearity of the predictor variables which can introduce bias into models (Peterson et al., 2011). There is high potential for correlation between environmental variables, especially as geomorphological data is derived from digital elevation models. It is also known that geomorphological variables correlate with soils which are formed as processes influenced by local topographies (I. D. Moore et al., 1993). We therefore needed to reduce the statistical collinearity (ridged correlation) between the environmental variables.

The initial model was created using a set of existing predictor variables (see Table 3.4.2); redundant variables were removed while building the model. The data-driven variable selection process was executed using the varSel function implemented in the "SDMTune" library. The function iterates all the variables in the order of maxent percent contribution. If the variable is found to have high Pearson correlation coefficient (R2) with any others a jackknife test is run and one of the variables is removed based on the model performance. The algorithm is iterated until highly correlated variables have been removed ($R2 > 7$). To account for model simplicity, variables not contributing to model performance were also removed using the SDMTune importance-based variable reduction function reduceVar (with threshold value of 1). Some variables which were highly correlated with others and led to lower model performance were also removed manually.

Several candidate models were then evaluated and the model with the best performance was selected. We preferred a model with more general soil categories (WRB main classification) as variables with high numbers of categories led to model overfitting. The resulting set of variables for the models were different for the NW-CWC and COCW groups but both models still included significant variables from all three main variable classes: distance to water, geomorphology and soil (Table 3.4.2).

Variable	Name	Permutation importance (NW-CWC)	Permutation importance (COCW)
DISTRIVER	Distance to river (log)	38.40	17.2
DISTSEA	Distance to sea (log)	26.60	9.9
DISTLAKE	Distance to lake (log)	7.40	19.5
WRB_MAIN	WRB soil class	7.40	19.5
WEXPO	Wind exposition	7.10	8.3

VRUG	Vector ruggedness index	6.20	11
LS_MEAN	LS factor (mean of the patch)	2.70	
TWI	Topographic wetness index	2.20	
AWC1	Available water capacity	1.40	4.4
C_INDEX	Convergence index	0.60	0.5
LS_MEDIAN	LS factor (median of the patch)		8.7
SLOPE	Slope		0.6
EAST	Eastness (aspect)		0.3
ROCK1	Rockiness (%)		
SOC1	Soil organic matter		
BD1	Bulk density		
CLAY1	Clay % in soil		
DISTSTWATER	Distance to sea or lake (log)		
K1	saturated hydraulic conductivity		
LS_STDEV	LS factor (stdev of the patch)		
NORTH	Northness (aspect)		
SAND1	Sand % in soil		
SILT1	Silt % in soil		
TPI_100	Topographic position index (100m range)		
TRI_MEAN	Terrain ruggedness index (mean of the patch)		
TRI_MEDIAN	Terrain ruggedness index (median of the patch)		
TRI_STDEV	Terrain ruggedness index (stdev of the patch)		

TWI_MEAN	Topographic wetness index (mean of the patch)		
TWI_MEDIAN	Topographic wetness index (median of the patch)		
TWI_STDEV	Topographic wetness index (stdev of the patch)		

Table 3.2: Variables used for modelling with permutation importance in the final models. These values are indicated for the variables that were considered important for describing settlement location choice and included in the final models.

The separation of distances to water by water body types increased model performance. All distances were also included as logarithms of the values, which better reflected intuitive understanding of proximity to water and also significantly increased model performance.

We also experimented with variables based on aggregates of larger regions (soil patches) provided by Kmoch et al. (2021), but only LS_FACTOR provided significant input to the model. We also tested topographic position index with different ranges (10 m, 50 m, 100 m, 300 m, 1000 m) and based on this chose decided to include only the variable with 100 meter range.

3.4.3 Model hyperparameters and performance and validation

MaxEnt models can be tweaked using several model "hyperparameters" which influence model output. These are the regularisation multiplier and number of iterations while training the model and five feature classes (linear, quadratic, product, hinge and threshold) that can be used in combination (for functional overview see Morales et al., 2017). The default setup is to use all the feature classes and a regularisation multiplier of 1. To find the hyperparameter set with the best performance while avoiding overfitting we ran the SDMTune function optimizeModel (Vignali et al., 2020). The function uses an evolutionary algorithm to search for the hyperparameter configuration that returns the best metric for prediction. The model configurations for NW-CWC and COCW are displayed in Table 3.4.3.

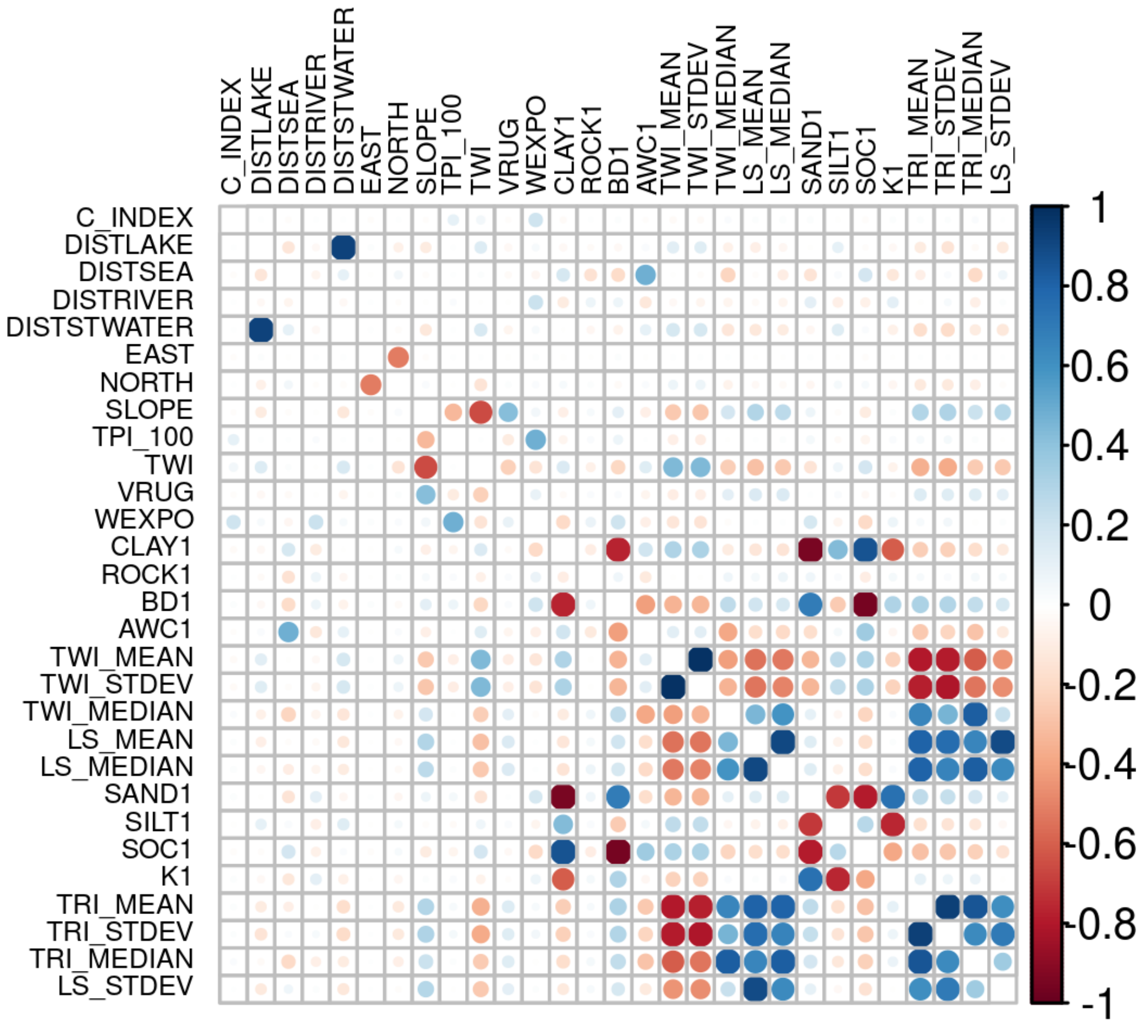

Figure 3.4: Correlation matrix of the predictor variables of the background points used for initial data evaluation.

Model	Regularisation parameter	Feature classes	Iterations	Thresholds
NW-CWC	1.8	linear, hinge	500	0.09
COCW	2.6	linear, hinge	500	0.21

Table 3.3: V Model configuration hyperparameters used and resulting binary classification threshold values.

The model data was divided into three groups: training, validation and test datasets each having more than 3000 items. All the modelling steps were evaluated with a cross-validation procedure using training and validation subsets with 500 iterations. The final model was then evaluated using receiver-operator curves (ROC) and summarised with the AUC (area under the ROC curve) (Merow et al., 2013), which is standard practice for both archaeological predictive models and ecological niche models (Fig. 3.7).

3.4.4 Spatial output

We generate a high-resolution raster map of the suitability of the environment for settling. The spatial output is in the 0 to 1 range as a relative probability raster, with 1 indicating highest suitability. The spatially explicit output is generated for a selected region in northern Estonia only (Figure 3.2, red rectangle) to benefit the high-resolution study. Raster models of the area were created based on predictor variables for corresponding site groups using complementary log-log link (cloglog; Phillips, Dudík, and Schapire, 2017) transformation for model prediction. The process resulted in spatially explicit probability rasters with different spatial configurations. For this study the general suitable area and niche overlap values were computed (see 5.2).

3.5 Model results

3.5.1 Variables and their contribution

The contribution of individual environmental variables was measured using the permutation importance metric (Table 3.4.2). This assesses the importance of variables by shuffling values and calculating resulting model performance loss. We also explored marginal response curves (Fig. 3.5, 3.6) for variables, created by holding all other covariates at their zero-centred means and predicting the density with a MaxEnt PPM using all the data. The results were converted into a relative probability (Vernon et al., 2020) using the complementary log-log transform (cloglog) (Baddeley et al., 2010; Phillips, Dudík, and Schapire, 2017). Marginal response indicates how potential suitability responds to changes in variables. Variable importance values together with variable response curves informed us about the variable values that determine suitability for habitation (Phillips, Anderson, et al., 2006; Phillips and Dudík, 2008).

It should be emphasised that the impact of variables does not imply direct causation as the same effect could potentially be expressed through a combination of other variables. The relationship between environmental variables and human choices is complex. For example combined slope and (modified) topographic and soil attributes are known to correlate with vegetation (I. D. Moore et al., 1993). So it is not always clear whether the landscape form itself is more important for humans or the vegetation or abiotic resources available in specific places. Although a causal link cannot be directly inferred from these measures, they still give insights into the first-order effects behind the point process and also model performance.

Metrics confirmed previous knowledge (e.g. H. Moora et al., 1935, p. 32; Timo Jussila and Aivar Kriiska, 2004, p. 4; Sikk, Aivar Kriiska, et al., 2020a) that hunter-gatherer settlement choice (NW-CWC group) was largely determined by proximity to water; closeness to rivers was the most important factor, making river deltas particularly sought-after places. Soil type at the location and various geomorphological variables had a slight effect. These include wind exposition, which might be an indirect factor, as it is likely that the windiness of the location was not a priority. It might describe the effect of higher, dry locations on the shoreline, which tend to be north- and east-facing and more exposed to wind.

For the COCW settlement this effect of proximity to water was significantly smaller, although proximity to rivers was still important. Geomorphological (wind exposition, slope, median of slope length and steepness factor) and soil (soil type, available water capacity) variables were more important. These variables describe higher, flat, less rugged locations with slopes nearby. The soils indicated as suitable by the model are podzols, regosols and retisols. The model therefore includes klint edges in northern Estonia and river floodplains, both of which have been associated with early agriculture. Previous coastal formations known from empirical data can also be included in the model. The difference in variable importance clearly illustrates the expected shift from shoreline-connected hunter-fisher-gatherer subsistence to an agrarian culture.

The exclusion of topographic position index and the minor influence of topographic wetness index contradicts causal thinking because it is known that dry locations were preferable as habitation sites. Previous research using the same data also showed that this variable on its own had a significant effect on settlement choice (Sikk, Aivar Kriiska, et al., 2020a). In the modelling process the choice was better described using other correlated variables.

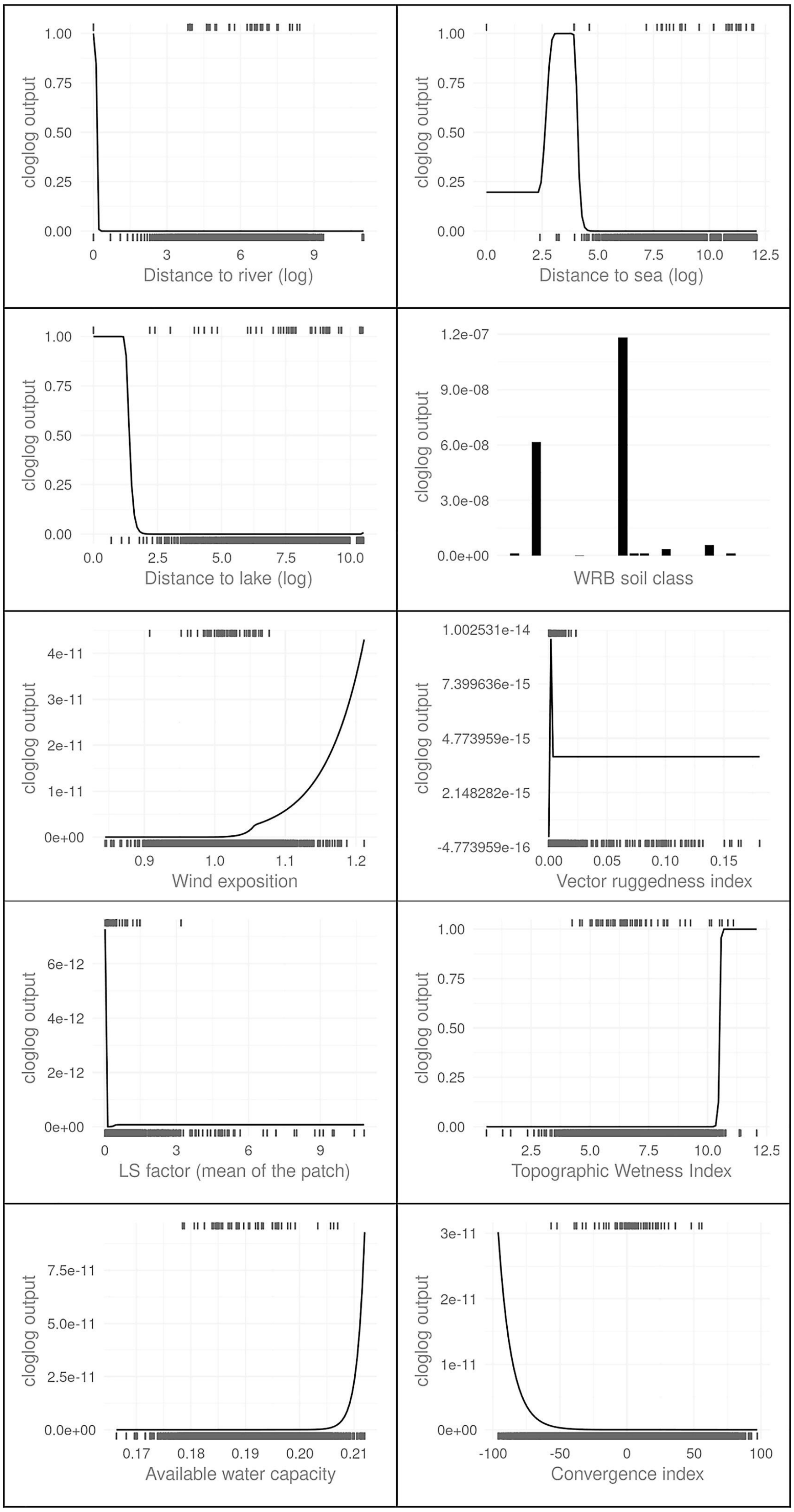

Figure 3.5: Marginal response curves for NW-CWC variables.

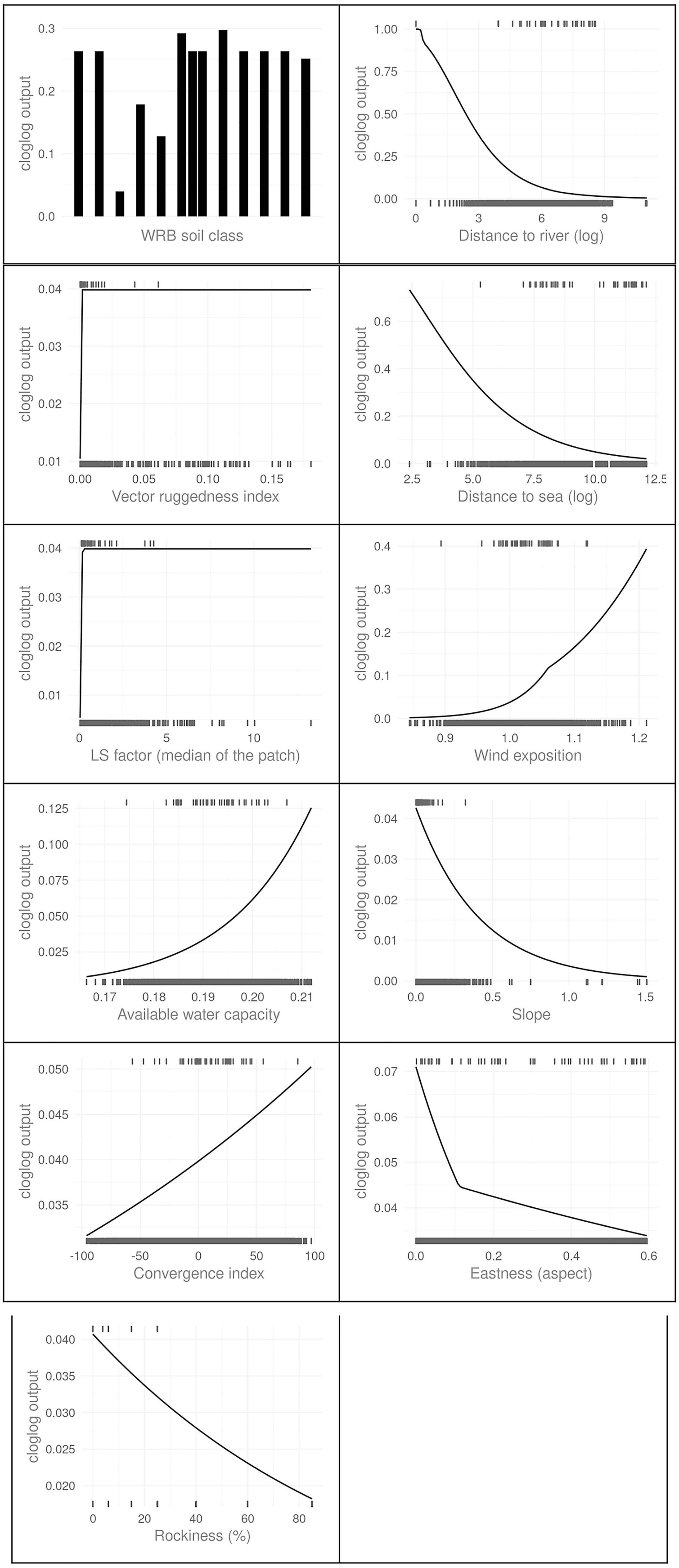

Figure 3.6: Marginal response of continuous variables used in the final COCW model.

3.5.2 Predictability

The MaxEnt toolkit provides tools to evaluate models' predictive performance with receiver-operator curves (ROC), which we summarised here with the AUC illustrating the relationship between true and false positive prediction rates (Merow et al., 2013; Phillips, Anderson, et al., 2006). The AUC values were calculated using both training and test datasets.

The statistic quantitatively indicated that model performance could be one of the reasons behind the existing observation that COCW site locations are harder to predict based on current knowledge than NW-CWC sites. During the model development all the model pairs had NW-CWC models with significantly higher AUC values than COCW models. Although the AUC score for the final COCW model was reasonably good it still indicated lower predictive performance (Fig. 3.7).

3.5.3 Statistical metrics

To compare the suitability models we calculated two measures: the total suitable area and niche overlap using the MaxEnt toolkit. The general area indicates the region that could have been considered suitable during the periods' eco-cultural systems. It was calculated by converting the general raster model outputs into binary form, indicating suitable and unsuitable pixels using thresholds (see Liu et al., 2013) provided by the MaxEnt system. The suitable pixels were then added together, resulting in a total suitable total area of 100.16km2 for NW-CWC and 1201.06km2 for COCW. This indicates an area about ten times larger that our model considered suitable to agrarian COCW groups in comparison to hunter-fisher-gatherer NW-CWC groups. These areas can not be taken as absolutes as the area of predicted presence is strongly affected by grain size, but they are sufficient for comparing models of identical environments.

Niche overlap helps to measure the degree of geographical similarity of the two model predictions. We used the I statistic (Warren et al., 2008) provided by the MaxEnt toolkit which reports values between 0 and 1, with 0 indicating no niche overlap and 1 indicating total niche overlap. The I statistic value for the NW-CWC and COCW models was 0.331, which indicates minor to moderate overlap between suitable areas.

3.5.4 Spatial structure

Spatially explicit environmental suitability rasters indicate a significant difference between general suitable environmental areas for hunter-fisher-gatherer NW-CWC and agrarian COCW. While NW-CWC settlement choice is restricted to areas on the

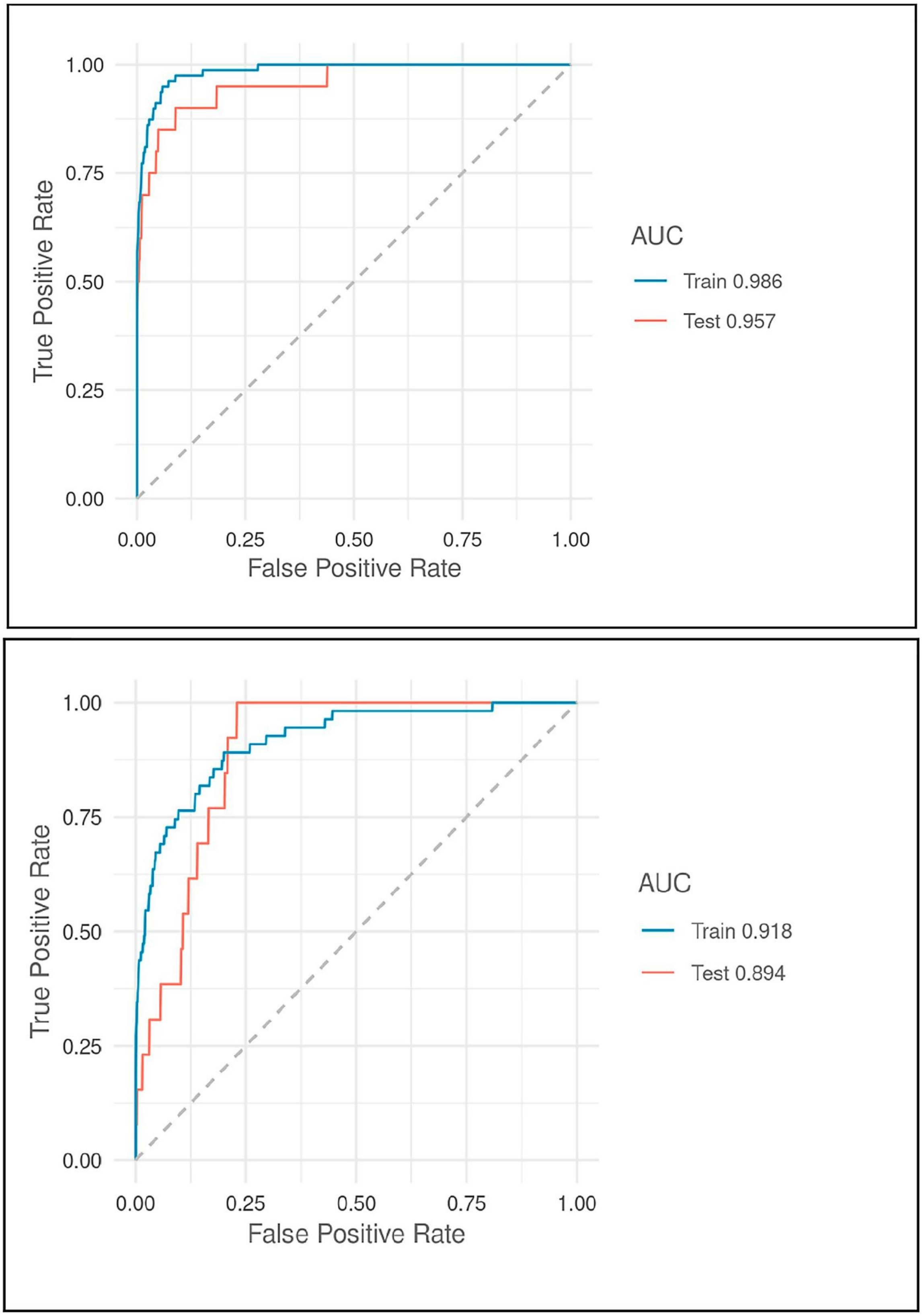

Figure 3.7: AUC curves indicating performance of NW-CWC (upper) and COCW (lower) models.

seashore and close to riverbanks, COCW settlement choice is free of this restriction, giving a tenfold increase in potential residential areas.

The model indicates that riverbanks and areas near sea and lakes were considered suitable by both settlement groups. For COCW, the suitability of regions close to water bodies was more variable and significant areas inland were also considered as suitable environments. As a result the spatial configuration of the suitable residential area was more homogeneous and the total potential residential area was much larger.

It can also be observed that the probability distributions for site presences are different. The NW-CWC model results in a more clear-cut distinction between higher and lower probability areas. For the NW-CWC model the areas can be separated into low and very high probability habitation, whereas the COCW model has a significant number of in-between areas.

3.6 Discussion and conclusion

3.6.1 Changing landscape

Our results confirm knowledge retrieved by fieldwork and univariate statistics (Sikk, Aivar Kriiska, et al., 2020a) about the suitable environmental conditions for habitation. The results were extended by spatially explicit suitability models which led to an overview of potential habitation zones in general. It indicated a significant expansion of usable areas for COCW compared with NW-CWC. The larger area available for early agrarian societies could have made tolerated immigration (as previously proposed by A. Kriiska, 2019, p. 20) possible as the newcomers could inhabit previously actively uninhabited areas. The new type of settlement system resulting from the migration of agrarian societies probably created new patterns of trade and social connections.

Despite new potentially habitable areas there was also a significant overlap of highly suitable areas close to rivers. The overlap of used residential regions is not only theoretical but can also be observed in archaeological material, for example in the Narva region, where both NW-CWC and COCW settlements were close to the Narva river mouth, although not contemporaneously (Aivar Kriiska, D. V. Gerasimov, et al., 2016, p. 107-109). The overlap implies that there could have been competition for certain areas between contemporaneous hunter-gatherers and early agrarian societies. In most cases COCW settlements followed previous hunter-gatherer habitation (e.g. Aivar Kriiska and Kerkko Nordqvist, 2012, Fig. 10), indicating expansion.

It is also possible that the overlap was only potential and did not result in competition. COCW sites in river flood meadows made riverbanks attractive to farmers, who only used them in certain regions, which is universally reflected in models. There

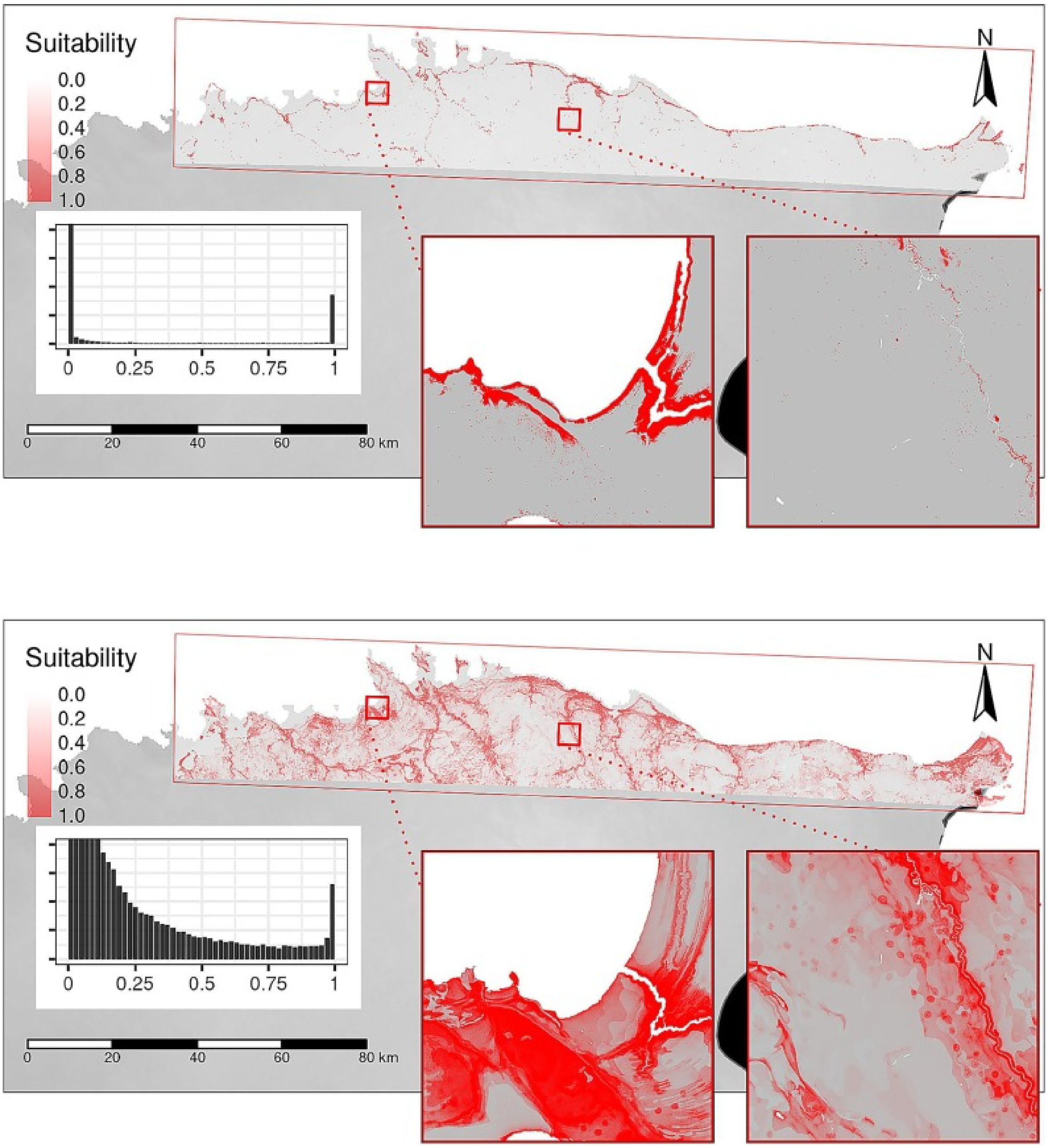

Figure 3.8: Point process model output for the research area indicating suitability for NW-CWC (upper) and COCW (lower) habitation. The two zoomed areas show river bay and inland riverbanks; the bar chart shows general raster value distribution.

could have also been an exchange resulting in COCW pottery being brought to CWC sites which ultimately led to possible misclassification of some of the hunter-fisher-gatherer sites as COCW sites.

3.6.2 Model predictability

Similarly to archaeologists' observations, the study revealed that COCW models do not predict settlement site locations as well as NW-CWC models. From the perspective of fieldwork, lower predictability could be an indication of larger suitable areas, as also shown by the model comparison. But the lower model performance suggested that another explanation is needed.

Various systemic effects on the predictive performance of inductive models have long been discussed. For example Ebert and Kohler (1988, p. 133-145) have argued in the context of forager studies that spatial heterogeneity, temporal expectedness and economic intensification influence settlement location predictability. Below we discuss three possible reasons for differing modelling performance.

3.6.3 Mixing settlement choice modes in one model

It is known that early agrarian sites used locations with varied environmental conditions, for example on the klint in northern Estonia and on river flood meadows in southern Estonia. The COCW model unified these different modes into one model. Furthermore, COCW habitations encompassed areas usable for agricultural land but also locations suitable for hunter-fisher-gatherers, sometimes even reusing their sites on sandy patches on the lake shoreline and riverbanks. This might be an indication of a more complex environmental effect including different site functions and available environment.

It is possible that the COCW settlement pattern contains two or more settlement choice modes occupying different spaces. For example one could be similar to hunter-fisher-gatherer mode and another to agrarian mode. Two distinct modes addressed through a single PPM could significantly lower model performance. Similar situations could arise if NW-CWC sites are misidentified as COCW sites because of pottery exchange, as proposed above (for effects of misidentification see e.g. Costa et al., 2015).

The related possible effect of temporal predictability of the model is currently not observable in archaeological data. COCW use of both agricultural lands and riverbanks and shorelines might indicate a different seasonal mode for COCW settlement which needs to be studied further. Different mobility modes also influence settlement patterns but a simulation study of foragers (Sikk and Caruso, 2020) has shown that mobility driven by the same resources does not significantly influence settlement location choice.

3.6.4 Effects of spatial configuration

It is also known that both niche breadth and the spatial structure of the environment influence the predictive power of models. In a dedicated study evaluating the predictive power of species distribution models (Connor et al., 2018) it was shown that model accuracy significantly deteriorated for homogeneous environments with a grain-size increase in observations, which is natural to archaeology. The results indicate that habitat specialists were more accurately modelled than generalist species. We can presume a similar situation for human cultures as a diversified economy provides generalist spatial features.

Ebert and Kohler (1988, p. 138-142) suggest that spatial heterogeneity or patchiness of the attractions required for settlement determines the effects of site location. The more evenly distributed such attractions are on the landscape, the more determined and thus predictable settlement locations are. This effect can potentially explain the difference between NW-CWC and COCW patterns, as NW-CWC settlements are restricted by water bodies and thus have very specific regions which are suitable for habitation, while COCW settlements are not restricted in a similar way. The EEM then indicates that COCW inhabitants had a very different perception of the landscape which made it possible to extend the potential residential area inland. Agrarian perspective transformed the perception of the landscape, giving it a more homogeneous spatial configuration with large areas of almost equally suitable locations for living. This can at least partly explain the lesser predictive power of the model.

3.6.5 Socio-economic organisation

In addition to eco-spatial principles, social factors, which can be considered second-order properties of a point process, can introduce spatial autocorrelation to the system and influence the predictability of site locations. The general question regarding this issue is: what proportion of human behaviour is immediate and based on perception (can be explained by proximity arguments) and what proportion is systematically organised? (Ebert and Kohler, 1988, p. 106). Intensification of hunter-gatherer economy and movement towards agricultural economic mode has been associated with increased population, increased packing, decreased residential mobility, increased storage and production of storable food resources. This kind of intensification has been considered to improve the predictability of settlement site locations (Ebert and Kohler, 1988, p. 141).

The increased predictability of NW-CWC settlement may suggest that they were undergoing economic intensification but that COCW were not, despite their agrarian subsistence. It might be possible that COCW brought with them agrarian culture developed elsewhere but immigrating groups did not have social properties associated with intensification.

It has also been hypothesised that as social complexity grows, settlement choice is determined less by environmental factors and more by social factors (J. Altschul, 1988, p. 81; Kvamme, 2005, which are less observable in archaeological records. The reason for this is twofold: firstly horizontal – more socially complex societies have diverse economic activities which can result in a multitude of different residential sites which follow different location choice principles and might be hard to isolate (see section 6.3). Secondly, social complexity leads to a vertical, hierarchical structure, which also has an impact on the spatial structure of settlement patterns. J. Altschul (1988, p. 81) argues that increased social complexities also led to development on different, central or "magnetic" sites which stood out from the general picture.

The known pattern of COCW settlement in the region contradicts the social complexity hypothesis, as central sites are known for the period; such sites are only known for the subsequent Bronze Age period. Archaeological material also contradicts social complexity, as monumental burial sites and most outstanding prestige items were introduced later, during the Bronze Age.

3.6.6 Conclusion

This study mostly confirmed previous knowledge of settlement choice principles. It explicitly indicated the geographical difference between suitable residential spaces available for hunter-gatherer NW-CWC and early agrarian COCW cultures, which might explain the conflictless immigration process. Potential residential regions have a certain overlap that can be further studied to explore the dynamic relations, including possible spatial competition, between hunter-gatherers and COCW during the general conversion to agrarian mode.

The created models provide robustly different performance measures which can be explained by mutually non-exclusive spatial and eco-social effects. These include hypothetical effects influencing systemic environmental determinism, such as spatial configuration of suitable spaces and economic intensification and diversity, which can be addressed by further quantitative modelling and simulation studies.

Chapter 4

Central Place Foraging Theory and its explanatory power for hunter-gatherers settlement patterns formation processes

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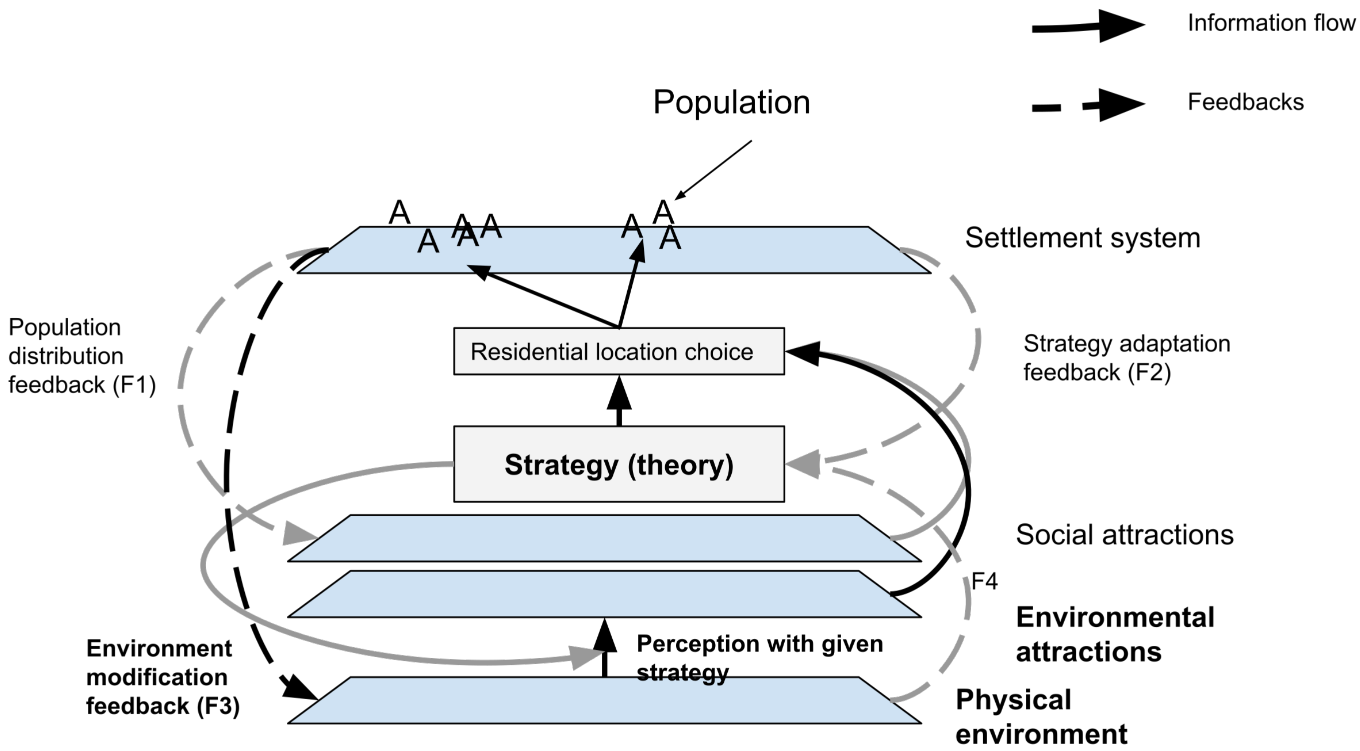


Figure 4.1: Information flows and feedback studied in the chapter with agent-based simulation experiments

4.1 Introduction

Mobility is one of the most distinctive features of hunter-gatherer lifeways and therefore has attracted a significant amount of research. Studies of empirical material collected by ethnographers have shown that varying rates of both residential and logistical mobility, i.e. respectively settlement decisions and day to day movements to get the required resources, are related to subsistence behaviour and environmental conditions. Mobility patterns observed in ethnographic studies have been used for explaining archaeological settlement patterns using correlates between known mobility and environmental variables (Lewis R. Binford, 1980; Lewis R. Binford, 2001; Kelly, 1983; Kelly, 2013; Washburn, Lancaster, et al., 1968). This allows archaeologists to draw hypotheses about the economy and organization of past societies.

Hunter-gatherer mobility patterns have often been explained by foraging requirements. They need good locations for foraging for resources and move when the conditions become less favourable due to diminishing foraging returns. The explanations are formalized in a number of models, mostly based on Optimal Foraging Theory (Emlen, 1966; MacArthur and Pianka, 1966; Schoener, 1979) and marginal value theory (Charnov, 1976). Both models were originally developed to predict animal behaviour while foraging the environment to fulfill their energetic requirements. Hunter-gatherers have more complex foraging organization than non-humans and their mobility strategy has been described as Central Place Foraging (CPF). They are assumed to set up a central base from which they make logistical forays to acquire food and other resources. Causal link between the logistic and residential mobility (Lewis R. Binford, 1980) is explained by depletion of required resources and need to move to a new location.

In the present paper, we consider in particular the CPF mobility model of Kelly (2013, p. 96-101), which formalizes the effects of the environment on mobility and assumes that the active foragers in a group dominate the choice of residential moves.

We construct an Agent-Based Model (ABM) that builds on Kelly's work in order to test CPF model robustness and explore residential mobility in the context of heterogeneous landscapes, hence heterogeneous environment and spatially varying distributions of resources. Spatial variations in environmental conditions and its influence on hunter-gatherer mobility patterns have been analysed before, but the simulation modelling so far has been focused on simulation of individual foragers in explicit cases. No CPF studies have been exploring residential mobility of camps in a theoretical setting. In current model we aggregate individual forager actions and include them into the agency of whole hunter-gatherer group.

Landscape heterogeneity can result from exogenous causes such as natural variations (soils, vegetation types, proximity to water, etc.) or arise endogenously from resource depletion due to foraging habits. If the environment is the key to understanding mobility patterns and the spatial distribution of Central Place foragers, we question here how its spatial distribution impacts our understanding of foraging and settling behaviour. In addition, since hunter-gatherers, by their actions, change the spatial distribution of the resources through time, we think it is important to consider the impact several hunter-gatherer groups have on a given landscape.

Kelly's original model assumed homogeneous distribution of energy resources in the environment. It involves a choice between staying or moving to alternative sites and focuses on the timing of this decision and the distance between sites. We introduce these decisions in a spatio-dynamic Agent Based Model. Our framework allows for multiple locational alternatives (not only distance) to be modelled in a spatially explicit environment where there is heterogeneity in the availability of resources. The likelihood of choosing a new base site, i.e. the utility of a particular location, is deterministically defined by a measure of access to resources from the location and idiosyncratic variability among agents (hunter-gatherer groups).

We explore the new insights that the spatially explicit model could offer us regarding settlement pattern formation processes and whether the CPF model can be used as a link to empirical settlement data. Kelly's model is an aspatial model, hence moving decisions are made irrespective of the existence of alternatives. By introducing a spatially explicit landscape, we add multiple choices and the decision to move results from the positive assessment of possible alternative locations. Adding spatial dimensionality allows us to understand the emergence of settlements across a given area. To do so we introduced several new components including the calculation of utility values of all locations in the environment, generalizing the foraging process without simulating individual foragers moves, depletion and recovery of resources and adaptive expectations of agents about their duration of stay in a settlement location.

The remainder of the paper is organized as follows: in the next section "Theory", we position our model within existing theories and models of hunter-gatherer mobility. In the section "Model description" we describe the components and the functioning of our model. Our experimental results are presented in the section "Simulation results" where we show the effect of varying environments on residential mobility and how this effect is mediated by two parameters of the model: the general level of resource available and the costs of moving. We then discuss the effect of heterogeneous resource distribution on mobility parameters. Conclusions follow in the last section. The details of implementation following ODD+D (Müller et al., 2013), an extension of ODD (Overview, Design concepts, Details) protocol (Grimm, Berger, Bastiansen, et al., 2006; Grimm, Berger, DeAngelis, et al., 2010), are described in appendix of the article.

Overall, we find that the CPF model is generally robust to initial environmental conditions. But we find that the energetic resource dispersal in the environment has a significant effect on the time at which move decisions are made. Environments with more clumped energy resources lower mobility rates while a more even spatial distribution increases mobility. We also show that the settlement location choice aspect of mobility can not be well explained by just energy distribution. Placement configuration of favorable local conditions for habitations play a more significant role. We discuss the CPF mobility model as a way to explain empirical settlement patterns in a spatially explicit way and conclude that it would require including information about conditions available locally at a prospective site location.

4.2 Theory

In this section, we contextualize our work within the hunter-forager modelling literature. A comprehensive literature review is out of scope rather we bring the essential theoretical (mostly from Kelly, 2013) and empirical elements related to CPF, foraging and mobility, from which we build our model. Then we position it with regards to other agent-based models of hunter-gatherers' behaviour.

4.2.1 Central place foraging and mobility

Theories of hunter-gatherer land use are mostly based on Optimal Foraging Theory (OFT), originally developed as a part of behavioural ecology describing animal behaviour. The anthropological version of the theory asserts that, in several domains, human decisions are made to maximize the net rate of energy gain. Together with dietary choices, foraging time, group size, residential mobility and settlement location decisions belong to those domains (Bettinger, Garvey, et al., 2015, p. 92). As mobility and settlement choice are the basic choices behind the emergence of settlement pattern formation, OFT can be used to explain at least a part of the process. According to OFT, hunter-gatherers choose their location in the environment so that they can gain maximal amount of energy with minimal effort. The choice of the location of a site is expected to be close to critical resources (eg. fuel or water) in case the resource is rare and bulky. But more generally it will be placed next to the acquisition center of food and mentioned critical resources (BRUCE Winterhalder, 2001, p. 21).

When explaining relations between energy resources and mobility, the marginal value theorem addresses the question of timing decisions of residential moves. It states that optimal foragers leave a patch when its declining marginal return rate equals the average level of the environment (Charnov, 1976). The timing of the move will then be determined by the gain curves of available resources. Although the theorem is originally developed for explaining animal behaviour it has been successfully applied for hunter-gatherer residential mobility (Hames, 1980; O'Connell and Hawkes, 1981; O'Connell and Hawkes, 1984; Bruce Winterhalder, 1981, eg). The empirical study of Batek showed that camp movements coincided with the point at which resource acquisition declined to a certain threshold level (Venkataraman et al., 2017).

Describing the timing of residential moves leads us to the concept of mobility which has long been considered as one of the most characteristic features of lifeways of hunter-gatherers. In his influential paper "Willow smoke and the dog tails", Lewis R. Binford (1980) introduces a distinction between residential and logistical mobility. Residential mobility refers to the movement of inhabitants from one residential base to another. Logistical mobility is the daily mobility required for acquiring resources and transporting them to the residential base. Drawing from this distinction, Binford proposed the concept of a forager-collector continuum. Compared to collectors, foragers have higher residential mobility, i.e. moving people to resources, while collectors rely more on logistical mobility, i.e. moving resources to people.

Residential mobility and logistical mobility are interdependent behaviours: a higher residential mobility lowers the logistical mobility and vice versa. Each hunter-gatherer group can be situated on the continuum based on how much use of both types of mobility is adopted. The optimal strategy (i.e. bundle of residential and logistical mobility) is the one that provides higher net foraging returns (Lewis R. Binford, 1980). Empirical evidence compiled by Lewis R. Binford (2001) from records documenting hunter-gatherers in ethnographic observations show significant variations in residential mobility. The number of residential moves per year ranges from 0 to 60 and the distance of the move ranges mostly from 5 to 10 km. In some cases residential moves go beyond 60 km (Kelly, 2013, p. 80-84 Table 4-1).

In order to explain the observed variations in residential mobility, Kelly (2013, p. 96-104) links individual foraging to camp movements and introduces the Central Place Foraging (CPF) mobility model. The CPF itself has been considered a distinctive feature of human foragers (as opposed to other animals, eg. Isaac, 1978; Lovejoy, 1981; Washburn and DeVore, 1961) who form camps and make logistical forays around them for gathering resources. The CPF model links individual foraging decisions to settlement pattern formation as seen in the archaeological record. It helps us explain how residential bases and their choice is related to foraging preferences. Formally, Kelly defines an effective foraging radius (r_e) as the distance at which the net return rate of foraging satisfies the calorific requirements of the group. The net return rate itself includes the energetic value (gross calorific returns) minus the costs of processing the food and commuting between the base and the foraging location. In the case of a homogeneous environment it is then optimal to move the residential base to a new location, at a distance of $2r_e$ rather than make foraging trips beyond the threshold distance r_e. The forager-collector continuum is then simply a function of the the effective foraging radius: higher values of r_e correspond to lower residential mobility and the collector strategy while lower r_e corresponds to higher residential mobility and the forager strategy. Variations in r_e are then crucial and depend on the environment, especially its level of resource availability, among other factors. Hence, one can move from the effective foraging radius to the mean overall return rate (r) of the environment given daily averaged trips (t), and formalize the foraging return associated with an environment. Following Kelly (2013, p. 97) and assuming 8 hours of daily foraging, the daily net return (R) for foraging is:

$$R = r(8 - 2t) - (2C_m t + C_t t) \tag{4.1}$$

which is expressed in number of calories per day, with: r = mean overall return rate of the environment (in calories per hour of foraging) t = time of moving to foraging location (in distance / speed (km / h)) C_m = energetic costs of a foraging trip due to moving to the location (in calories) and

C_t = energetic costs of a foraging trip due to carrying the foraged food back to camp (in calories)

Obviously after foragers settle in a camp, the resources start depleting, forays get longer and returns are diminishing. As soon as the return rate (R) no longer satisfies the energy requirements of a group (ρ_a), foragers are forced to resettle. According to Sahlins (1972, p. 33) foragers do not wait for resources to deplete completely but weight the costs of remaining at a place i and foraging further out against the benefits of moving to a new location j. Therefore, following Kelly (2013, p. 97-102), the camp is moved when the return rate (R_j) of a new location j, minus the moving costs are higher than the return rate (R_i) of staying in the base for a certain time. While theoretically elegant, the timeframe hunter-gatherers use for evaluating returns as well as the perceived costs of moving to another location are however not evident from empirical observations (Kelly, 2013, p. 100).

4.2.2 Agent based simulations of settlement choice and foraging

Our proposed conceptual framework is based on Agent-based modelling (ABM) – a computational simulation method that lets us observe how the relatively simple behaviours of components of a system lead to the emergence of complex phenomena. ABM offers an opportunity to test theories based on behaviour of individuals and project them to multiple social and spatial scales (Kohler and Gumerman, 2000) creating a means of constructing scenarios that could never normally be observed (McGlade, 2005, p. 558). ABM allows us to join the analytical nature of CPF model with simulated, artificial landscapes which can include a higher complexity of problems and use "local knowledge" to guide agent decision making. Agent-based models have been extensively used to study residential choice in urban and land use change contexts (for a review see Huang et al., 2014). Those models generally include a decision making process and push and pull factors related to specific locations. The factors can be differentiated as coming from environmental, economic or social domains, or both of them (Thober et al., 2018).

ABM simulations have also been created to model hunter-gatherer foraging processes and its implications to other aspects of their lives. Some of the models are used to develop theory of optimal foraging to implement it in archaeological inquiry (eg. A. Costopoulos, 1999; Andre Costopoulos, 2001; Janssen and K. Hill, 2016; Lake, 2000). Several domains of hunter-gatherer lives have also been studied from the standpoint of OFT by ABM including social cooperation (Premo, 2004; Premo, 2012), cultural transmission and diversity (Premo, 2015; R. Reynolds et al., 2001), cooperation while foraging (Janssen and K. Hill, 2014; Santos et al., 2015).

Premo (2015) constructed a spatially explicit ABM based on aforementioned Kelly's central place foraging model and explores how effective foraging radius (r_e) affects the size of the metapopulation composed of CPF groups. The results show that higher logistical mobility can inhibit group interaction and increase effective size of population.

An agent-based model was developed by Janssen and Hill (2016) to explore Ache mobility based on explicit environmental data of their actual environment. The purpose of the model was similar to our study, namely to assess the influence of heterogeneity of resource distributions on mobility and group size. The results showed that much greater heterogeneity in resource distribution does not favour larger camp size as expected (Kelly, 2013) and has a modest effect on camp mobility.

While the Ache mobility model is constructed based on ethnographical data, a similar model has also been published to reconstruct Stone Age foraging behaviour. Wren et al. (2019) constructed a "Paleoscape" model based on the model of Janssen and K. Hill (2016) using explicit paleoreconstruction of the environment of the South African coastal landscape. They published several model outputs analysing proportions of food resources, effects of population size change and planning while making foraging decisions. The inquiry behind those models is aligned with the goals of this paper, but is based on simulating individual hunter-gatherers' actions in an explicit case. Different patterns of individual food procurement activities are extremely varied. As our purpose is to create a generic model we generalize the process of individuals foraging based on CPF theory and create a decision model based on camp level without going into details about specific foraging activities. We also create a generalized model which can be used with artificial random resource distributions and measure its impact to central place foragers mobility and settlement location choice.

To our knowledge, so far no ABM s have been developed to link OFT to settlement choices. In previous models using residential moves the location choice has been based on distance and not on specific utility of the evaluated location. An ABM model of animal foraging has been created, extending MVP into spatially explicit space with the purpose of assessing foraging effectiveness with different spatial distributions of resources (Nonaka and Holme, 2007).

To formalize the agents' residential decision process, we use the principles of a discrete choice model, often used to describe residential mobility. Discrete choice model implies the existence of a finite choice set and an abstract utility value assigned to every choice. For settlement choice the set is composed of possible locations known to an agent with abstract utility values used to quantify the attractiveness of the locations. As described before, according to CPF theory, the utility value for hunter-gatherer residential choice is based on foraging net return rates accessible from a given location.

4.3 Model description

In this section we describe the general purpose, structure and concepts behind the model. The technical overview of the implementation of the model will be given in the Appendix to the article.

4.3.1

Purpose

The purpose of the model is to test the implications of Kelly's CPF mobility choice model (2013) when space becomes explicit and differentiated. The first purpose of the experiments presented in the current paper is to evaluate how the abundance and placement of resources in the environment affects hunter-gatherer residential mobility and thus test the robustness of Kelly's model and CPF approach in general to initial spatial configurations.

According to OFT and empirical observations, we assume that settlement choice is to an extent determined by foraging conditions which are in turn shaped by access to food resources (Lewis R. Binford, 2001; Kelly, 2013). The ABMs spatially explicit implementation enables also to experiment with foragers mobility choices influence on the settlement location choice. The simulation model is designed as an experiment to isolate the effect of energy resource topography on both hunter-gatherer mobility and settlement choice.

Model structure

The model has two kinds of entities: the environment representing the resource distribution landscape and agents representing groups of people inhabiting the landscape by forming residential camps on it.

Environment is presented as a raster grid with each cell (i) in it having a state variable representing the potential net return rate of energy (R_i). It is the amount of energy that can be foraged from it during a day by a camp of given population with available technology and social organization. As the net return rate depletes after resource use, the amount of currently available energy is stored in an additional variable.

The environment is generated by an external model configuration which determines the general characteristics of it. Configuration variables are selected so that the summed energy rate of the environment will not be depleted by artificial population and will achieve a stable equilibrium state.

As the goal of the model is measuring spatially explicit mobility patterns we decided not to use a toroidal environment and thus it has a certain edge effect. The edge effect makes edge areas less desirable for habitation. As a result agents move away from it so it does not have a significant impact on the overall results of the model. The edge area is ignored while measuring spatial autocorrelation of the environment.

The model is a stylized representation of settlement pattern formation processes, not meant to be used in comparison with empirical data. But in order to draw conclusions that have meaning in empirical reality and to avoid anomalies of scale we fit it into realistic spatiotemporal frames. For this we assume that every cell in the grid has an area of one km^2 making the whole area of the landscape 10 000 km^2. Every step in the modelling process is equivalent to one week of time as being a realistic minimum time of stay (Kelly, 2013, p. 88), so a run of 52 steps would be equivalent to one year.

Agents represent hunter-gatherer residential units composed of an amount of people. As every individual in the camp is having energetic needs, the population value is used for determining the energy consumption of an agent. The measure of population is included in the system as a constant agent parameter (BASE-POPULATION = 20) because the demographic dynamics are irrelevant for research goals of the current simulation. In case of using the same model for different simulation experiments the number can be varied. Each agent in a system is located in a specific position in the environment and consumes resources it can access by logistical mobility. Agents also include a state variable representing the duration an agent is expecting to stay at its next location.

Process overview

All agents are selected in random order and their tasks are then executed. The first agent action is evaluating the costs of staying at its current location as opposed to the best alternative location for a base. As a result the agent then either moves or stays depending on the choice.

As agents needs to satisfy an energy consumption rate determined by their population, the agents first harvest cells around it. We generalize the process without explicitly simulating the activities of individual foragers as done in OFT simulations presented in the previous chapter. A number of adjacent cells are selected and their return rate is decreased in proportion to required energy.

Over a specified time period the resources recover and original rate is restored. The resource and recovery processes are described in the submodels section.

Theoretical and Empirical Background of the Conceptual Model

The essential component in agent based models involving discrete choice is a currency or utility which an agent tries either to maximize or to satisfy its requirements. In this section we discuss the construction of such an utility value.

Any mobility theory based on depletion of resources implies that agents have certain required resources that are depleted during the usage. The current model is based on food resources, namely how much energy hunter-gatherers can obtain from the environment during a period of time, a measure which is called the net return.

The net return rates in particular cases have been estimated by ethnographers, and vary to large extent. For example the Ache are estimated to gain 1115 kcal/h from hunting with foraging offering even higher returns (Kelly, 2013, p. 52). On the other end of the spectrum Smith (1981) estimated hunting Inukjuak obtaining only 1700 kcal per hunting party member per day with 2000 kcal per day usually considered to be minimal energy requirement for adults.

The return rates depend on specific resources, ease of access, technology of their procurement and a lot of other details. Also an area usually includes a variety of resources eg. small game animals and plant food for foraging. As we are creating a generalized model we do not take into account the huge variety of circumstances affecting the rates. In our model the rate R_i represents aggregated rates of resources at a given cell i including local searching, harvesting and handling costs. As R_i stands for a local potential it does not include costs of moving from base camp to a given area.

Our implementation of Kelly's model (2013, p. 97–102) involves settlement choice. The original is explained using an environment with a homogeneous energy distribution. Although it has a sound analytical meaning we want to test its applicability with different and dynamic energy distributions.

Before we do so we simplify the model and remove individual foragers energy expenditure of logistic mobility from the formula determining return rates and consider it as a part of energy requirements of the whole camp. The separate energy expenditure would be important if an individual forager would be foraging for itself, social sharing mechanism would be implemented or if foraging would use significantly more energy than other activities. In the current model energy requirements will be satisfied and there is no intra-group sharing implemented. Also we consider individual foragers requirements as part of the requirements of the whole camp population. It has been argued that an individual spends more energy while procuring a resource, for example Grimstead (2010) has provided model calculating energy expenditure of long distance hunting. However some recent studies contradict it by showing that energy expenditures and thus requirements of hunter-gatherers are not significantly dependant on their activities (Pontzer et al., 2015), but are more dependent on their personal features. Thus we consider that the individual energy expenditure during foraging is insignificantly different from the idle energy expenditure. We therfore remove it from the formula without contradicting the essence of the CPF model.

For our model we create environment configurations where every cell is assigned a local energy rate R_i that would result in foraging at the location for a fixed period of time (details explained in environment generation section the Appendix). As we are currently building a stylised theoretical model we use the human daily energy requirement (about 2000 kCal / day) as a unit of variable R_i.

This rate is obviously not enough to rank the location as a potential place for settlement. Hunter-gatherers move around in the landscape as part of their logistical mobility and thus other cells in the logistical range of the camp are also used for food procurement. To calculate the energy rate accessible from a base positioned at given cell i, assuming an 8 hour working day as was done in Kelly's original model (Kelly, 2013, p. 99), we calculate accessible return rate P_i:

$$P_i = \sum_{n=1}^{|N|} R_n = \sum_{n=1}^{|N|} (r_n * (8 - 2\frac{d}{s})) \tag{4.2}$$

where: N is the set of neighboring cells around i in a maximum logistic range (12 km from base in case of speed of 3 km/h); s is the speed of moving to the foraging location, we use 3 km/h which is measured foraging speed as used by Kelly (2013, p. 97); d is the distance between base i and cell n and has a maximum value of 12 km with used movement speed; r_n is the local hourly energy rate for location n in vicinity N.

As we can calculate both P_i and R_i for all the cells in the environment we get two distributions – local return rate distribution (S_r) and accessible return rate distribution (S_p) that can be used for describing the current environment.

For formulating settlement choices we need to relate accessible energy rates of cells (P_i) to agents a, which are defined by their location and energy requirements. For this we define a function U_i that returns an utility value cell i has for an agent.

Kelly's model and empirical data suggest that a forager's goal is to maximise foraging return rates (Kelly, 2013). For central place foragers it implies that the purpose is to minimize travel time (Orians and Pearson, 1979). Our goal is to create an abstract model and not to solve an explicit problem using any energy data, therefore it proved to be more straightforward to use time costs as a reversed utility value to be minimized instead of energy rate.

The marginal value theorem is based on the concept that while resources are foraged their amount in the environment is reduced leading to diminishing returns. Empirical equivalents of the decline of energy rates are hard to study.

Venkataraman et al. (2017) evaluated asymptotic, sigmoidal and linear functions for describing gain curves based on data collected while observing Batek foraging activities by Kirk and Karen Endicott. They found that some of the resources were not depleting before the move, but the best fitting depletion models for the remaining cases were based on firstly sigmoidal and secondly asymptotic functions. The dataset used was not big enough to create any data calibrated functions but the shape of the depletion curve is enough to use in our current stylized model. Although the sigmoidal curve starts collection of resources slower in the long run the general shape is very similar to asymptotic function, which we simulate in our energy depletion function.

The declining returns according to MVT have been defined by Charnov and Parker (1995) as a negative exponential function of acquired energy at a given moment:

$$g_t = G(1 - e^{-ct}) \tag{4.3}$$

where c is a scaling factor and G is the initial energy.

In the current model we also want to isolate the rate of the energy needs of the population and relate it to the rates at a given location. We assume that the depletion process lowers the return rate by a similar scaling factor, D. We also take into account ρ_a which is the energy requirements of an agent (a) as calculated by the population multiplied by the energy requirement of one person.The agent with smaller requirements deplete a plot in a longer time period. For this we multiply D with $\frac{\rho_a}{P_i}$ multiplied by the requirements of agents ρ_a relation to environmental rate. We use a simple step function to describe the depletion of a cell with calculating its current accessible return at time step t:

$$P_{it} = P_{i(t-1)} - \frac{DP_{i(t-1)}\rho_a}{P_{i(t-1)}} = P_{i(t-1)} - D\rho_a \tag{4.4}$$

where D is the depletion rate after the foraging event of the cell and Pi(t-1) is the rate before the current time step. We notice that as the requirement grows relative to the remaining resource rate the function takes a linear form.

To get time the costs of the agents fulfilling their needs we write a differential equation so that:

$$\frac{dP_i}{dt} = -D\rho_a \tag{4.5}$$

The differential equation is solved as:

$$P_{it} = P_0 - (D\rho_a t) \tag{4.6}$$

As we are interested in the inverse gain function - time costs used for foraging to satisfy need during a specified time period (T_t), we can use the formula

$$T_t = \frac{\rho_a}{P_{it}} \tag{4.7}$$

and write it as a differential equation

$$\frac{dT_t}{dt} = \frac{\rho_a}{P_0 - t\rho_a D} \tag{4.8}$$

which could be solved as a time costs function, used as a costs function for agents

$$U_{ait} = T_t = \frac{\log(P_0)}{D} - \frac{\log(P_0 - tD\rho_a)}{D} \tag{4.9}$$

with boundary conditions of $tD\rho_a < P_0$ and $P_0 > 0$.

Time variable t in the function is the considered time frame for staying in one location. The function returns time costs of foraging to satisfy the energy needs of the population of an agent for a given time period t assuming depletion at rate D.

Decision-Making of Agents

At every iteration of the model every agent chooses its next place of residence. The choice can be broken down into two decisions of when and where to move. According to Kelly's theory the central place foragers decision to move is based on optimizing the workload of individual foragers with food procuring. We deduce from his model that if the foraging time expenditures of the current location grow higher than the foraging costs plus the costs of moving to the new location, the foragers move. In addition to just mobility costs the costs of moving involve camp breakdown, setup and movement of populations and belongings from one site to another. In archaeology those fixed costs are brought together under the umbrella term of site investment. We include those fixed costs in our implementation as a separate global variable (MOVE-START-COST). In the agent based simulation for every agent all cells j in the vicinity are evaluated so that V is the time effort put into foraging in order to satisfy the needs of agents (a) population during given time frame t including the moving costs C_{ij} to a new base location including fixed costs.

$$V_{jt} = U_{jt} + C_{ij} \tag{4.10}$$

C_{ij} are the moving costs from agents' current position i to j. The best alternative location is selected, which has a minimal V value. If

$$U_{jt} + C_j < U_{it} \tag{4.11}$$

the decision is made to move to the best alternative location j. In the reverse case, the agent stays at the current position. The agent decision described here includes the anticipated timeframe (t) of staying at a new location. In Kelly's model the timeframe of stay is not specified as there is no empirical evidence to back it. For our ABM model we create a simple agent learning process for finding an optimal timeframe of consideration.

Adaption process of timeframe t

The agents' learning process considers finding an optimal time of stay (t) while evaluating alternative locations for the next settlement. To illustrate this we describe the optimal time frame problem. If the time frame is very small then moving costs (C_j) are relatively high in comparison to time used for harvesting leading to small returns. For example when considering the time costs of only one day and moving costs of 6 hours, it is not worth moving because the day will be lost on just moving. This leads to a situation where moving does not offer any gains until the resources are completely depleted and the move will be made after a period of time longer than one day. Conversely, when the group plans a longer time period, the residential move becomes profitable relatively quicker, meaning that the in case of a homogeneous environment there is an optimal duration somewhere in between.

Although there is no empirical evidence, we assume that hunter-gatherers evaluate the length of stay by the timeframe set by their previous experience. The timeframe of stay is optimized by an adaptive process so we assign the t variable a mean value of the two last durations of residential stay. In this way the t reaches an optimal value for a given environment by the choice process and should approximate an average length of residential stay. In our model implementation the agents will get a stochastic number of turns as a starting t value and although no collective learning is included the standard deviation of the considered timeframes decrease quickly as the simulation progresses.

Information in the model

Agents in the model have complete information about the R_i values of each cells in their residential range. This information is used to calculate the utility which is based on the location choice. Effectively though as the moving costs grow the cells further away are not evaluated just because of their significantly lower return rates considering the costs of moving.

Although having information on the current status of all locations is never the case in real-life situations, hunter-gatherers had an impressive knowledge of their surrounding landscapes. For example according to Lewis Roberts Binford et al. (1983, p. 206) Nunamuit maintained general knowledge of 250000 km^2 and Pintupi had knowledge of 52000 km^2 (Long, 1971).

Individual agents do not process any information about other agents as direct interactions between agents are not in the scope of the current model.

Agents do not have direct interactions in the model, site selection and resource depletion processes imply that competition rises between agents sharing a territory. An agent already depleting an area will make it less attractive for others who tend to choose their next residential site further away from depleted areas. Therefore, competition creates a spatial dispersal force for agents' placement.

4.4 Implementation and experiments

4.4.1

Implementation and variables

To introduce a spatially explicit heterogeneous space and control the generation of environments we introduce two variables: the mean energy rate of the cells in the environment (MEAN-ENERGY-RATE-KM) and the standard deviation of energy rate distributions (STD-ENERGY). We process those randomly generated environments with a smoothing algorithm with differing diffusion strength, resulting in energy rate distributions having different spatial autocorrelations.

To study the effect of environment to mobility we observe two groups of variables – first containing information about environment and second collecting information about formed mobility patterns.

The first group contains I-RESOURCE and I-UTIL, the Moran's I spatial autocorrelation coefficients of the raster of energy distribution S_r and accessible energy distribution S_p (determined by access to adjacent resources) of the environment. For randomly generated landscapes, the Moran's I value ranges from 0 to 1, with 0 having the most rough and 1 having most evenly distribution of values.

The observed variables describing mobility are a subset of mobility measures defined by Kelly (1983): MOVESPERYEAR – number of residential moves per year (mean of all agents); MOVELEN – mean length of a residential moves during the model run by all agents; MOVELEN-STD – standard deviation of the length of a residential moves during the model run by all agents; LOGMOBTURN – length of the logistical foray per residential stay (mean of all agents).

Although the calculation of the first two variables is straightforward and can be quite similar to the empirical observation, the length of logistical forays is hard to measure as logistical mobility is not really simulated by agents. So it is calculated as a sum of distances to locations of resources made during a residential stay. The results emerging while observing the parameters are described in section (4).

Experiments

We present three experiments that we conducted with our ABM implementation of the CPF model. The first experiment was run for face validation of the new mechanisms added into Kelly's interpretation of CPF.

To show how logistical mobility and residential mobility are influenced by the spatial heterogeneity of the landscape we conducted two ABM experiments.

To verify whether the classic CPF results still hold in the spatially explicit model we tested whether it responds to global parameters the mean environmental return rates and the moving costs as assumed by CPF. In experiment 2 we vary the environmental variable MEAN-ENERGY-RATE-KM and the fixed costs variable MOVE-START-COST for different environments (see submodels section in the Appendix for description of environment generation) resulting in varying values of I-UTIL and I-RESOURCE. Other values in the model were held constant and the correlation between the mentioned variables and the variables defining mobility (MOVESPERYEAR, LOGMOBTURN, MOVELEN) were studied.

We conducted experiment 3 to assess the model's sensitivity to spatial autocorrelation of resource and utility destribution. We varied the landscape generation parameters smoothness and standard deviation, and held other variable constant. We measured spatial autocorrelations of both energy distribution in the environment (I-RESOURCE) and the utility distribution measured by the access every location has to energy resources (I-UTIL). We analyse changes in the 3 variables describing mobility(MOVESPERYEAR, LOGMOBTURN, MOVELEN) along changes of the spatial autocorrelation of the landscape and global parameters of STD-ENERGY.

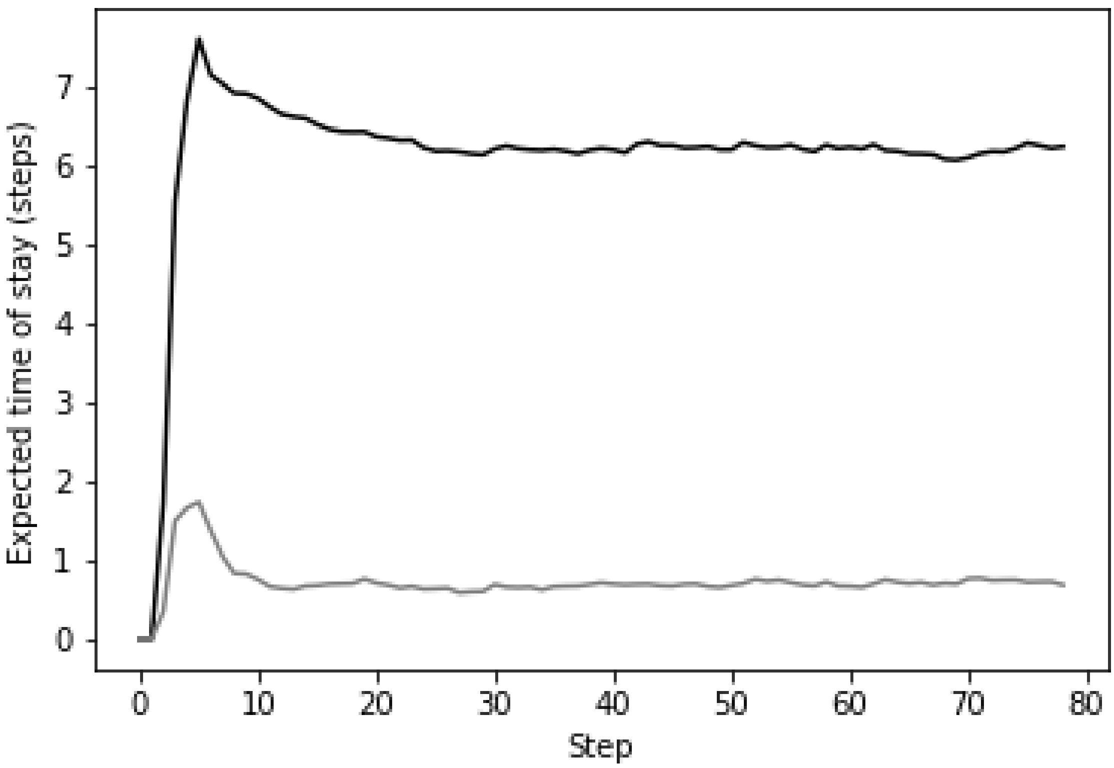
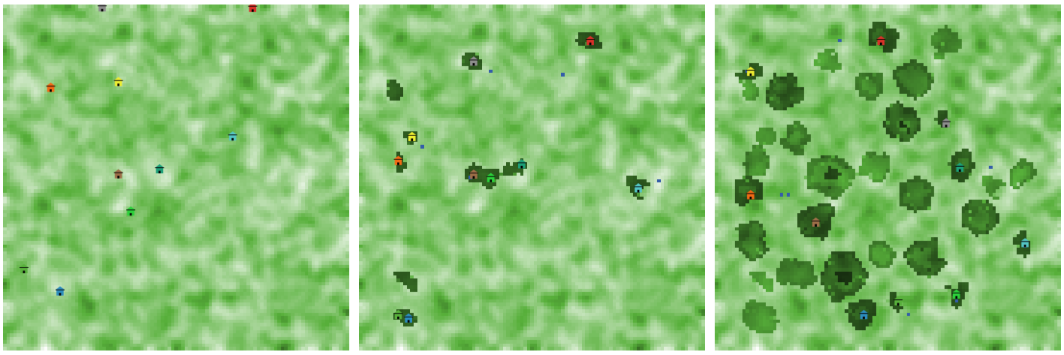


Figure 4.2: Achieving equilibrium of expected time of optimal expected stay (t) in one settlement location. Darker line is the mean value of all agents (10) over runs (n = 41), and the lower line is standard deviation of those values.

4.5 Simulation results

4.5.1 Experiment 1: base model evaluation



(a) Initialized map. (b) 5 steps. (c) 30 steps.

Figure 4.3: Netlogo model running process with energy distribution and agent locations (colored markers) visualized. Lighter green pixels have more available energy and the darker less energy. A declustering of the landscape can be observed until reaching an equilibrium. We can see different equilibrium states with and without agents.

Adapting to optimal duration of a stay at one location

The adaption mechanism of calculating the optimal time range of a stay at one location is required to run original Kelly's model as a simulation. To solve this currently lacking mechanism, we use agents experience for predicting their time of stay by calculating the mean values of their previous stay durations. Results of the simulations showed that the strategy quickly leads to an equilibrium optimum value. Here we illustrate this convergence (Figure 4.2) with the standard deviation of the return rate of environment being set to 1. The simulations start with all agents having a time span of planning for just one turn. Given this time span it makes it worthwhile at step=1 to move only after local resources have been depleted, which results in a longer period of stay in the beginning of the simulations which peaks at about step=7 of the current simulation. Then the time span of planning lowers slowly and achieves an equilibrium of optimal value (around value t=6.5). The values relate to the given particular example but it illustrates simple, intuitive logic of planning future behaviour using previous experience. Although it has not been empirically documented it is obvious that hunter-gatherer cultures have a more complex memory process of predicting conditions. Our simple solution can be used as an heuristic for current purposes, but it must be taken into account that optimal choices for a given environment might start to be taken only after certain number of steps (about 25 with current model configuration)

Resource depletion process

The process of resource use and depletion significantly changes the characteristics of the environment itself. The change is illustrated in figure 4.3 showing the depletion process impacting the initially relatively homogeneous return rates distribution. In figure 4.4 it can be seen that the spatial clustering of return rates of environment (I-RESOURCE) decreases significantly while the accessible returns distribution (I-UTIL) remains almost the same. We can observe a declustering of the landscape until approaching equilibrium. It illustrates the significant change of resource distribution on the landscape in the case of mobility driven by depletion.

As utility is calculated as a sum of neighboring energy rates it functions as a smoothing function. Though the available energy in the environment decreases the utility values of the landscape, in general it remains relatively constant. Thus the depletion process is not significantly influencing the settlement location choice.

While every agent is depleting resources around itself it makes the area less attractive to other agents which in turn creates a force of dispersal for agents. This leads to a more dispersed form of the settlement pattern which in turn impacts the pattern of depletion. Note that the dispersal of agents may be balanced by social and cooperative interactions in reality but these are not incorporated into this model.

4.5.2 Experiment 2

The second simulation experiment demonstrated that resource abundance of the environment and moving costs have a significant effect on the mobility patterns. Figure 4.5 illustrates the inverse non-linear relationship between yearly residential mobility (MOVESPERYEAR) and mean return rate of the environment (MEAN-ENERGY-RATE-KM) and cost of residential moves (MOVE-START-COST). We find negative exponential relationships with a much lower range of variation in yearly mobility by the move cost as compared to the environmental return rates. The increase of the environmental return rate can lead to sedentism while the residential move costs can become extremely large but agents are still forced to move when the resources in the environment are depleted.

Similarly the effects of MEAN-ENERGY-RATE-KM and MOVE-START-COST on logistical mobility (measured by LOGMOBTURN) are illustrated in figure 4.6. The results show that the mean environmental return rate has a negative exponential

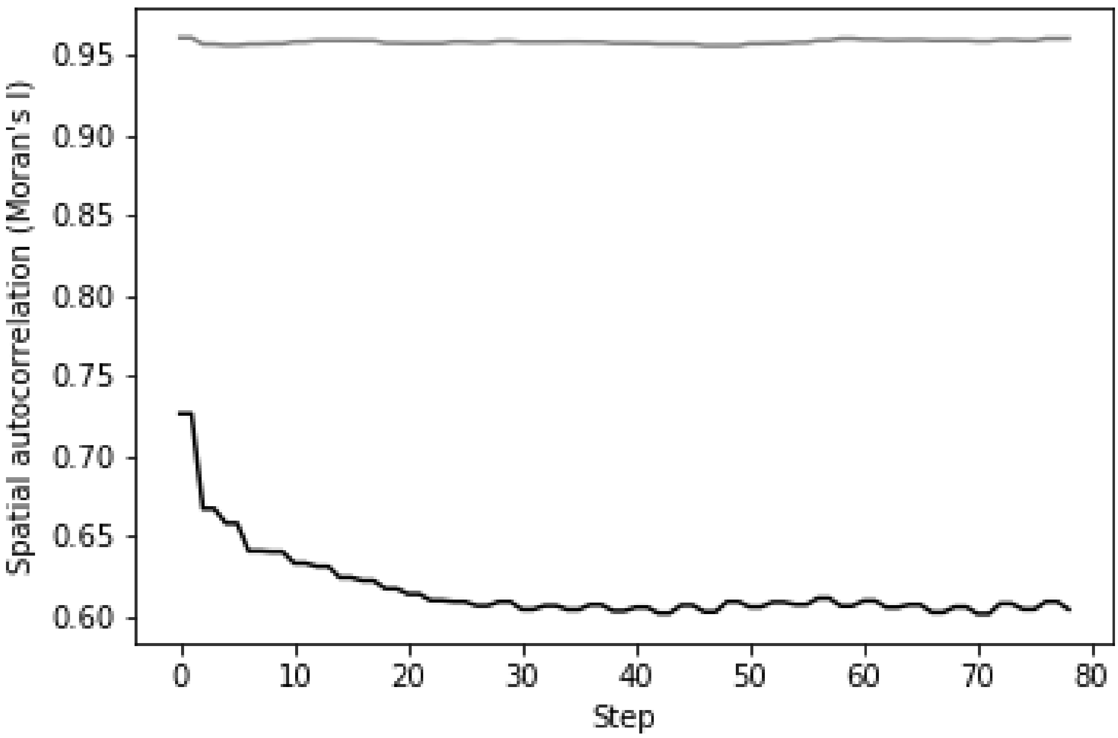


Figure 4.4: Moran's I autocorrelation value dynamics of resources (dark gray) and utility (light gray) based on access to them

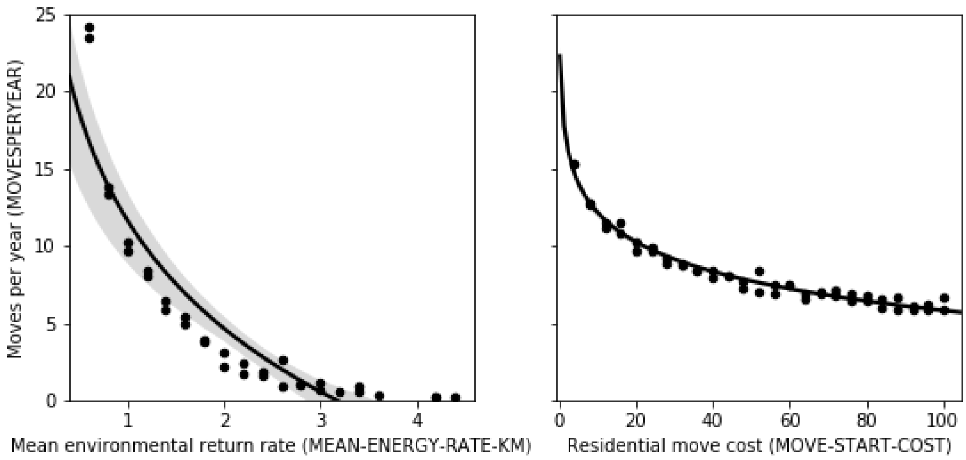


Figure 4.5: Influence of variance of residential move cost and mean environmental return rates to residential mobility while varying one variable and keeping the other fixed. MOVE-START-COST is fixed to value 20 and MEAN-ENERGY-RATE-KM is fixed to 1 accordingly.

effect on the effort put into logistical mobility, but the cost of theresidential move has a modest positive linear effect.

The results were expected by both analytical predictions which serves as an internal validation of the spatial CPF model. It has also been shown in the empirical observations that high abundance and accessibility of resources is negatively correlated with residential mobility rate, in the case of terrestrial foragers (Kelly, 2013, p. 88, 103, 104).

The positive correlation between residential move cost and logistical mobility can be explained intuitively. In the case of higher costs of moving to another camp it is preferable to put more effort into local forays before undertaking the costly move. The influence is modest compared to the influence on residential mobility which can be explained by the impact of environmental configurations influencing the effort put into logistical mobility.

Finally, residential move length is another important characteristic especially because of its potential for explaining past settlement processes. Surprisingly there is no correlation between MEAN-ENERGY-RATE-KM and mean residential move length over the runs as seen in figure 4.7. But there appears to be an increase in the standard deviation of residential move length with higher MEAN-ENERGY-RATE-KM values. This implies that environments with high returns support variance in mobility strategies and perhaps more freedom in location choice.

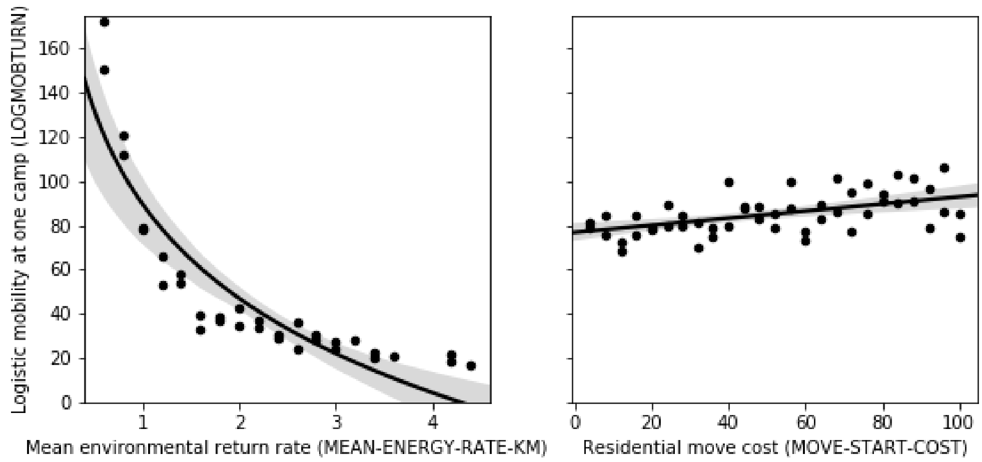


Figure 4.6: Influence of variance of residential move cost and mean environmental return rates to logistic mobility while varying one variable and keeping the other fixed. When not varied on the diagram MOVE-START-COST is fixed to value 20 and MEAN-ENERGY-RATE-KM is fixed to 1 accordingly.

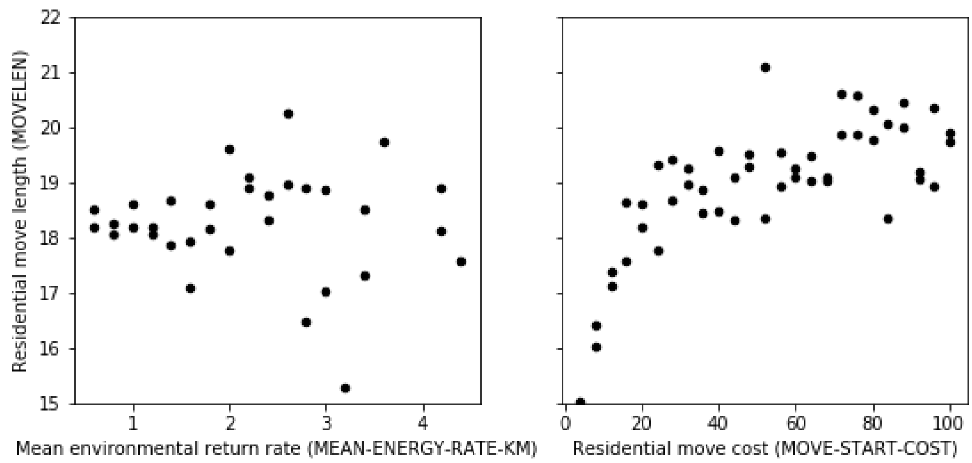


Figure 4.7: Influence of variance of residential move cost and mean environmental return rates to residential move length

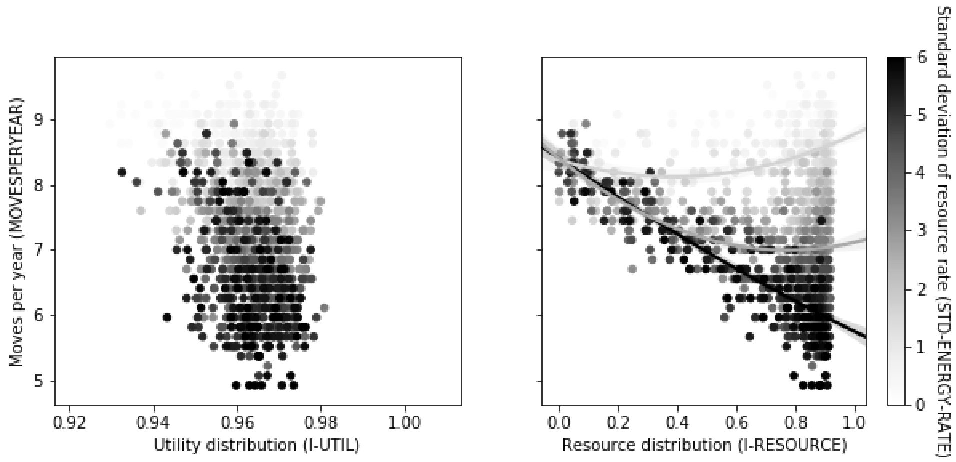


Figure 4.8: Influence of energy and utility distributions to residential mobility. As utility is a result of accessibility to resources its distributions in only in Morans I spatial autocorrelation range of 0.93 .. 0.98 while energy distribution is in range from 0 .. 1. To illustrate combined influence of clumpyness of the environment (I-RESOURCE and STD-ENERGY-RATE) three second order regression lines are drawn with colors corresponding to STD-ENERGY-RATE

The positive correlation between residential move costs (which does not include moved distance) and move length is a spatial nature of depletion processes. Increased costs force a longer stay and results in extended depletion area which requires agents to move further away from their previous location.

4.5.3 Experiment 3

The third simulation experiment was conducted to measure the sensitivity of the CPF model to initial spatial configurations by varying environments and measuring mobility. For fixed MEAN-ENERGY-RATE-KM random environments were generated and diffused at different levels. The variables STD-ENERGY, I-RESOURCE and I-UTIL were then measured and used for describing the spatial configurations. During simulation runs characteristics of residential and logistic mobility (MOVESPERTURN and LOGMOBTURN) were measured.

The experiment showed that the tested variations spatial configurations influence mobility patterns. There was a weak correlation between I-RESOURCE and MOVESPERYEAR (r=-0.19) and LOGMOBTURN (r=0.36) so spatial clustering in itself does not have a significant effect on mobility. But by isolating the standard deviation of the energy rate STD-ENERGY (figure 4.8 ;figure 4.9) we can see that the clumpedness, measured as a combination of STD-ENERGY and I-RESOURCE, reduces residential mobility, n.

In figure 4.8, three regression lines illustrate the effect of standard deviation of energy distribution on residential mobility. The environment with a high standard deviation and high spatial clustering represent clumped environments and leads to a decrease in residential mobility. The result is in line with the experiment of Janssen and K. Hill (2014) who, by simulating individual hunters' movements, concluded that clumped habitats favour lower residential mobility. Similar empirical conclusions have been proposed for patchy environments (Lewis R. Binford, 1980; Fitzhugh and Habu, 2002, p. 261) but not explained as a spatial effect on settlement choice but by predicting more complex hunter-gatherer procurement strategies.

Counterintuitively, any relation between spatial clustering of return rates and logistical mobility is weak and environments with higher I-RESOURCE lead to higher mobility costs. The pattern is caused by different residential strategies adopted in those case, which result in longer stays and thus longer overall logistical activity in one camp.

Overall it has to be concluded that the mobility model is less sensitive to spatial distribution of return rates over the environment than mean overall return rate. For example in the current simulation, the variance of MOVESPERYEAR while modifying environment configurations is just 5, while modifying the overall mean rate covered the whole range of the experiment of 1 to 25 moves per year. This shows that the CPF model is generally robust to initial spatial configurations in spite of some influence from spatial clustering of the environment.

It must be considered though that the model is only manually calibrated to variables and we have no information on the spatial structure of hunter-gatherer energy resources in empirical data. This might lead to lack of coverage of output space, thus for analysis of real life situations variables should be calibrated based on empirical data.

The relations between utility distribution I-UTIL (figures 4.8, 4.9) and residential and logistical mobility (MOVESPERTURN and LOGMOBTURN) are significantly weaker. The reason for it lies in the nature of the two spatial distributions used. As explained above, the utility value describes a locations access to resources in the logistical range. As the access is calculated by summing values of other locations in the vicinity it works as an averaging filter kernel with the size of the logistical mobility range. Because of its effect as a smoothing function it increases spatial autocorrelation of the original energy distribution with Moran' I values in range of 0.925 – 0.981. The range is about 10 times smaller than the spatial autocorrelation of energy distributions (with Moran' I values in range of 0.023 – 0.948) from which it is calculated by.

The smoothing function has a higher access range of results in a greater degree of spatial autocorrelation and thus smaller significance for any location choice. As the

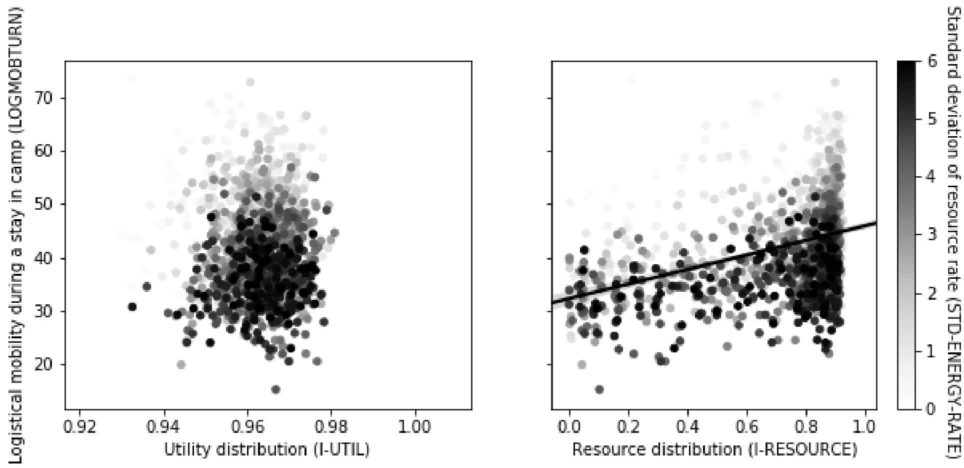
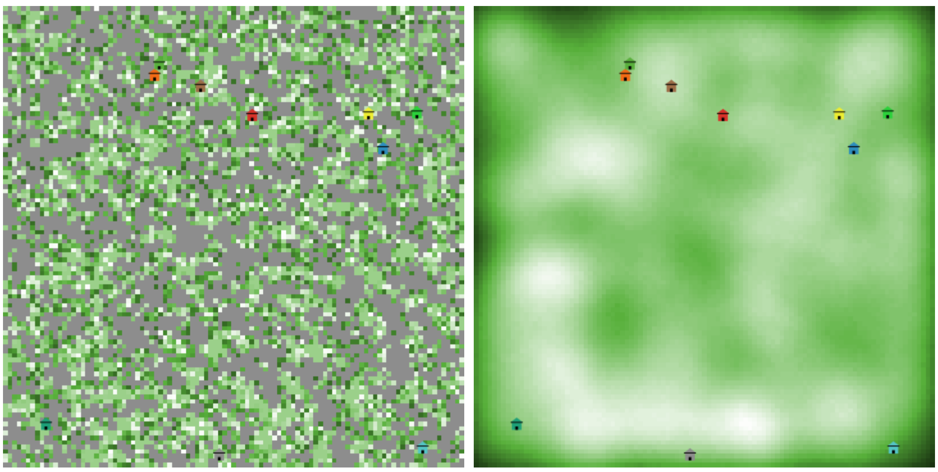


Figure 4.9: Influence of energy and utility distributions to logistical mobility



(a) Initialized map.

(b) 5 steps.

Figure 4.10: Energy distribution and utility value distribution in the same artificial environment. Lighter green has more energy than darker and gray has zero energy.

difference is dependant on the logistical range of a given resource it can be said that the effect of settlement choice on mobility patterns decreases as the possible range of access grows. Therefore the effect of the spatial configuration of the accessible energy rate distribution is significantly smaller than the spatial distribution of resources that require direct access. As the utility which measures access to resources is used for evaluating settlement location choice we can conclude that the energy rate distribution in the environment has a modest effect on it.

Spatial configuration of return rates is closely related to the timing of mobility, as it determines foraging process at a local level. Spatial configuration of utility based on access to resources, on the other hand, is more related to the choice of new settlement locations.

From this we can conclude that the environmental energy return rate distribution is not enough for simulating settlement choices in a spatially explicit setting eg. in case of solving archaeological problems. Kelly (2013, p. 100) discusses the issue as the stay length is also related to move distance which is not only determined by energy. The ethnoarchaeological studies show that settlement site locations are determined by direct access to critical resources like water and firewood (eg. Kelly, 2013, p. 90, 100, 126). Foragers always stay close to water resources, for example it has been documented that Hadza carry water to camp from a maximum distance of 700 m. Archaeological data also shows that hunter-gatherer settlement sites were positioned close to water and additionally had a preference for other geological features such as sandy soil which can drain water or a specific elevation. In real life situations the set of possible alternatives is reduced to locations having requirements for a campsite. This reduction of alternatives might only have a moderate dispersing impact on mobility choices, but could completely change the influence the environment has on settlement choice.

To further study the landscape effect on settlement location choice using the CPF model the distribution of local features required for setting up a residential base should be included. Archaeological predictive models of settlement locations can potentially be used to describe the distribution of suitable places on the landscape and its relation to residential mobility. Combining settlement choice models with energy availability, the CPF model could potentially be used for describing mobility, settlement choice and therefore settlement pattern formation in general.

4.6 Conclusion

We proposed an agent based model to explore the effect of heterogeneous environments on hunter-gatherer mobility choices built upon Kelly's (2013) CPF model. The first goal of the model was to test the robustness of the CPF approach to spatial conditions and measure the effect of spatial autocorrelation of the environment to mobility. The second goal was to explore the possibilities of agent-based spatial CPF model for exploring mobility and settlement choice as ABM opens new possibilities in addition to analytical methods.

The original model was an aspatial model assuming a homogeneous environment. A major addition was the introduction of explicit geographical space with a heterogeneous resource distribution. The model includes abstracted agency and, alternatively to most CPF ABMs where individuals are modelled, the agent is a whole community. This enabled us to build a model based on the abstract CPF theory and avoid going into details of individual behaviours which are more complicated to link to empirical data.

We introduced the generation of energy distribution on artificial landscapes, generalizing the foraging process without simulating individual foragers' moves. It widened the residential choice set from two choices to a wider range of alternatives and hence adding settlement location choice to agents. For simplicity we modified the concept of utility not to be the energy taken from the environment but the time costs used for various tasks. The change is based on principles of CPF and thus has no functional impact on the model. To experiment with a spatial heterogeneous environment we introduced a discrete choice simulation model, which required additional adaptations of the CPF model and the addition of two new mechanisms.

The original analytical model missed an important variable of a timespan of planned stay for evaluating potential residential locations. By using ABM simulation we could create an iterative optimization process so that the variable was modified by agents' previous experience and achieved an optimal value. The adaptation mechanism achieved an equilibrium state which responded to global configuration variables.

To model the dynamics of human-environment interaction we created a mechanism of depletion and recovery of resources. Although we have no empirical data on the depletion rate we manually calibrated its values based on theory and known empirical ranges of mobility parameters. The depletion mechanism caused a significant alteration of the resource distribution in the environment. This in turn resulted in competition between agents creating a population dispersal force in the model.

We conducted three experiments. The first experiment served as a face validation for the mechanisms described above.

The second experiment confirmed the previous analytical results of the original model and served as an internal validation of the spatial model. The mean return rate of the environment had a significant impact on measures of mobility shown by a negative exponential correlation. Residential movement costs on the other hand had a small positive correlation to logistical mobility. Residential move length was also measured and surprisingly had no correlation with the energy rate in the environment but was related to fixed costs of moving.

The third experiment was conducted on the model's sensitivity to the spatial configuration of the environment. To analyse the effect of the environment on mobility we measured the spatial autocorrelation of return rates of cells in the environment and the utility values calculated by the access every cell has to adjacent energy resources. More "smooth" return rate distributions resulted in higher mobility while more clumpy environments had it reduced. Although the effect was present it was significantly smaller than the effect of the mean return rate. The effect of utility values based on cells access was primarily in determining alternatives for settlement location choice. As the utility distribution had a very high autocorrelation compared to return rate distribution by definition the effect was virtually non-existent.

Those results show that the CPF model is generally robust to initial environment configurations, however spatial autocorrelation of the resource distribution has a certain effect on optimal mobility decisions.

We also questioned the usability of a spatially explicit CPF model for explaining settlement pattern formation. As discussed above, according to CPF, the environment has a strong influence on the mobility, which is one cause behind settlement pattern formation. It became apparent that in CPF models the settlement location choice is not determined by energy dispersal at least at the given scale of observation. Based on empirical material we know that critical resources like water and firewood and other local conditions like shelter and geological features determine specific site locations. For modelling settlement choice a submodel of those resources should be incorporated as they might have more significant effects on formed patterns than access to energy.

The introduced model implementation can be used as a baseline model for other simulation experiments of both theoretical nature and for solving explicit archaeological problems.

For theoretical simulations it must be taken into account that the current model uses an artificial environment with a mean known energy return rates of environment and with a variance generated by a stochastic Monte Carlo process without any specific spatial structure. Our main results are generic and hold irrespective of a particular context. For applied predictive work, though it would necessitate further calibration of the parameters related to costs, energy use, etc., for which structured empirical material would be needed.

The spatial distributions of the hunter-gatherers' energy resources and other factors of settlement choice also need to be researched. The first one can be further explored with a similar theoretical approach using different environment generation processes which themselves would need to be empirically verified.

Chapter 5

A spatial agent-based model to disentangle environmental determinism and agglomeration effects in the emergence of settlement patterns

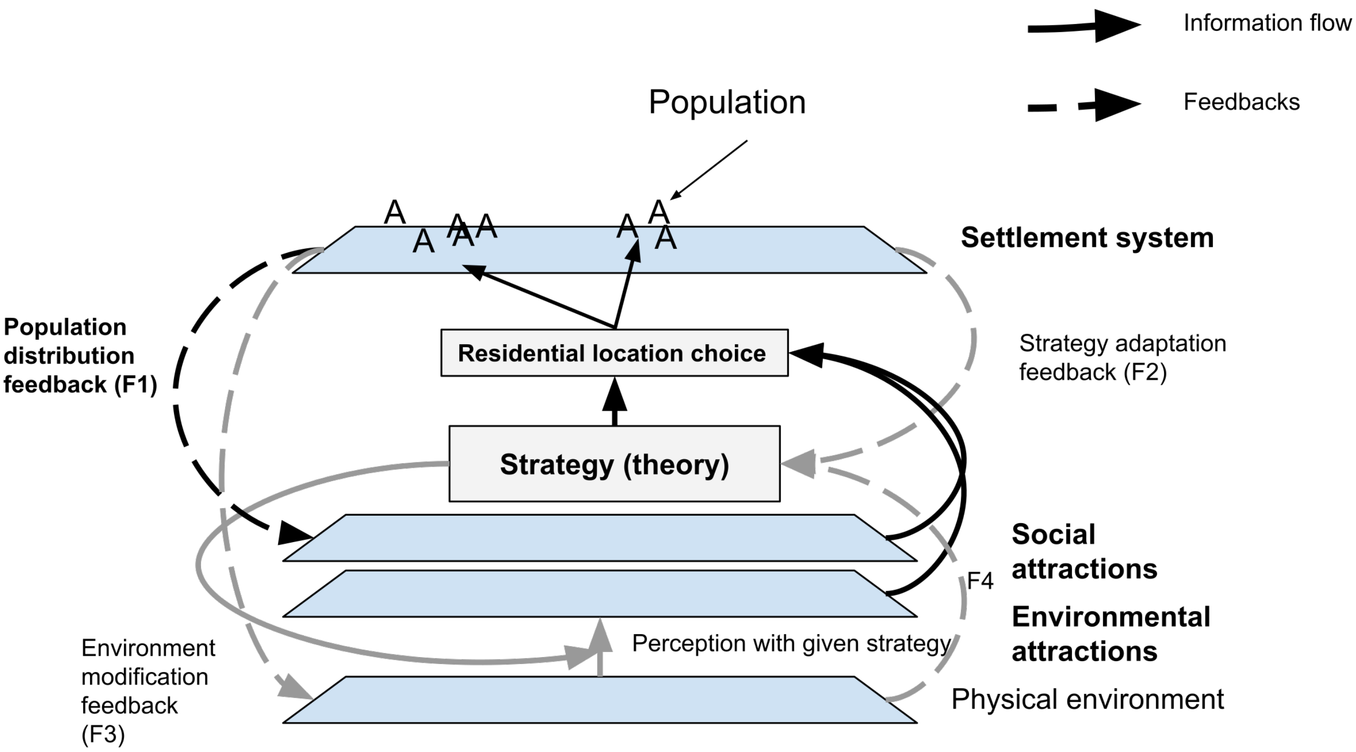


Figure 5.1: Information flows and feedback studied in the chapter with agent-based simulation experiments

5.1 Introduction

Archaeologists have long noticed regularities in the environmental conditions of past settlement sites. Knowledge deduced from these observations has been used to search for unknown archaeological sites and to explain socio-economic reasons behind these regularities (Sikk, Aivar Kriiska, et al., 2020a; also Chapter 2). During the 1980s, archaeological predictive modelling was developed together with the introduction of geographical information systems (Mehrer and Wescott, 2005; Verhagen and Whitley, 2012, see overview in). These models soon proved their effectiveness for site location prediction, but both their explanatory value and the robustness of environmental effects have been subject to discussion (Judge and Sebastian, 1988; Verhagen, 2018; Verhagen and Whitley, 2012; Whitley et al., 2010).

Environmental determinism in itself has been a frequent subject of discussions in geography following the 19th-century naturalist school and the emergence of regional geography. It has also been debated in anthropology and in archaeology (for a recent discussion see Arponen et al., 2019). Within those disciplines, the processualist movement that started in the 1950s and 1960s considered the environment to have a determining influence on settlement pattern formation. In the subsequent period of domination of post-processual thought in archaeology, the role of determinism in both environmental and cultural systems was significantly downplayed. Instead of systemic determinism the focus moved to agency and a variety of individual experiences, which were considered to be more effective in providing explanations for the patterning of archaeological records (Verhagen and Whitley, 2012).

Predictive models have provided a way to explicitly indicate the existence of significant environmental effects on site location. But variations in the performance of these models have led to discussions on systemic properties that influence model outcomes. Ebert and Kohler (1988, pg. 106) summed up the issue by asking: "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 was then hypothesised that the growth in social complexity increases the proportion of social factors in settlement choice (J. Altschul, 1988, p. 81; Kvamme, 2005, pg. 18, 19) and subsequently leads to a decrease in the role of the natural environment and hence in models' predictiveness. The effects of social organisation on residential choice transpire from the observation that individuals do not choose their residential location only based on environmental conditions but by using their position in relation to the existing population.

Seen through a geographical lens, residential choice is then influenced by spatial structure and particularly by the clustering of population in space. This is the spatial interaction principle (gravity model), which includes both proximity and size and is known to be significant in contemporary contexts (e.g. Holm et al., 2004; Page, 1999). Some environmental effects also are presumed to remain. Not only are location choices influenced by the environmental conditions of each particular place, but the wider settlement pattern is then influenced by the spatial configuration of the physical environment, i.e. the structure of the landscape. From this perspective, environmental effects are thought to be less observable when environments are more homogeneous across space (Ebert and Kohler, 1988, pg. 138-142).

The purpose of this study is to tackle these long-standing questions with a theoretical model that goes beyond case specificities. How do social and environmental systems combine and affect individual choices? How does the spatial configuration of the environment influence both the level of spatial clustering of settlements and the level of environmental determinism in residential location choice? To study these effects, we consider settlement patterns as resulting from a complex set of social and ecological interactions within adaptive systems, i.e. complex adaptive systems (CASs) and more particularly socio-ecological systems (SESs). We define a settlement system as the spatial distribution of a population over a territory and in relation to its environmental characteristics. We consider its formation (emergence) as resulting from a dynamic adaptation process leading to a gradual development of optimal spatial distribution of the population. The mechanism of adaptation is driven by individual residential choices of members of the population (Holm et al., 2004), who consider both the environment and the relative spatial proximity and clustering of other population units.

The adaptation process is simulated through a theoretical agent-based model (ABM). An ABM is particularly suited to modelling complex adaptive systems given repetitive interactions across space and time and forward and backward interactions between the micro scale of an individual decision maker and the meso scale of higher-level patterns (Benenson, 2004; Léna Sanders, 1998). The theoretical setting, rather than a real landscape, frees us from spatial heterogeneities and case specificities.

Agents make residential decisions (in time and space) and we explore how variations in individual residential choice strategies lead to the emergence of different spatial and statistical population distribution patterns. The first goal of the model is to explore the spatial interactions between the natural environment and social organisation and their combined influence on population distribution. The second goal is to explore the robustness of these processes by studying the effects of the randomness of agents' choices on environmental determinism and the form of settlement patterns.

5.2 Background and related work

5.2.1 Conceptual framing: residential location choice to macro settlement

For the study we adopt the general framework proposed in Chapter 1, which seeks to explain the emergence of large-scale phenomena based on individual micro-actions. As the system contains social and environmental components, the settlement pattern is considered as a socio-ecological system (SES). This makes it possible to use analytical tools developed for SESs also for the study of settlement patterns. The framework then considers the settlement system formation process as driven by the individual choices of population groups taking residential choice decisions (Benenson, 2004). The form of a settlement pattern as a whole is therefore determined by an accumulation of subsequent spatial decisions. These mobility decisions lead to changes in the spatial configuration of population dispersal which in turn leads to changes in physical and also social spaces and how they are perceived. As residential choices are dependent on the perceptions and subsequent evaluations of these spaces, a dynamic adaptation process emerges.

Chapter 1 therefore described settlement systems as dynamic systems composed of information flows, residential choices based on them and feedbacks that are key to a spatial adaptation process of populations to the environment. Spatial adaptation refers to a process leading to the optimal placement of a population in a given environment. As is typical for SESs the adaptive process can lead to a variety of steady states (Scheffer et al., 2002) and can cause shifts between them as a result of exogenous influences. These steady states and processes of adaptation can be observed as empirical settlement patterns with different spatial configurations.

5.2.2 Residential location choice

The generative mechanics of the settlement system formation process are driven by individual residential decisions. For the purposes of this study we explore how variations in the processes behind residential choice influence the whole system. As argued in Chapter 1, residential choice is a spatial choice carried out by individuals or populations. These decisions are influenced by a multitude of factors which can generally be divided into two broad groups: perception (information) of the physical environment and perception (information) of social space created by the existing population. These factors function as perceptions and are communicated to individuals as information which then influences individual choices.

Environmental influences include access to resources, water or suitable soils, which we generalise as access to outputs of ecosystem services ((Program), 2005) from which humans derive direct or indirect benefits (Lamarque et al., 2011). The second group of influences includes needs that depend on the existing population, such as security, marriage networks and cultural attractions. It also includes systematically organised access to ecosystem services, for example through various forms of cooperation, exchange and trade. These social factors can be lumped together and described by a function of distance weighted population density that describes general population density expected by individuals.

We assume that we can describe the residential choice process in a given society using a rule set, defined as residential choice strategy, and that we can break down this strategy based on these two groups of influences described above. This division is justified by empirical evidence: studies using empirical inductive models have proven the significance of environmental effects for site locations observed in archaeological material (Mehrer and Wescott, 2005; Verhagen and Whitley, 2012). However, empirical research has resulted in models with varying predictive power. In a move towards identifying the systemic reasons behind variations in predictive power, Ebert and Kohler (1988, p. 106) asked 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 is strongly related to the environmental determinism of settlement choice (e.g. Judge and Sebastian, 1988; Kvamme, 2005; Verhagen and Whitley, 2012), which can then be formalised as a proportion of influences coming from social domain as opposed to environmental factors. It has been assumed that the growing significance of population density dependence comes with growing social complexity. In addition to organisation through social complexity (J. Altschul, 1988, p. 81; Kvamme, 2005, pg. 18, 19), systemic properties of past human–environment relations like economic intensification (Ebert and Kohler, 1988, pg. 141) and the spatial configuration of the environment (Ebert and Kohler, 1988, pg. 133-145) also influences environmental determinism.

The influence of social factors has been empirically studied using population densities and spatial clustering. Population agglomeration has been explored from hunter-gatherer societies (e.g. Hamilton, Milne, et al., 2007) to contemporary urban contexts (e.g. Caruso et al., 2007) It has often been assumed that there is a natural pull towards higher population density, which is restricted by energetic constraints. Ethnographic and archaeological studies of forager and early agrarian communities relate spatial structuring of settlements based on energetic resources (e.g. Kohler, Varien, et al., 2008). Studies of urban agglomeration typically focus on the economic benefits accessible in specific urban locations (see Chapter 1 for examples).

5.2.3 Socio-ecological systems and agent-based modelling

In this paper we implement an ABM model of the settlement system as an SES. SESs can be seen as being positioned within the general framework of CASs (CAS; Holland, 1992) and they come with a suitable tool kit for exploring such systems. ABM is the natural choice for theoretical exploration of SES systems as it exposes the ways in which agents' micro-behaviours lead to the emergence of large-scale patterns. The principles of ABM for modelling complex adaptive systems enable us to build a dynamic model operating at both micro and meso scales and to explore the links between individual choices and higher-level patterns (Benenson, 2004; Léna Sanders, 1998). ABM provides key benefits for exploring relevant complex adaptive systemic properties like non-linearity, emergence, feedback loops and self-organisation. The framework has been adopted for SESs (for an overview see Filatova et al., 2013) and has also been used for modelling urban residential choice (Benenson, 2004) and exploring long-term economic and population developments using archaeological data (e.g. Kohler, 2000; Kohler and Varien, 2012). Interactions between natural and social processes have been explored with simulation before (e.g. Christiansen and Altaweel, 2006), but these have been based on a series of relatively fine-grained details and assumptions in line with on specific conditions, while our purpose is to provide an abstract, theoretical study.

5.3 Simulation model

The particular goal of the model is to explore how (i) the spatial structure of the environment, (ii) population density preferences, (iii) the importance of social organisation and (iv) the randomness of agents' choices influence the formation of settlement patterns. Those emerging meso-level patterns are then described by spatial clustering and environmental determinism. We consider environmental determinism to be high when there is a strong match between selected residential locations and the areas with highest environmental attractiveness. The model has been developed based on the general framework of settlement pattern formation and the general theory of residential choice principles (see previous section).

Chapter 1 contained a general outline of the whole settlement system formation process including information flows leading to settlement choice and feedbacks through emerging spatial structures that form feedback loops. In this study we implement a simplified model containing only essential information flows from social and environmental attraction space to individual residential choice. We include only the feedback loop between residential choice and social attraction space to explore settlement system formation in the case of a static environment and socio-economic

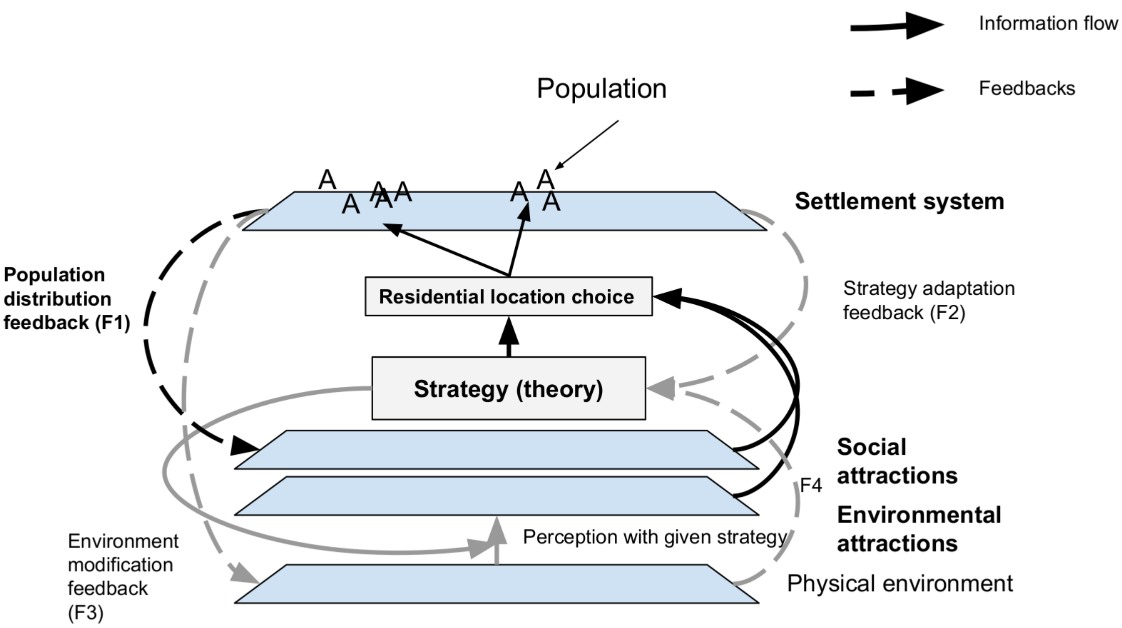


Figure 5.2: Diagram showing formation of spatial adaptive settlement systems with the information flows and feedbacks explored in this article highlighted.

strategy. This reflects a relatively short term settlement system formation process that does not include longer processes of environment modification and development of new technologies. Physical attraction space is therefore not dynamic in our study but is only varied by model parameters across different models to explore how initial spatial configuration influences pattern formation.

The influence of other information flows and feedback loops is considered to be covered by the stochasticity of residential choice as implemented in the model. Introduced randomness is also considered to represent general modelling error, the nature of communication, the diversity of individual perspectives, bounded rationality and exogenous effects and is used to test the robustness of the model.

We are not trying to represent a specific historical settlement system but intend to explore universal spatial laws emerging from basic relations within the system. In this section we describe the general principles of the model; for a more detailed description in ODD (Grimm, Railsback, et al., 2020) format see Appendix 3.

5.3.1 Agent-based model structure

We formalise the settlement system formation model as an ABM consisting of a geographical space, a synthetic population composed of agents, and their socio-ecological organisation. The population size is static; the purpose of the model is to study the spatial reorganisation of a finite number of agents. The geographical space in the model includes three raster layers. The first layer represents the attraction space of the natural environment as perceived by the agents. Each cell in the layer represents an abstract suitability value of the given location as perceived by agents in the system and is largely determined by the strategy followed by the population. The attraction field therefore represents a relational entity which depends on both the natural environment and land-use strategy. As our goal is to test the effects of spatial configuration of the environment, the layer is generated as a neutral landscape model with a controlled spatial autocorrelation of attraction values (LS-LAMBDA). The second layer represents local population density on each pixel. The layer is dynamic and formed as a feedback from agents' cumulative location choices. The third layer contains random values and is used to introduce stochasticity into agents' choices.

We consider the spatial configuration of environmental attractions to be part of socio-ecological strategy. We do so because we consider here the spatial structure of utility values which are relational and are determined both by the natural environment and by the way land is used and functionally perceived by the population. For example two different attraction spaces of hunter-fisher-gatherers can be similar even if situated in separate natural environments. At the same time, the space perceived by those groups can be completely different from that perceived by early agrarian society in the same natural environment (Sikk, Caruso, et al., 2022).

Agents in the system represent population units who make mobility decisions. Although we do not specify the size and nature of these units, households would be good candidates (Léna Sanders, 1998) for modelling specific systems. All agents in the system follow the same socio-ecological strategy for finding the best place to settle and differences in their behaviour are caused by local knowledge and stochasticity.

The socio-ecological strategy in the model is a set of global parameters:

- The spatial autocorrelation of the physical attraction space (LS-LAMBDA).
- Preferred population density (DENSITY-PREFERENCE).
- The proportion of social factors as opposed to natural factors in settlement choice (COEF-SOCIAL).
- The proportion of randomness in residential choice (COEF-RANDOM).

The meanings of these variables are explained in the following section.

5.3.2 Residential choice mechanics

The model's micro-level mechanism is economic: agents in the system choose the best suitable location for them in the geographical space. The process is achieved through direct objective seeking, with agents moving to the best location in their local neighbourhood, and the attractiveness of the place is calculated by a residential location choice utility function. It is based on the assumption that the utility of a location can generally be described as a normalised abstract value and that the value can be broken down into physical and social components (Bevan and Conolly, 2006, Chapter 1). We define these components as environmental and social utility as perceived by population units.

The physical component represents the attractions of environmental features and is observable in archaeological record as correlations between site locations and environmental variables (Sikk, Caruso, et al., 2022). Empirically environmental variables then represent ecosystem services directly provided by the location (Chapter 1). In modelling studies of forager and early agrarian societies the environment is typically represented by the energy it can provide (e.g. Hamilton, Lobo, et al., 2016; Kelly, 2013). In this study we make environmental utility more abstract as the goal is not to explore a specific system but rather the spatial rules governing settlement systems in general. We include the sum of factors from the physical environment in the variable UT-ENV that is attached to each cell in the model.

While the physical component represents one agent's direct access to ecosystem services in a location, the social component describes systemic properties involving other agents. The sum of these components is represented by social utility in the model (UT-SOCIAL); it has also been previously termed "neighbourhood dependence" (Bevan and Conolly, 2006), which we here quantify through the local population density at a given location.

Utility values are attached to all cells in the system and form two separate layers of physical and social attractions that are spatial entities and can be approached using spatial tools. In this model we directly define the spatial structure of the physical attraction space by its spatial autocorrelation but the social attraction space is dynamic and re-calculated after every change in the system. We argue that the social attraction space can have a different spatial structure depending on the socio-ecological strategy.

Historical evolution towards highly populated cities and agglomerations (World Bank 2015) allows us to assume a universal human preference for maximising population densities. It has also been shown that this tendency already existed for hunter-gatherer societies (Hamilton, Milne, et al., 2007). But both economic geography and archaeology provide indications of limits to this trend and examples of opposing repulsion forces.

The typical limit considered in archaeology is the availability of resources, or more generally the carrying capacity of the land (Bintliff, 2000; Flannery, 1976), and scalar stress because of limited human information processing (G. A. Johnson, 1982). Similarly in economic geography the repulsion effect becomes visible if controlling for known factors. The utility of locations is therefore controlled by both attraction and repulsion forces, which have previously been used in theoretical ABM simulations of urban environments (Page, 1999, e.g.).

As in this theoretical model we do not need to explore the empirical relationship between push and pull forces, we describe the social component of utility using a unified attraction-repulsion variable: preferred population density (DENSITY-PREFERENCE). In real-life systems, this optimal density is dependent on socio-ecological systems and available technology; it is known that it differs significantly for foraging, agrarian and urban societies (Tallavaara et al., 2018; Weinberger et al., 2017). Higher preferred population density represents agglomeration forces and lower preferred densities can indicate the intensity of population pressure in the system. The UT-SOCIAL of every cell is then calculated as a normalised value of similarity to the DENSITY-PREFERENCE.

To explore the effects of exogenous influences on individual agents' choices, possible randomly induced path dependencies and the robustness of the model, we also introduce a random component to agents' perception of space. The randomness is stored as a separate spatial layer which has a UT-RANDOM variable for every cell in the system. This randomness is dynamic, spatially unstructured and represents unknown factors including bounded rationality and exogeneous effects on the system.

The model builds on the assumption that for modelling purposes we can attach weight to social and physical components in the utility function: the greater the social complexity, the more weight social components have. This difference can be observed in different socio-ecological modes of society. It is known that foragers depend on local resources, which can be harvested in quite small groups. For early villages, the agricultural system requires higher population density, while in the case of cities the natural environment of the dwelling is often not considered at all.

The utility function is run over the agent's local neighbourhood (NEIGHBORHOOD = 20), returning an abstract utility value (UT-FULL) for each cell. Essentially the NEIGHBORHOOD parameter describes the spatial extent of information available for agents and therefore the information component in mobility. It uses global strategy parameters (COEF-SOCIAL, COEF RANDOM) and values from spatial layers for the given location (environmental utility: UT-ENV; social utility: UT-SOCIAL; random utility: UT-RANDOM) as an input.

COEF-SOCIAL is used as a proportion of social utility as compared with environmental utility. The proportion of social components indicates the extent to which location choice is determined by proximity arguments for ecosystem services as opposed to higher social organisation. The variable is used as a proxy of environmental as opposed to social determinism, presumably caused by social complexity.

Similarly COEF-RANDOM represents the proportion of RANDOM-UTILITY in the overall utility value and therefore controls the randomness of agents' individual behaviours compared with the given system strategy.

5.4 Experiments and results

To explore the effects of different residential choice strategies on settlement system formation, a model exploration was conducted. The face validation of the model indicated that while running with any fixed parameters it resulted in stable steady states representing optimal population distributions in the environment with given strategies. Despite feedback loops in the system the steady states were achieved promptly (mostly $T < 20$ in simulations with reasonably small random components in the location choice function).

Four experiments were conducted to isolate and describe the effects of model parameters, and each simulation was run until a steady state was achieved. Those experiments were mostly deterministic with stochasticity being introduced just by the initial spatial configuration of the model setup. As a fifth experiment a sensitivity analysis of the model was conducted including the robustness testing for randomness in individual choices. Variable interactions indicated by second order sensitivity indices were explored.

In the following experiments we measured agents' clustering by the nearest neighbour index (NNI). Environmental determinism was measured through the mean and standard deviation of the environmental utility values(variables MEAN-UT-ENV* and STDEV-UT-ENV*) for agents' positions after simulation has achieved steady state .

5.4.1 Experiment 1. Effect of environmental homogeneity.

To isolate and describe the effect of environmental homogeneity (LS-LAMBDA), we removed the effects of all other model parameters by setting COEF-SOCIAL and COEF-RANDOM to 0. We then varied LS-LAMBDA from 0 to 1 and measured NNI and environmental determinism (MEAN-UT-ENV* and STDEV-UT-ENV*).

The results show that homogeneous environments, despite having the same average utility values , lead to lower mean values of environmental utility at final agent locations This confirms previous hypotheses (Ebert and Kohler, 1988, pg. 138-142) that the homogeneity of the environment decreases environmental determinism and therefore also the predictability of site locations.

For field archaeologists searching for sites in the landscape, homogeneity would make it harder to distinguish suitable from unsuitable areas and might increase the suitable search space. There is also a systemic tendency for agents to fail to choose the greatest environmental attractions (Fig 5.3). There are no interactions between agents in the model apart from agents preventing others from occupying patches. Hence the effect is caused by a perceived neighbourhood range that limits agents' information about the environment and attracts them to local maxima. In homogeneous environments agents do not move beyond regions around these local maxima, while in heterogeneous environments paths of movement to other regions with higher values are more probable (see Fig 5.4 for illustration).

More homogeneous environments lead to clustering of the settlement while heterogeneous environments enforce spatial randomness (Fig 5.4). These effects of space arise intuitively from principles of maximisation based on local knowledge, with agents following local maxima (Fig 5.4). Higher spatial autocorrelation implies the clustering of local maxima which also leads to the clustering of agents (Fig 5.4).

The described effects do not include any interactions between agents. If there are attractions between agents the effect is expected to increase. This means that in the event of attractions between agents, the heterogeneity (low spatial autocorrelation) of the environment can be considered as a limiting factor for population clustering. The results give indications about spatial behaviour based on information from attraction spaces in general. So if social attraction space makes the perceived combined attraction space homogeneous, the resulting settlement system tends to be more clustered and individual locations can be less influenced by local environmental conditions.

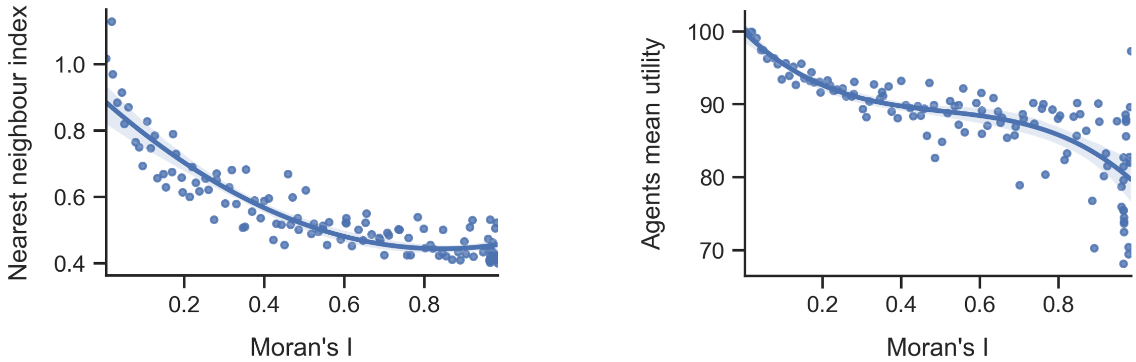


Figure 5.3: Higher spatial autocorrelation (Moran's I) tends towards agent clustering (lower NNI) and lower environmental determinism (MEAN-UT-ENV*).

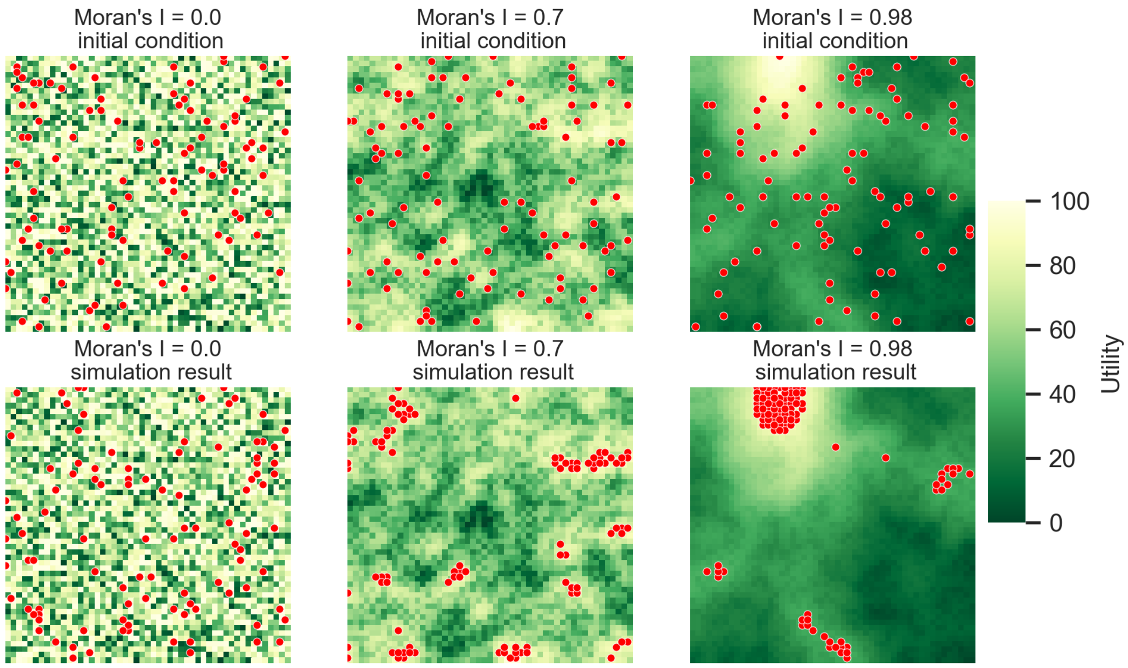


Figure 5.4: Three spatial presentations of simulations illustrate how spatial autocorrelation can lead to population clustering. The upper images are the initial states of the model and the lower images show the achieved steady states of the model. Red dots represent the agents in space.

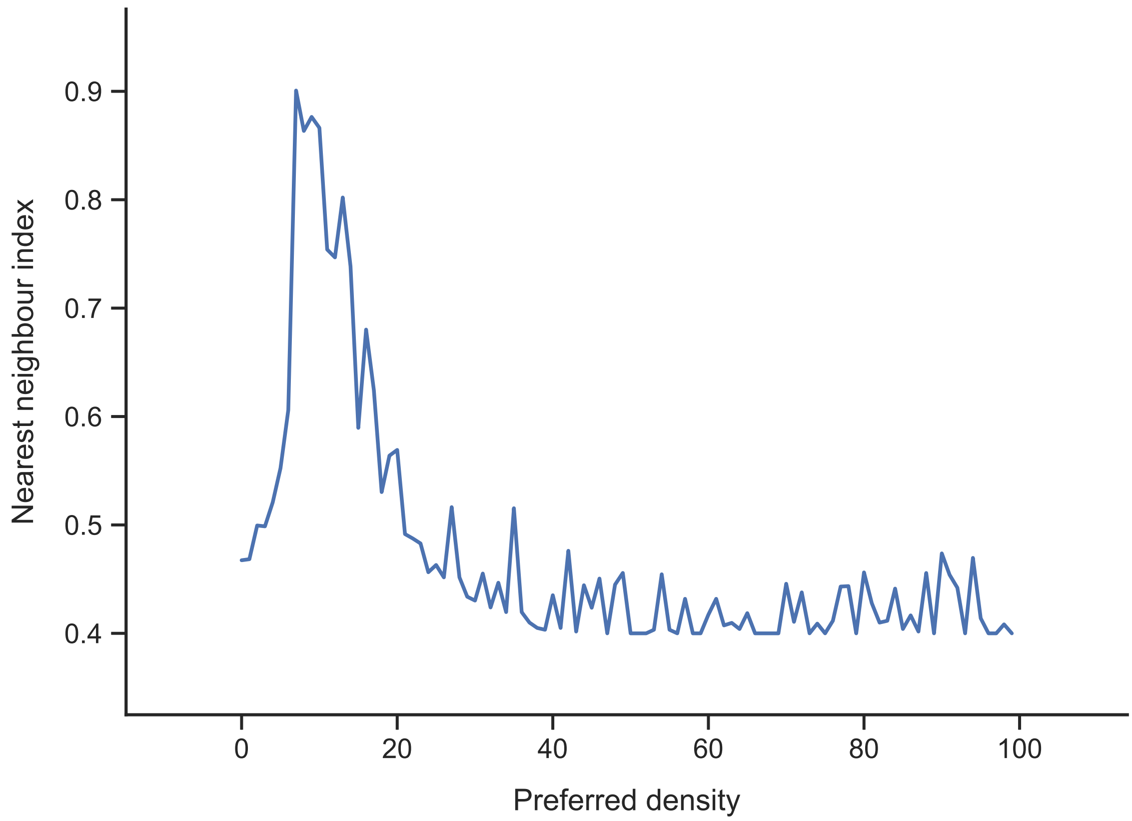


Figure 5.5: Relationship between preferred population density and agent clustering. If the overall population density in the available space is not equal to preferred population density, there is a spatial effect towards population clustering.

5.4.2 Experiment 2. Effects of preferred density on population clustering

To explore the effects preferred density has on clustering we removed other effects by setting COEF-SOCIAL to 1 and COEF-RANDOM to 0 and varying DENSITY-PREFERENCE from 0 to 100. The variable was found to have no direct effect on environmental determinism but there is a nonlinear effect on clustering.

The link between preferred population density and clustering reveals three different modes:

1. population pressure, a state where the preferred density is lower than global density of population in the available space;

2. the global population density is close to the preferred density;

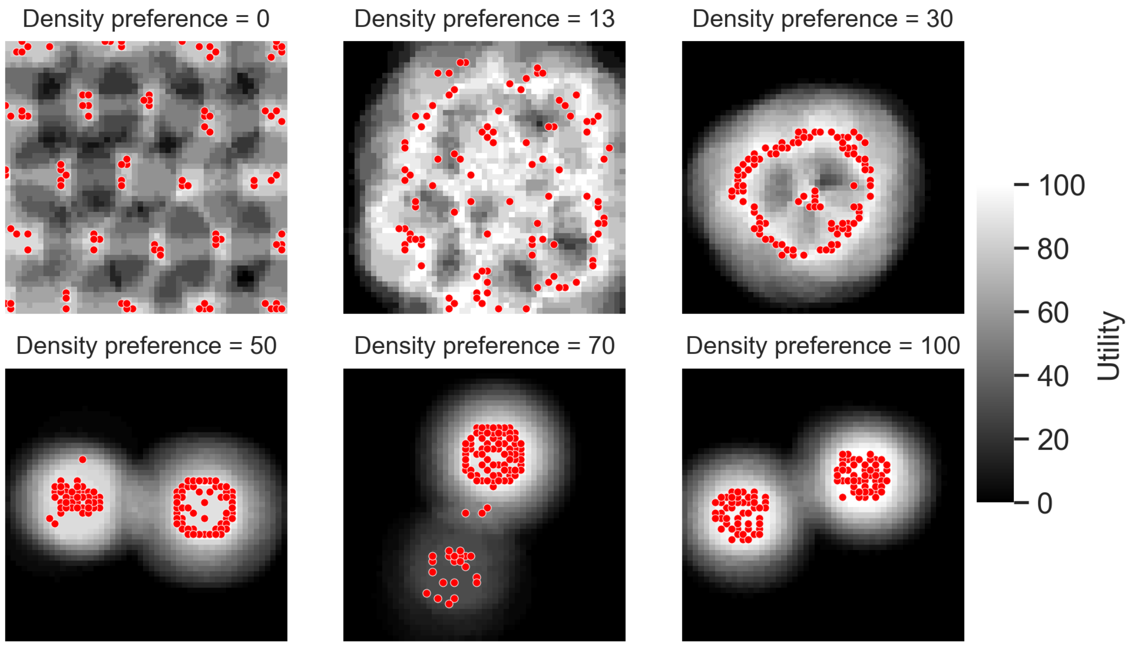


Figure 5.6: Model steady state outcomes using runs with varying preferred densities to illustrate various forms of clustering.

3. agglomeration process, the population prefers a higher density than the global density in the model.

With mode 1 the population forms a grid with small clusters distanced according to perceived neighbourhoods in the model, which results in the lowest local population density for all agents. In mode 2 the population evenly fills the space and results in population dispersal. Mode 3 starts the agglomeration process by forming lens-like structured population clusters. With higher population densities, agglomeration leads to one or more dense population clusters. The random initial placement of the agents has considerable influence on the outcome, resulting in either monocentric configuration or configuration with multiple centres.

All the phases of expected population densities create a tendency towards certain spatial structures. If the initial conditions of the model do not satisfy the preferred population density the spatial adaptation process leads to population clustering. Otherwise there is a tendency towards spatial randomness. Optimal spatial conditions drive the process without the need for any additional cultural or competition-related mechanisms to be introduced into the system.

It is also worth noting that with both population pressure and satisfactory global density, all the agents end up in locations with relatively equal utility values. Agglomeration, on the other hand, results in significant spatial inequality, with some agents ending up in significantly less attractive places than others. This inequality was measured using the variable MEAN-FULL-UT, the full utility of agents' locations.

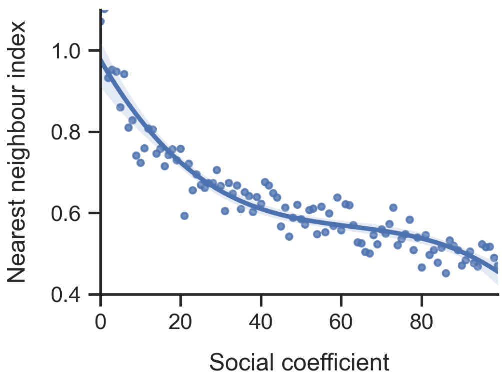
High but not maximal population density also leads to an empty area in the middle of the population, which is visible in the event of emerging monocentric configurations. A similar effect has been also shown in the Newling model (Newling, 1966) and seen in the empirical data of larger urban centres (Latham and Yeates, 1970); it has been termed a population crater. This simulation indicates that population density preference leads to a steady state of spatial distribution that also includes spatial effects like clustering, randomness and population craters.

5.4.3 Experiment 3. Effects of the importance of social attractions versus physical attractions

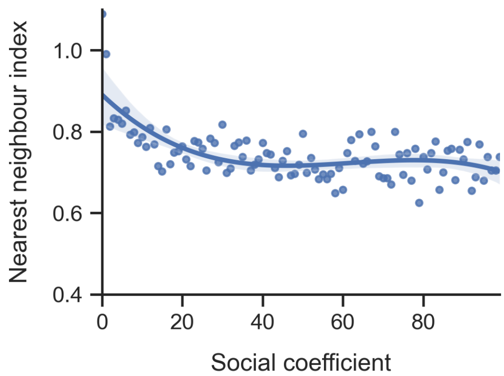
The proportion of social factors in locational choice represents a balance between social (UT-SOCIAL) and environmental utility values (UT-ENV), including effects discussed in previous subsections. As social attractions generally work towards population clustering we fixed LS-LAMBDA to 0.1 to provide a contrasting counter influence towards population dispersal. We conducted separate experiments to explore different phases of DENSITY-PREFERENCE with values of 0, 13 and 100. During the experiment we varied COEF-SOCIAL in its full range from 0 to 1.

As expected, with heterogeneous environments COEF-SOCIAL has an effect towards population clustering in all cases of density preference. If density preference reflects the overall density of the model and provides no additional spatial pressure, the effect is significantly smaller and the difference is observable only when COEF-SOCIAL < 30. In the event of maximum agglomeration the clustering is more pronounced and creates tight population clusters, even with very low COEF-SOCIAL values.

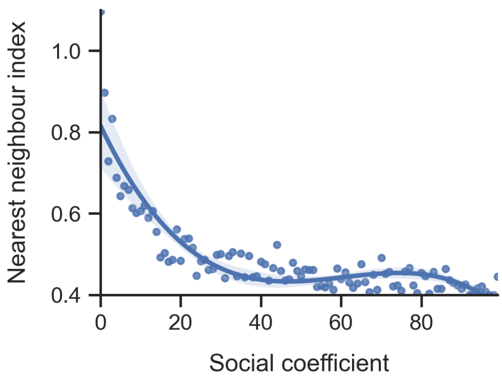
The decreasing MEAN-UT-ENV* variable indicates that an increase in COEF-SOCIAL unsurprisingly leads to a decline in environmental determinism. In the event of satisfactory conditions of population density the effect is virtually non-existent and overall all agents go to environmentally best locations resulting in a settlement pattern that can be observed as completely environmentally deterministic. With population pressure there is a steady decrease in environmental determinism as COEF-SOCIAL increases. With maximum agglomeration and high COEF-SOCIAL the mean environmental utility values in different models vary a lot more. In case of strong agglomeration force environmental determinism is considerably less robust to variation in the initial conditions of the model.



(a) DENSITY-PREFERENCE = 0; population pressure

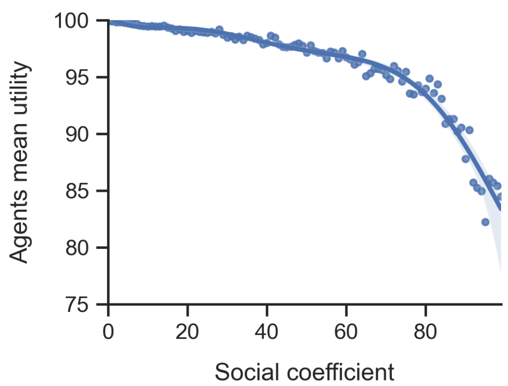


(b) DENSITY-PREFERENCE = 13; satisfying density

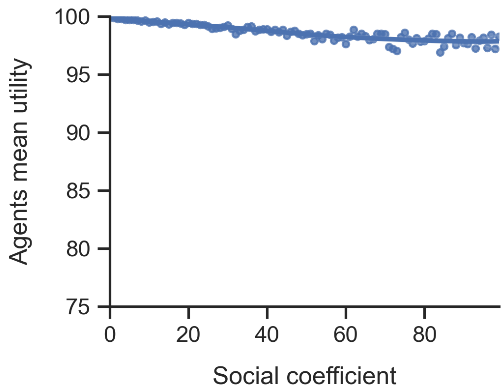


(c) DENSITY-PREFERENCE = 100; maximum agglomeration

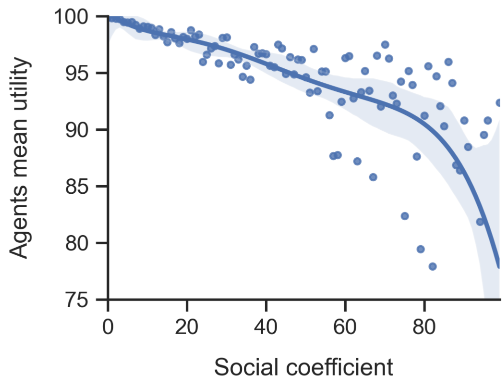
Figure 5.7: Effect of COEF-SOCIAL on preferred densities (DENSITY-PREFERENCE values from top to bottom: 0 (population pressure); 13 (satisfying conditions); 100 (maximum agglomeration)).



(a) DENSITY-PREFERENCE = 0; population pressure



(b) DENSITY-PREFERENCE = 13; satisfying density



(c) DENSITY-PREFERENCE = 100; maximum agglomeration

Figure 5.8: Effect of MEAN-UT-ENV* on preferred densities. DENSITY-PREFERENCE values from top to bottom: 0 (population pressure); 13 (satisfying conditions); 100 (maximum agglomeration).

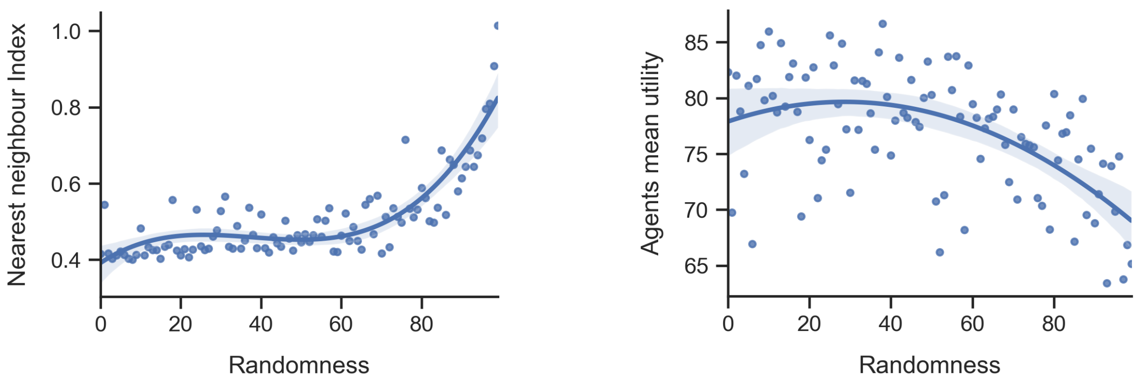


Figure 5.9: Influence of randomness to population clustering and environmental determinism.

5.4.4 Experiment 4. Effects of random attractions

To explore randomness in agents' choices and the robustness of the model, and to search for possible path dependencies, we introduced a random component to the individual location choice process. To explore the effects of randomness we conducted another experiment. We fixed LS-LAMBDA and COEF-SOCIAL to 0.5 and DENSITY-PREFERENCE to 100 and varied COEF-RANDOM from 0 to 100.

The results indicate that a random component in location choice decreased agent clustering and also environmental determinism, but the latter only to a small extent unless there was a very high proportion of randomness in location choice. With COEF-RANDOM values around 40 the MEAN-UT-ENV* achieved the best performance, with all runs having relatively high values. The phenomenon can be explained by the fact that randomness can make agents more mobile and help them escape regions close to local maxima, thus enabling them to find better locations in other regions as a result. This indicates that a certain amount of randomness (bounded rationality) makes system adaptation more effective and possibly more resilient.

5.4.5 Experiment 5. Model sensitivity analysis.

To explore the sensitivity of the model outputs to input parameters we conducted a sensitivity analysis for the model. The model was run on varying input parameters: LS-LAMBDA, DENSITY-PREFERENCE, COEF-SOCIAL, COEF-RANDOM. The mean and standard deviation of the environmental utility of agents' positions (MEAN-UT-ENV*, STDEV-UT-ENV*) and agent clustering (NNI) were measured.

Model input parameter sets were created using Sobol sampling, which resulted in 5120 model runs. We calculated Saltelli first- and second-order sensitivity indices for all input and output variable combinations and also interactions between input variables that are responsible for variations in the model results (Saltelli et al., 2004).

The results of the sensitivity analysis are visualised below using two diagram types. The first diagram shows the contributions of all variables to the overall model variance. Every variable is visualised by a disc, with the following rules:

1. The size of the disc indicates Saltelli total sensitivity index (ST) combining first and second-order indices
2. The size of the black disc indicates Saltelli first-order sensitivity index, indicating the extent to which a variable individually influences model outcomes (S1)
3. The line width of the connector lines between the variables indicates the second-order sensitivity index (S2) of the two variables in interaction

The second diagram type is used to show variable interactions based on the model run results with the input parameter sample used for the sensitivity analysis. The diagram illustrates the relationship between the variables, with two of them being shown on the diagram axes and third indicated by colour. To improve the visualisation, LOESS lines are drawn on the diagram to indicate the results in the event of third variable values in the first quartile (blue line), second and third quartiles (black line) and fourth quartile (red line).

Despite some interactions with other variables, the spatial configuration of physical space does not significantly influence population clustering in most theoretically possible cases. Its dispersal and clustering effects shown in Experiment 1 can be seen in the event of low social and random effects (figure 5.11b). Figure 5.11b shows that because of these effects, high LS-LAMBDA (spatial homogeneity) always leads to population clustering event in the event of high COEF-SOCIAL resulting from inter-agent interactions and low COEF-SOCIAL caused by spatial homogeneity.

The clustering of agent populations is mostly determined by DENSITY-PREFERENCE and COEF-SOCIAL and the interactions of those variables (Section 5.4.2 and 5.4.3; Figure 5.11c).

The results (Figures 5.10 and 5.11d) show that spatial clustering based on preferred density and the importance of social perception is very robust. Randomness introduced into individual choices obviously somewhat weakens the effect, but in the adaptation process it only has a moderate influence on clustering.

Environmental determinism is represented by two variables MEAN-UT-ENV* and STDEV-UT-ENV*. For both of them, DENSITY-PREFERENCE individually has only a marginal influence. The non-linear patterns as seen in 5.4.2 can be observed

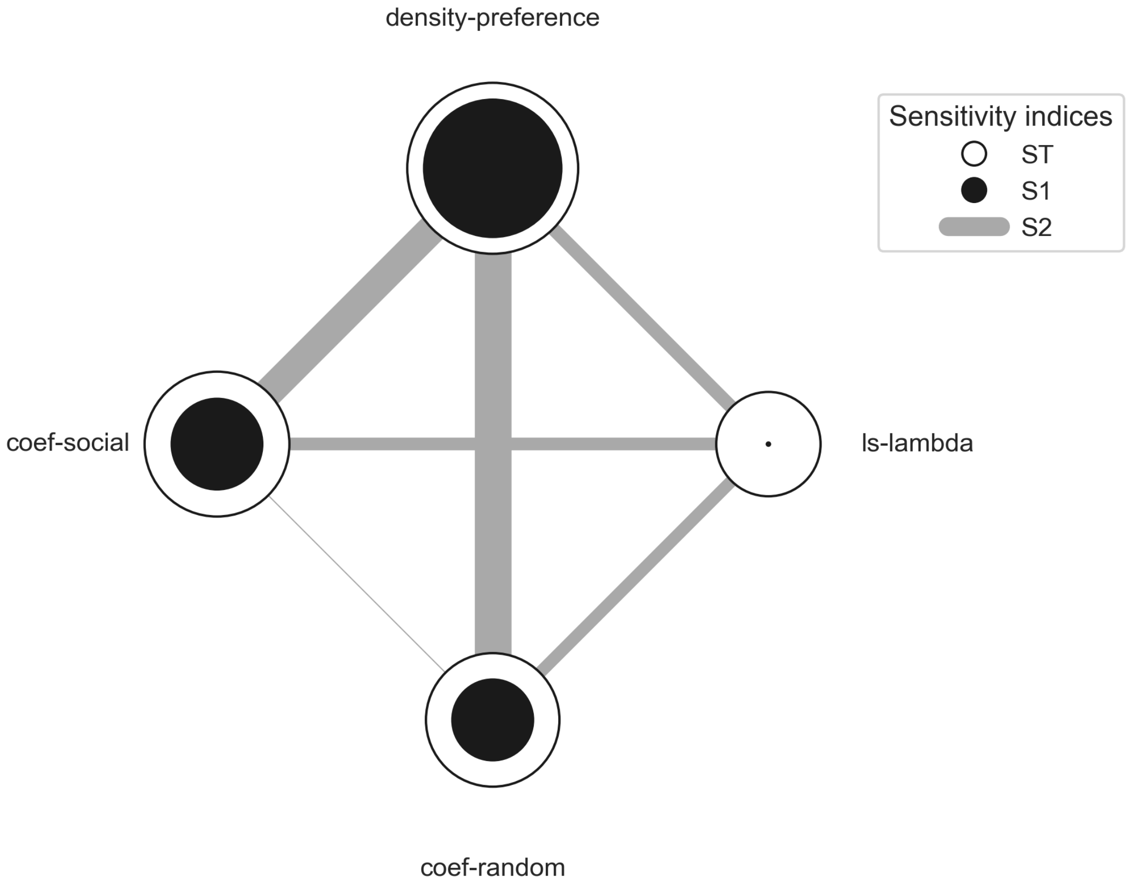
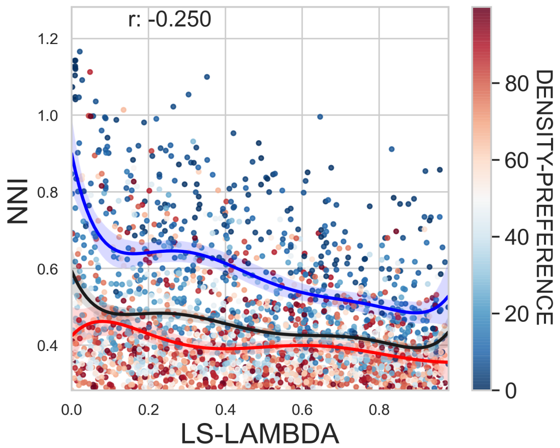
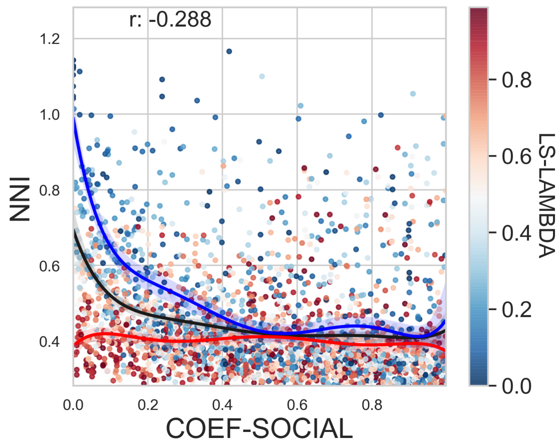


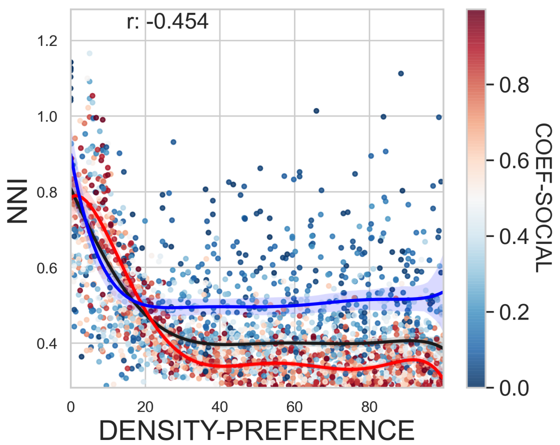
Figure 5.10: Input parameters contribution to agents clustering (NNI).



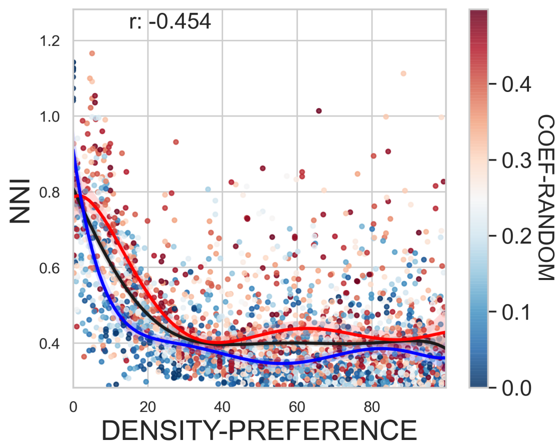
(a) Variables: Spatial homogeneity (LS-LAMBDA) and preferred density (DENSITY-PREFERENCE)



(b) Variables: Share of social utility (COEF-SOCIAL) and spatial homogeneity (LS-LAMBDA)

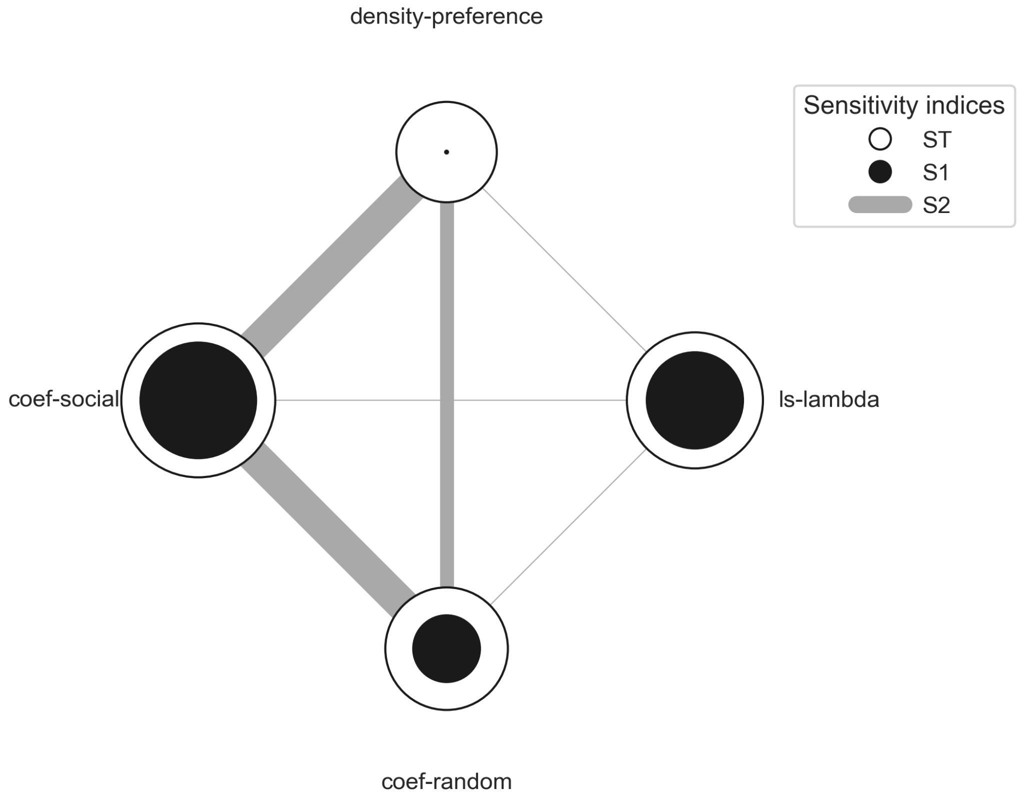


(c) Variables: Preferred density (DENSITY-PREFERENCE) and share of social utility (COEF-SOCIAL)

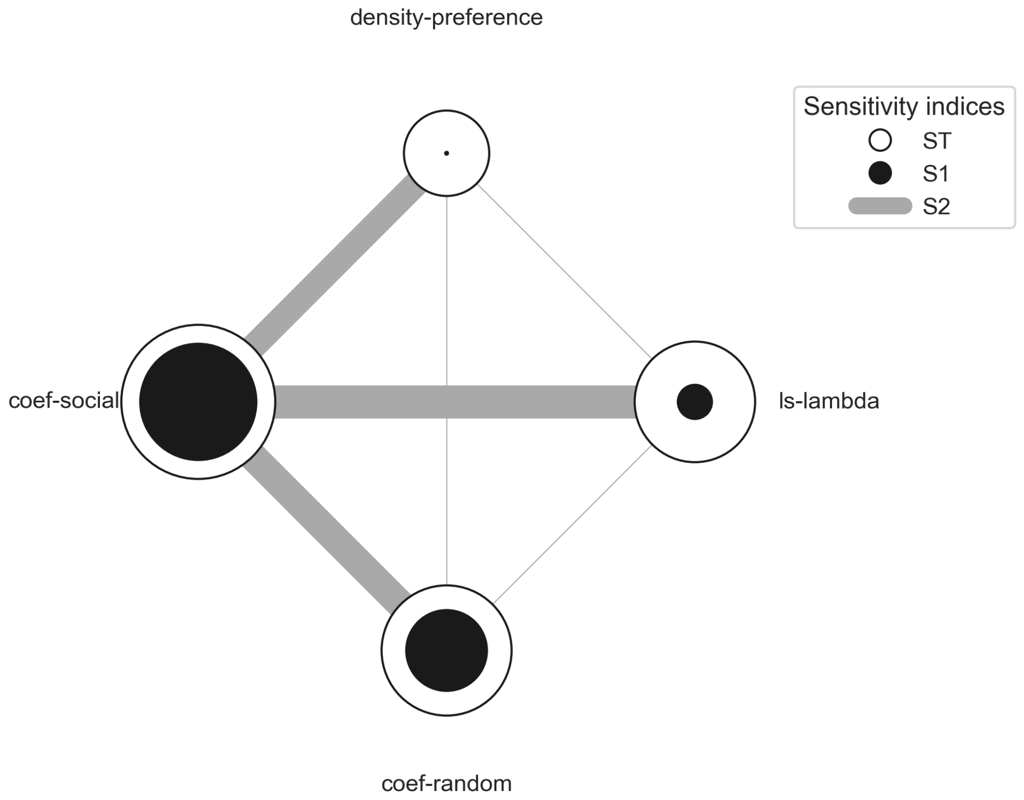


(d) Variables: Preferred density (DENSITY-PREFERENCE) and share of random utility (COEF-RANDOM)

Figure 5.11: Variable interactions influencing nearest neighbor index (NNI).

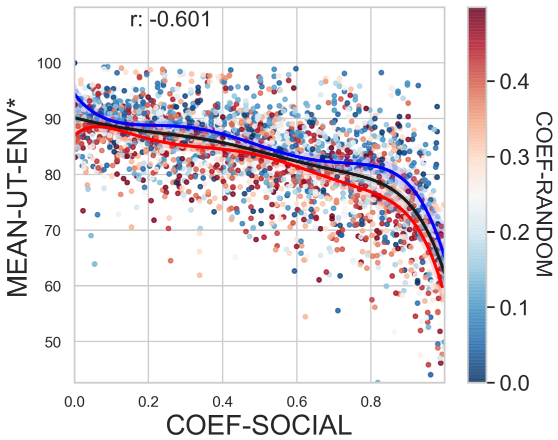


(a) Contribution of input parameters to mean selected utility (MEAN-UT-ENV*).

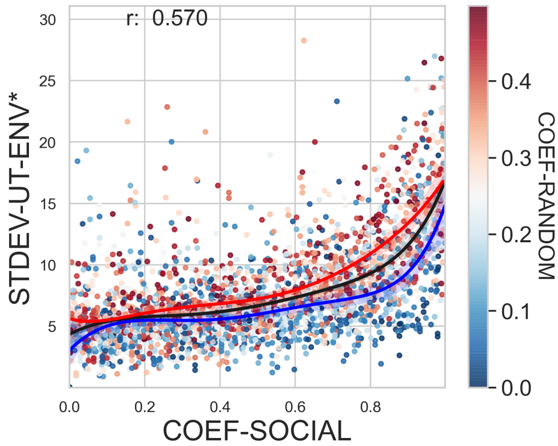


(b) Contribution of input parameters to standard deviation of selected utility (STDEV-UT-ENV*).

Figure 5.12: Sensitivity diagrams of emerging environmental determinism



(a) Variation in mean selected environment utility (MEAN-UT-ENV*)



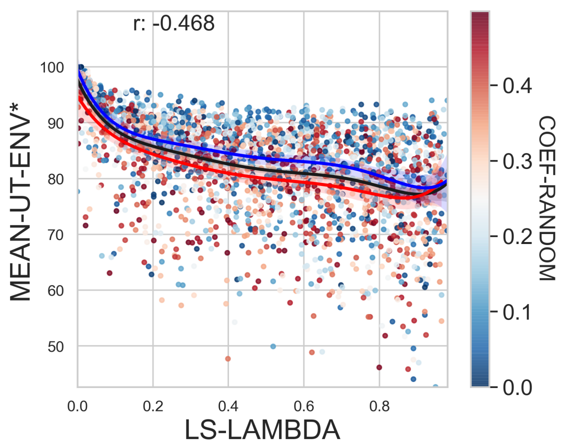
(b) Variation in standard deviation of selected environment utility (STDEV-UT-ENV*)

Figure 5.13: Variable interactions of social utility (COEF-SOCIAL) and share of random utility (COEF-RANDOM) influencing environmental determinism

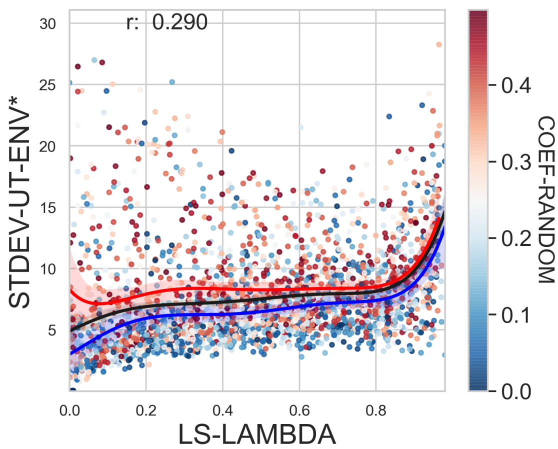
only in cases of high COEF-SOCIAL values (5.11c). COEF-SOCIAL has the dominating influence on both model outputs directly (Figure 5.12) and in linear interactions with other variables (Figure 5.13). An increase in COEF-SOCIAL leads to a decrease in MEAN-UT-ENV* (5.4.2) and an increase in STDEV-UT-ENV*. This implies that in societies with higher social organisation, the environmental conditions in residential locations are more variable and might be dominated by social values. It must be noted that the influence becomes truly significant only when more than 90% of the location's utility value (COEF-SOCIAL > 90) comes from social factors. With lower values other influences are still significant.

LS-LAMBDA has a significant effect on MEAN-UT-ENV* (5.4.1; Figures 5.14a and 5.15a). The positive influence on STDEV-UT-ENV* is smaller (Figures 5.12, 5.14b and 5.15b) as compared with the similar influence of COEF-SOCIAL and is most effective if COEF-SOCIAL is low (Fig 5.14b). A higher COEF-SOCIAL conversely with lower LS-LAMBDA forces agents to choose locations with lesser environmental utility. The influence of COEF-SOCIAL and LS-LAMBDA on environmental determinism differs in several ways and the difference is visible mostly with high values (COEF-SOCIAL > 90 or LS-LAMBDA > 0.9).

As for population clustering the measures of environmental determinism are robust to randomness in agents' choices (Fig. 5.13 5.14). These figures also show that randomness has more effect in heterogeneous environments and that homogeneous

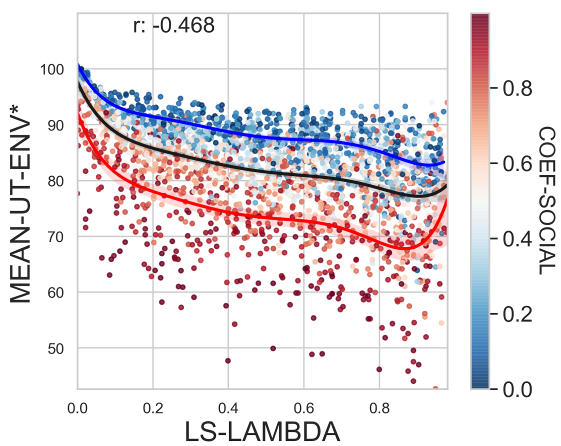


(a) Variation in mean selected environment utility (MEAN-UT-ENV*)

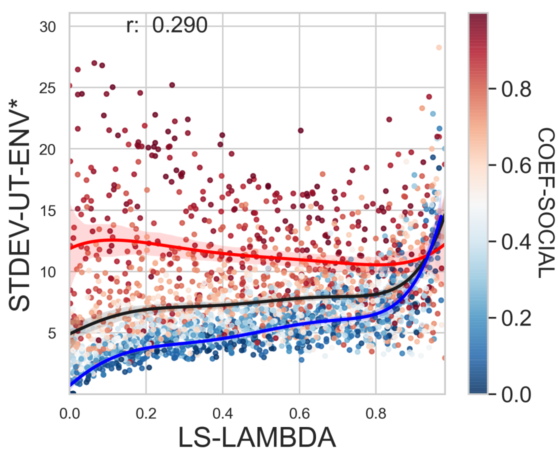


(b) Variation in standard deviation of selected environment utility (STDEV-UT-ENV*)

Figure 5.14: Variable interactions of spatial autocorrelation of environmental attractions (LS-LAMBDA) and share of random utility (COEF-RANDOM) influencing environmental determinism



(a) Variation in MEAN-UT-ENV*



(b) Variation in STDEV-UT-ENV*

Figure 5.15: Variable interactions of spatial autocorrelation of environmetnal attractions (LS-LAMBDA) and share of social utility (COEF-SOCIAL) influencing environmental determinism

environments conversely provide more stability.

5.5 Discussion and conclusion

Simulation modelling results revealed several effects of location choice strategies on the spatial and statistical characteristics of settlement systems. Multiple characteristics of settlement choice strategies can influence population clustering. Most intuitively, the high importance of social factors, or neighbourhood dependence, in a given socio-economic system has an effect on population clustering. The type of effect depends on the optimal (preferred) population density of a given society. If the population can disperse in the environment according to its preferred density there are no restricting effects leading towards spatial randomness. If the preferred density increases, for example as a result of more effective agricultural technology that increases land carrying capacity, the settlement starts to cluster together, resulting in large agglomerations.

Population pressure, which can be caused by a sudden population increase or a lack of resources, counterintuitively leads to another type of optimal spatial clustering pattern: small clusters of populations being separated from each other by perceived local neighbourhoods. The size of the neighbourhood in the model represents an area perceived as a locality and in empirical reality could represent a perception of community size. The most optimal placement is then clustering with maximum free available space around the clusters. In the theoretical case of the whole model area being perceived as the local community and complete information for the whole area, the most optimal placement with population pressure is clustering in the corners of the area (Page, 1999). We can assume that early agrarian societies were sedentary and had limited logistical mobility and communication distance. The model indicates that population pressure in such societies leads to optimal spatial structure of small population clusters.

Homogeneous environments have a tendency towards population clustering, and heterogeneity can prevent this in the event of low neighbourhood dependence, regardless of the preferred population density in the given society.

Different patterning of clustering has implications for both empirical and theoretical studies. Recently several studies have experimented with models that include exogenous population densities for site location prediction, for example based on the concept of ideal free distribution (Vernon et al., 2020). Our simulation exposes potential nonlinear spatial effects to spatial distribution patterns that need to be considered while incorporating population density into archaeological predictive models.

Results also reveal spatial conditions that may have allowed the historical development of population agglomerations, which could in turn have evolved in several cycles of adaptation. Technological and social innovation is considered to have been made possible by information exchange in a sufficiently large population requiring a certain density (Crema and Lake, 2015; Fogarty and Creanza, 2017) and sedentism. According to the model, pathways to the process then include two groups of spatial prerequisites. The first, a purely environmentally determined set of conditions applying to societies with low social organisation, includes an area with a sufficiently high carrying capacity and a homogeneous environment (5.4.1 and 5.4.5). The second involves the existence of population pressure with a sufficiently large neighbourhood (possibly caused by logistical mobility) to create population centres that start an innovation process (5.4.2 and 5.4.5). The original Oasis theory of the Neolithic Revolution proposed by Raphael Pumpelly in 1908 and subsequently re-formulated by V. Gordon Childe in 1940 has implicitly included both of these spatial conditions on different scales, with environmental pressure on a continental scale and homogeneous environments (oasis) on a regional scale.

Randomness in individual agent choices adds a tendency towards spatial randomness and lesser clustering. The spatial effects are quite marginal, indicating clustering to be a robust process that is not particularly dependent on individual and temporal variation and therefore should be well observable in empirical data.

The model results indicate that spatial clustering of the population is correlated with a decrease in environmental determinism. Homogeneous environments and social variables leading to clustering also result in lower environmental determinism. Breaking environmental determinism down into mean and standard deviation of environmental utility in agents' locations led to regularities in results. The results show how indirect interactions between individual agents lead to the emergence of higher-level patterns with regular outcomes. They also show that there is a good level of observability through empirical data on environmental conditions of locations. The results show that systems with a high level of spatial autocorrelation and a high level of social organisation behave differently, which provides the potential to distinguish between the effects of social structures and the spatial configuration of the perceived environment. For example, environmental heterogeneity seems to be a prerequisite for achieving predictive models with high mean environmental utility values (Figs. 5.14,5.15).

Similarly to spatial clustering, randomness in individual agents' choices decreases environmental determinism, but randomness in individual choices causes surprisingly modest levels of variation in model output. Environmental determinism variables, especially MEAN-UT-ENV*, are robust to randomness. Although spatial clustering in itself decreases environmental determinism it can provide an explanation of the robustness of environmental determinism. Population clusters can be considered as having a group agency formed as a result of spatial effects and interactions after adaptation to optimal space usage. Even in the event of low individual importance of the environment after aggregation of location choices including feedback from the existing population, agent clusters still end up in environmentally good places. Therefore populations still generate new patterns and follow principles of environmental determinism, even if individual agents have very low environmental priorities. Their behaviour is a lot less stochastic than that of individual agents. In real-world examples, group agencies would probably have an even larger effect because of various forms of information exchange between members of the population.

The formation of group agencies can explain several aspects regarding environmental determinism and archaeology. It provides a possible causal reason for the predictive success of locational models in archaeology, but also disconnects the meaning of model results from individual perception and choices. Even in the event of limited individual knowledge, social priorities and bounded rationality, group knowledge can lead to the selection of the best environmental locations through the temporal accumulation of interactions within existing populations. We can observe an agent group as having a wider range of spatial information even if the information is not explicitly exchanged by individual agents but is stored in the settlement system through actions.

Empirical observability because of robust processes therefore gives us information about group behaviours but does not necessarily allow effective reasoning about the causality of individual choices. Explaining and predicting settlement choice through individual experience or cognition (Verhagen and Whitley, 2012, see discussion within) with concepts like environmental affordances (Gibson, 1979; for a discussion on more recent approaches see Kempf, 2020) can potentially work only in the case of small human groups with a low level of organisation. It may possibly be used to describe specific modes of archaeological sites, e.g. highly specialised hunting camps. For more complex societies, environmentally deterministic patterns are created through group agency formed by an accumulation of spatial interaction between agents of the population, and in real systems they are probably strengthened by forms of information exchange. It is also possible that residential location choice is based on cultural best practices that have evolved over time and the principles of effective adaptation of residential choice strategy are not individually reflected within a given society. The experiments presented in this paper illustrate an example of a system in which micro-level individual processes and their variation and diversity have a relatively small impact on a system when observed on a meso scale. The whole system is more dependent on its dominant socio-economic strategy. For further work, in addition to describing the theoretical implications of model assumptions, the model framework should also be used to quantitatively explore a specific settlement system of the past. This would allow the model to be calibrated to explore the variable extent and also to explore real variable extents and the effects that are seen in real cases. It would also enable us to find the optimal scale and granularity of observation to explore large-scale processes through settlement patterns. A potential large-scale process to be explored based on empirical data would be the adaptive process with potentially multiple pathways towards agglomeration. This would also require methodological research on the use of empirical data. Attempting to explain processes through population clustering is already an established practice and it has been proposed that archaeological locational models could be used as a potential data source (Chapter 1). These sources could be used to calibrate this model to study a real-life system. The most effective means of ABM calibration need to be explored, either through summary variables, like spatial autocorrelation of the environment, or directly with predictive models. This would open up possibilities to study other spatial factors like neighbourhood and access ranges, the overall explanation of feedback loops in settlement system formation, and more generally long-term settlement processes.

Conclusion

The purpose of this thesis was the development and exploration of a conceptual framework of settlement pattern formation which links micro-level choices of small population units with emerging patterns on the meso level to contribute to the evolving theory of settlement. We decided to adopt this perspective because of its potential to open up new ways of studying empirical archaeological data. Significant parts of this thesis study how the settlement system formation process can be explored through archaeological locational data and models.

To this end, a spatial complex systems approach was adopted and the tools associated with it were explored. A theoretical model of settlement system formation was formulated (Chapter 1) through systems mapping built upon concepts of space, information (and perception), choice (cost-benefit), feedbacks and cross-scale feedback loops. The mapping enabled the selection of abstract entities to give a meaningful perspective to empirical archaeological material with a principle of parsimony in mind. Indexing existing relations between system entities based on archaeological and socio-ecological systems theory resulted in a dynamic systems model which exposed relations between micro- and meso-scale interactions and empirical data and served as the theoretical backbone of the research design of the thesis.

The model described the settlement system as resulting from individual residential choices made based on information from the environmental and social spaces. As a result of these choices, both social space and environment are modified, leading to a dynamic process. As indicated by simulations, the process exhibits the properties of a typical socio-ecological system: it soon achieves a relatively stable steady state but can switch between states as a result of disturbances in external conditions.

The subsequent chapters of the thesis focused on an exploration of different aspects of the model, mostly selected information flows and feedbacks. Two of the chapters developed a case study based on the Stone Age in Estonia and compared hunter-fisher-gatherer and early agrarian settlement systems using statistical (Chapter 2) and spatial (Chapter 3) models. The final two chapters were theoretical agent-based simulations: one explored central place foraging within the context of the proposed spatial settlement system formation model and the other was aimed at building settlement pattern theory using assumptions developed in the first chapter. These chapters served both as a validation of the usefulness of the conceptual model and also as a means of addressing the questions that arose from the goals of the thesis.

5.5.1 Key results and methodological contributions

Conceptualising the system started from the point of view of individual residential choices, which is often a typical approach in humanist and archaeological literature. The theory of location choice, if mapped as part of a complex adaptive system, exposed questions of emergence and agency and opened up new ways of structuring empirical data and theoretical knowledge. Because of the diversity of the environments and societies under study it was useful to divide possible influences into two abstract classes by method of access: local (through logistic mobility) or social (provided by others both directly and through social organisation). Based on this distinction we were able to construct concepts of environmental and social attraction spaces reflecting how people in the given society perceived space. We argued that archaeological inductive models based on environmental variables reflect the environmental attraction space but also include influences from the social attraction space which reduce environmental model performance. In Chapter 3 we proposed a way to use existing archaeological and environmental data to start isolating environmental factors from socio-cultural ones reinterpreting currently used methods.

Chapters 2 and 3 empirically proved the existence of the relation between environment and location choice and showed that environmental preferences regarding location differed between population groups. Based on statistical data it was possible to draw general conclusions on the subsistence system of the societies concerned. For example the significant similarity between the residential choice principles of hunter-fisher-gatherer Narva and Comb Ware stage sites was shown. The study also quantitatively exposed their difference from early agrarian Corded Ware settlement, where settlement choice was mostly determined by soil type. Although these results had been generally anticipated based on archaeological reasoning and archaeologists' experience, the addition of a spatial dimension in Chapter 3 as an environmental effect model (reflecting environmental attraction space) offered several new insights. It explicitly showed the areas considered suitable for early agrarian societies in comparison to hunter-fisher-gatherer groups, indicating that agrarian Corded Ware society had significantly expanded their economic and residential niche. Hunter-fisher-gatherers were confined to the vicinity of water bodies, while agrarian society was more dependent on soils, which have a different spatial configuration in the landscape. This spatial difference made possible the probable tolerated immigration and co-existence for about a millennium in the region. It also illustrates the significant competitive advantage of agrarian societies over hunter-fisher-gatherers. By migrating to larger areas, some of which may have been only temporarily abandoned by hunter-fisher-gatherers, they expanded and because of sedentism permanently occupied new lands. The study raised new research questions about spatial competition in Estonian territory as certain regions on the shorelines of water bodies were suitable for both agrarian societies and hunter-fisher-gatherers.

The study opened up new theoretical insights that led to new ways of interpreting environmental inductive models in archaeology. Without exception, the MaxEnt-based environmental effect models for agrarian groups all offered a worse predictive performance in comparison with hunter-fisher-gatherer models. We explored this as a systemic effect that could be explained through the lower environmental determinism of individual location choices. Based on the conceptual model we explained the lower determinism to be the result of either the unobservable social attraction space or the spatial configuration of the physical environment. The methodological literature contains several systemic hypotheses to explain model predictive power.

Agent-based simulation experiments (Chapter 4 and 5) were conducted to test the hypotheses of possible factors reducing environmental determinism:

- higher mobility
- level of social organisation
- spatial homogeneity of the environment

The factors "level of social organisation" and "spatial homogeneity of the environment" were found to have a similar effect. The simulation results statistically strengthened the hypothesis that Corded Ware stage culture was not more socially organised but that socio-technological means of agriculture had changed the perception of the world to a much more homogeneous form. Because simulation models were not calibrated to specific conditions, the results are far from conclusive, but they also correspond to knowledge of Corded Ware stage in Estonian territory. Current research provides no indications of higher social complexity in comparison with the Comb Ware stage population.

In addition to explorations of empirical locational data, ABM simulations resulted in a number of theoretical insights into the conceptual model. In Chapter 4 an existing central place foraging model was embedded into the proposed framework to explore the impact of resource depletion-based mobility on settlement system formation. The simulation study illustrated the emergence of a fast dynamic feedback loop between environment modification and location choice. Resource depletion mechanisms made the perceived environment very dynamic and also added a dispersal force to the environmental structure, making population clustering and the resulting development of social complexity impossible. The model illustrates a very fast depletion- and mobility-based feedback loop in human-environment interactions, while later societies produced much slower processes which might result overall in stronger effects on the environment (see Chapter 1).

The final chapter of the thesis provided a spatial agent-based model of settlement system formation that was developed to explore the feedback loop between social influences and residential location choice and disentangle the complex relations between social and environmental influences. The study indicated the nonlinear spatial effect that expected population density in a society (due to either carrying capacity or cultural reasons) can have on the system. Of the three different phases – population pressure, environment with expected density, and agglomeration –, only the middle one leads to random spatial structures. Population pressure was found to lead to small population clusters and agglomeration to the emergence of large monocentric forms. The model also indicated the existence of environmental configuration effects (spatial autocorrelation) on population clustering. It identified initial conditions with a low level of social organisation and a homogeneous environment that could open a pathway towards population agglomeration in early human history.

The influence of the environment on agents' choices was found to be unexpectedly robust. Even in simulations with high rates of social organisation and individual randomness, agents moved to environmentally attractive places. The experiment showed that predictive archaeological models are effective despite social influences and randomness introduced into individual choices. This can be explained by indirect spatial interactions in the model which lead towards two potential pathways. First, if the importance of social factors is low, agents select the best places in the environment, leading to equally high environmental attraction of all agents' residences. Second, if high priority is placed on social influences, groups form but then slowly move to the most optimal places. In this case there is a strong inequality between the environmental attractiveness of individual residences, but the group overall is still in the best possible place. The process illustrates agent clustering and the resulting formation of a group agency that starts operating on a different level. The spatial adaptation process is environmentally deterministic despite significant randomness in individual perceptions of the agents that form the group. It must also be noted that in the current model we only applied indirect attractions to the population in general; we did not include information flows between individuals, which would significantly strengthen the effects of group agency. This effect can be considered as a spatial version of a social emergence process where individuals are not directly aware of the systemic effect of their actions, which are free from individual perspective but form a relatively deterministic system.

The result explains the detachment of individual perceptions from the residential choice process, which emerges on a higher level and is therefore robust to individual-level diversity. We therefore argue that individual experience or cognition-based explanations (e.g. using the traditional concept of affordances) for residential choice can work only in exceptional cases where the populations are very small or social interactions sparse.

The conceptual model based on the complex systems framework provided a solid structure both for guiding research by designing modelling experiments and for interpreting their results. Since it is a complex adaptive system in itself, this implies that settlement patterns must be explored as whole systems, taking into consideration all the main components of these systems. Possible causal questions cannot be explained using just one facet of the whole. Several problems arising in the research process could therefore be turned into research hypotheses because of the explicit framing of the conceptual model. As an example presented above, questions of differing empirical model performance were explored through ABM simulation. As well as addressing direct hypotheses, ABM proved to be useful for developing theory and offering new explanations for the general relations between micro- and macro-level processes.

Another significant benefit of the complex adaptive systems framework is the transferability of the models and the formal language that can link several research fields. This made it possible to use concepts from the socio-ecological systems modelling paradigm and bridge terms like ecosystem services, which provide very useful abstractions for studies of the past. Similarly, archaeological modelling for long-term processes can also potentially be included in other fields. The use of explicit formal language can bridge the gaps caused by subtleties of terminology and meaning.

5.5.2 Continuing this work

The main purpose of the thesis has been to develop a new way to approach settlement systems. It was written to introduce new ideas, mostly from geography and complexity science, that can serve as a starting point for tackling new questions in archaeology and other fields of humanities and historical sciences. Therefore the research can be continued on several levels. Below I have described some of my ideas for possible future advances based on my experience of working with the complex systems approach in a team together with archaeologists, historians, geographers and computer scientists.

The empirical case studies presented (Chapter 2 and Chapter 3) raised the question of spatial relations between hunter-fisher-gatherer groups and early agrarian populations. This issue can be further studied based on the proposed framework. It did not fit into the format of this thesis because several further steps needed to be accomplished first. These steps include collecting new empirical data, developing ways to directly use empirical data in ABMs and studying how to model micro-level processes of spatial competition.

The development of direct connections between empirical archaeological data and agent-based simulation models could be the most significant further methodological advancement. In this study, spatial and statistical analyses were used to isolate environmental factors from social ones based on principles of the proposed conceptual framework. At the same time, agent-based models were used to explore both empirical and theoretical hypotheses through theory building based on qualitative knowledge. A direct empirical connection by means of calibration or quantitative comparison of certain measures would be a step forward. This would allow us to conduct simulation studies of real-life settlement systems to describe their inner mechanics and isolate different mechanisms. The calibration of ABMs to regression models is currently a developing methodology but the practice still needs to be introduced to archaeology.

Empirically calibrated ABMs could be used to comparatively explore the residential choice in specific settlement systems. They could be used to explore spatial competition as proposed for the case of the Estonian Stone Age but also to explore different populations that lived during different time periods and in different environments. The proposed systemic framework allows a wide variety of questions to be asked about settlement systems. For example we could study features of migrating societies that bring their subsistence and culture with them: do they create different settlement systems compared to locally evolved systems?

In this thesis only some of the feedbacks within the settlement system formation model were explored. To achieve a more comprehensive understanding of settlement systems, studies need to be conducted to explore all the other loops in the system, both theoretically and based on empirical case studies. Conceptualising relations between population and land use can open up new ways of approaching human-environment interactions, especially if backed by off-site archaeological data. Adding micro-level land-use mechanisms to the current conceptual model would make it possible to include both human impact on the environment and vice versa within one system. These interactions could then be explored within our model through a feedback loop between aggregated location choices and environmental modifications. Potential research topics include relations between socio-ecological systems and spatial settlement patterns and general studies of human-environment relations focusing on specific concepts such as Stone Age deforestation and its relation to settlement. Multiple pathways for the emergence of population agglomeration and its role in Neolithic revolution and urbanisation could also be explored.

Discussions with archaeologists, geographers, computer scientists and historians contributed to the writing of this thesis. These collaborations provided very interesting insights into the scientific benefits of complex systems approaches in general. The first benefit was interdisciplinarity, which complex systems approaches universally impose but also help to effectively communicate. A general systemic understanding of various mechanisms and the emergent processes is shared among different research fields. Although most researchers are not willing to delve into the mathematics involved in complex systems approaches, the typically used tools provide relatively intuitive visualisation, offering a quick overview of ways of thinking about the phenomena under exploration. For example, showing a running simulation of settlement system formation can very quickly lead to discussions about relevant systems mechanics and raise research questions.

Another helpful tool for interdisciplinary collaboration proved to be systems mapping, in which different entities can be structured and linked to each other. In the current study we created systems maps (Chapter 1) in which entities can be spaces, rulesets and populations that can be linked through information flows and feedbacks. Systems mapping is currently underused in archaeology and humanities, but it is a worthwhile approach that can be used to specify several entity and linkage types as a means of clarifying the relevant mechanics of systems under study.

Complex systems approaches have been established in both geography and archaeology for more than two decades now but have been so far neglected in history. Based on my experience I consider the cause of this to be the essentially different goals of narrative and systemic thinking. The narrative contingency of historical processes is an effective way to explain the past and in most cases provides best results for public communication. At the same time there are many recurrent topics in historical studies which have inspired a great deal of effort but which I believe are not solvable using narrative logic. These include "chicken and egg" problems, which are paradoxical as narrative processes but are easily explainable with systemic thinking. Examples of such problems include theories as to why the Roman Empire collapsed or the reasons behind the emergence of heresy and inquisition: was it because of the ambitions for power of the church or grass-root level development of new ideas and followingthe political activism of dissidents? Although individual narratives enrich our knowledge of human experience, explanations in these cases require a systemic understanding of larger-level processes. Similarly, from social sciences we know that the whole is more than the sum of its parts, meaning that in many cases individual stories can come together to create a counterintuitive social process.

The distinction between narrative and systemic logic is also evident in archaeology, where simulations are typically created as individually deterministic stories of agents which cannot be used for robustness testing. While the system involves human choice, we have to deal with limited information, unknown factors, exogenous effects and pure randomness arising from within the complexity of human cognition. All of this has to be taken into account when exploring a system. In the case of settlement pattern formation we showed that the system is very robust: even if there are high levels of individual stochasticity the behaviour at societal level (group agency) is fairly deterministic. When creating model scenarios this robustness needs to be closely studied.

Disciplines involving human agency have long given rise to many theoretical studies communicated as grand narratives, e.g. ekistics (settlement studies), as coined by Doxiades, which provided inspiration and theoretical background for the systems mapping in this thesis. Complex systems approaches and particularly the use of ABMs provide avenues for in-depth explorations of such theories, which can be combined to explain specific empirical phenomena. All in all these approaches offer an excellent opportunity to build a solid foundation of knowledge about individual perspectives and social processes in both the past and the future.

Appendix A

Stone Age settlement sites in Estonia

* Column 1 – site location number. Locations which were inhabited during several periods have the same number while appearing number of rows corresponding to number of habitation phases.

* Column 1 – period number, the field is filled if the location was inhabited during several periods and is used to distinguish between the periods.

* X, Y – the coordinates of the estimated center of the site in L-EST97 coordinate system (EPSG:3301).

* SITE NAME – name given to the site

* STONE AGE STAGE – the name of the Stone Age stage where the site belongs to. If a location was inhabited during several periods, a separate record is created for each of the habitation phases.

A.1 Pre-pottery Mesolithic sites

		X	Y	SITE NAME	REFERENCES
1		6475587	539466	Pulli	L. Jaanits and K. Jaanits (1975)
2	1	6594258	643993	Kunda Lammasmägi	C. Grewingk (1887) and Indreko (1948b)
3	1	6478700	688748	Akali	L. Jaanits (1955) and Lembit Jaanits et al. (1982)
9		6530238	396949	Kõpu II	L.Kriiska Lõugas et al. (1996)
10	1	6588896	739099	Narva-Joaorg	Л. Янитс (1966)
12		6602195	601481	Vihasoo I	Aivar Kriiska (1996)
13		6602498	601126	Vihasoo II	Aivar Kriiska (1996)
14		6551725	492892	Valgeristi I	A. Kriiska (2001b)

15		6458488	540074	Metsaääre I	A. Kriiska (2001a)
16		6458315	540316	Metsaääre II	A. Kriiska (2001a)
17		6587738	528300	Liikva I	unpublished
18		6587206	523679	Liikva II	unpublished
19		6587420	523622	Liikva III	unpublished
20		6488965	404713	Võhma I	A. Kriiska (1998)
22		6487269	404531	Võhma II	A. Kriiska (1998)
23		6486928	404388	Võhma III	A. Kriiska (1998)
24		6489519	405881	Võhma IV	A. Kriiska (1998)
25		6489123	405777	Võhma V	A. Kriiska (1998)
26		6489881	405811	Võhma VI	A. Kriiska (1998)
27		6489818	405628	Võhma VII	A. Kriiska (1998)
28		6492210	407598	Pahapilli I	A. Kriiska (1998)
29		6492126	407603	Pahapilli II	A. Kriiska (1998)
30		6530549	397091	Kõpu III	L.Kriiska Lõugas et al. (1996)
31		6530753	397191	Kõpu IV/V	L.Kriiska Lõugas et al. (1996)
32		6530891	397264	Kõpu VI	L.Kriiska Lõugas et al. (1996)
33		6531014	397264	Kõpu VII/VIII	Kiristaja et al. (1998)
34		6531314	397653	Kõpu IX	L.Kriiska Lõugas et al. (1996)
36		6531821	396097	Kõpu XVII	Kiristaja et al. (1998)
37		6407314	455192	Ruhnu I	A. Kriiska and Ü. Tamla (1998); A. Kriiska and Saluäär (2000a)
38	1	6407664	455335	Ruhnu II	A. Kriiska and Saluäär (2000a)
39		6407844	455780	Ruhnu III	A. Kriiska and Saluäär (2000a)
40	1	6406579	456063	Ruhnu IV	A. Kriiska and Saluäär (2000a)
41		6406747	455477	Ruhnu VI	A. Kriiska and Saluäär (2000a)
42		6494208	578009	Lepakose	Янитс К. (1975)
43		6407852	455457	Ruhnu V	A. Kriiska and Saluäär (2000a)
44		6494357	579407	Tamme	Lembit Jaanits et al. (1982)
45		6495036	579361	Maltsaare	unpublished
46		6496189	582258	Jälevere	K. Jaanits (1981)
47	1	6480655	621509	Siimusaare	L. Jaanits (1965)
48		6478272	618536	Leie I	Kiristaja et al. (1998); Aivar Kriiska, A. Haak, et al. (2003)
49		6479560	620791	Moksi	Indreko (1932)
50		6482078	620243	Lalsi I	Kiristaja et al. (1998); Aivar Kriiska, A. Haak, et al. (2003)
51		6482375	620087	Lalsi II	Kiristaja et al. (1998); Aivar Kriiska, A. Haak, et al. (2003)

52	1	6481455	621840	Kivisaare	A. Kriiska and Johanson (2003)
53		6492681	622558	Umbusi	Янитс К. (1977); K. Jaanits and Ilomets (1988)
54	1	6483984	637510	Valmaotsa II	A. Kriiska and Tvauri (2002)
55		6482747	637493	Valmaotsa I	A. Kriiska and Tvauri (2002)
56		6471027	661958	Ihaste	Kiristaja et al. (1998); Johanson and A. Kriiska (2007)
57		6470688	662081	Ihaste II	Johanson and A. Kriiska (2007)
58		6469949	534838	Sindi-Lodja I	A. Kriiska (2001a)
59		6470142	535085	Sindi-Lodja II	A. Kriiska (2001a)
61		6467729	644963	Keeri I	A. Kriiska and Tvauri (2002)
62		6467344	645009	Keeri II	A. Kriiska and Tvauri (2002)
63	1	6467926	644648	Keeri III	A. Kriiska and Tvauri (2002)
64		6467955	642366	Võsivere I	A. Kriiska and Tvauri (2002)
65		6467759	642283	Võsivere II	A. Kriiska and Tvauri (2002)
66		6466393	644250	Nurmeotsa	A. Kriiska and Tvauri (2002)
67		6440591	620261	Pikasilla I	Aivar Kriiska, A. Haak, et al. (2003)
68		6439918	621647	Pikasilla II	A. Kriiska and Tvauri (2002)
69		6441211	622486	Purtsi Voore	A. Kriiska and Tvauri (2002)
70		6495683	597349	Maalasti	A. Kriiska and Tvauri (2002)
71		6493346	632782	Jüriküla	A. Kriiska and Tvauri (2002)
72		6476595	615539	Oiu I	Aivar Kriiska, A. Haak, et al. (2003)
73		6476254	615428	Oiu II	Aivar Kriiska, A. Haak, et al. (2003)
74		6475286	614833	Oiu III	Aivar Kriiska, A. Haak, et al. (2003)
75		6475129	615678	Oiu Laine	A. Kriiska and Tvauri (2002)
76		6415152	676698	Tamula II	A. Kriiska and Tvauri (2002)
78		6491158	626453	Madisemägi	A. Kriiska and Tvauri (2002)
79		6592237	566411	Jägala Joa III	A. Kriiska, Rappu, et al. (2009)
80		6471310	386682	Paju	T. Tamla and K. Jaanits (1977);A. Kriiska (2007)
81		6483431	651422	Lammiku	A. Kriiska and Tvauri (2002)
82		6447054	617699	Sõõriknurme	Aivar Kriiska, A. Haak, et al. (2003)
83		6443772	620281	Karumäe	Aivar Kriiska, A. Haak, et al. (2003)
84		6474869	635118	Rekusaare	A. Kriiska and Tvauri (2002)

85		6595894	643406	Vahtra	Sander and A. Kriiska (2018)
86		6493619	629029	Liivaku	unpublished
87		6405300	638395	Karula	unpublished
88		6399671	647564	Ala-Konnu	unpublished
89		6477841	620311	Källisaare	unpublished
90		6477063	619681	Leie Lohu	unpublished
91		6478190	646579	Leetsi	unpublished
92		6475227	680676	Kavastu	Tvauri and Johanson (2006)
93		6593481	585644	Mölga II	A. Kriiska and Tvauri (2002)
94		6591864	576606	Valkla II	Vedru (2004)
95		6439870	616565	Leebiku I	Aivar Kriiska, A. Haak, et al. (2003)
96		6440450	616600	Leebiku II	Aivar Kriiska, A. Haak, et al. (2003)
98		6478650	618365	Leie II	Aivar Kriiska, A. Haak, et al. (2003)
99		6477695	618690	Leie III	Aivar Kriiska, A. Haak, et al. (2003)
100		6593121	581964	Tülivere	Konsa and Ots (2004)
101		6489175	633855	Altnurga	Konsa and Ots (2004)
102		6497190	637125	Kursi	Konsa and Ots (2004)
103		6486829	634757	Siniküla Kodasmäe I	Konsa and Ots (2004)
104		6487494	634826	Siniküla Vati I	Konsa and Ots (2004)
105	1	6487674	634480	Siniküla Vati II	Konsa and Ots (2004)
106	1	6500200	635175	Tammiku	A. Kriiska and Tvauri (2002)
107		6498555	638400	Tõrve	Konsa and Ots (2004)
108		6471196	646334	Rõhu III	Konsa and Ots (2004)
109		6433995	645640	Nüpli	Konsa and Ots (2004)
110		6500485	603540	Loopre	Aivar Kriiska, A. Haak, et al. (2003)
111		6496500	599045	Venevere	Aivar Kriiska, A. Haak, et al. (2003)
112		6497120	599335	Venevere Matsimärdi	Aivar Kriiska, A. Haak, et al. (2003)
113		6466858	638351	Mäeotsa	Konsa and Ots (2004)
114		6498825	615350	Väike-Kamari	Aivar Kriiska, A. Haak, et al. (2003)
115		6435415	621945	Soontaga I	Konsa and Ots (2004)
116		6496785	584705	Jälevere II	Aivar Kriiska, A. Haak, et al. (2003)

117		6452760	616875	Järveküla	Aivar Kriiska, A. Haak, et al. (2003)
118		6446625	616605	Marjamäe	Aivar Kriiska, A. Haak, et al. (2003)
119		6453135	610155	Pikru	Aivar Kriiska, A. Haak, et al. (2003)
120		6457315	612480	Sooviku	Aivar Kriiska, A. Haak, et al. (2003)
121		6595132	588619	Uuri-Saki	Vedru (1996)
122		6457065	613225	Säga	Aivar Kriiska, A. Haak, et al. (2003)
123		6593549	585438	Tooma-Hansu	Vedru (1996)
124		6444800	615645	Vooru	Aivar Kriiska, A. Haak, et al. (2003)
125		6464420	610715	Väluste	Aivar Kriiska, A. Haak, et al. (2003)
126		6514986	580662	Laupa	Konsa and Ots (2004)
127		6474313	608352	Tänassilma I	Aivar Kriiska, A. Haak, et al. (2003)
128		6474490	607935	Tänassilma II	Aivar Kriiska, A. Haak, et al. (2003)
129		6467665	604660	Vasara I	Aivar Kriiska, A. Haak, et al. (2003)
130		6467141	604720	Vasara II	Aivar Kriiska, A. Haak, et al. (2003)
131		6499420	566825	Lüüste I	Konsa and Ots (2004)
132		6500550	568695	Määra	Konsa and Ots (2004)
134		6492295	652410	Tabivere II	Konsa and Ots (2004)
135		6428883	620506	Jõgeveste	Aivar Kriiska, A. Haak, et al. (2003)
136		6440360	619445	Kiisa	Aivar Kriiska, A. Haak, et al. (2003)
137		6483742	619676	Lalsi III	Kiristaja et al. (1998); Aivar Kriiska, A. Haak, et al. (2003)
138		6485132	619387	Lalsi IV	Kiristaja et al. (1998); Aivar Kriiska, A. Haak, et al. (2003)
139		6478598	586786	Risti	Aivar Kriiska, A. Haak, et al. (2003); T. Jussila and A. Kriiska (2006)

140		6446775	616825	Maltsa Lohu	Aivar Kriiska, A. Haak, et al. (2003)
141		6471930	614239	Tuisu	Aivar Kriiska, A. Haak, et al. (2003)
142		6469874	593416	Viljandi ordulinnus	Aivar Kriiska, A. Haak, et al. (2003)
143		6591105	620905	Aaspere	Konsa and Ots (2005)
144		6448175	576050	Vana-Kariste Kuivsaapa	Konsa and Ots (2005)
145		6424465	611415	Koorküla I	Konsa and Ots (2005)
146		6422575	611015	Koorküla II	Konsa and Ots (2005)
147		6592433	566208	Jägala Jõesuu IIA	Konsa and Ots (2005); A. Kriiska, Rappu, et al. (2009)
148		6593757	585067	Aabrami	Vedru (1996)
149		6443250	587035	Pöögle	Konsa and Ots (2005)
150		6497108	636281	Kursi kiriku ak	Konsa and Ots (2005)
152		6494040	589030	Navesti	Konsa and Ots (2005)
153		6596132	643290	Aasa	Konsa and Ots (2005); Sander and A. Kriiska (2018)
154		6427091	612140	Patküla	unpublished
155		6591233	560650	Võerdla II	Konsa and Ots (2006)
156		6477215	385758	Kehila	Konsa and Ots (2006)
157		6592715	577213	Valkla-tagune II	Konsa and Ots (2006)
158		6493930	624970	Umbusi Soo	Konsa and Ots (2006)
159		6442111	622773	Pühaste	Konsa and Ots (2006)
160		6475049	625331	Vaibla Kaabe kenk	Konsa and Ots (2007)
161		6513003	646022	Kuremaa II	Konsa and Ots (2007)
162		6404729	703692	Kalatsova II	Konsa and Ots (2007)
163		6474454	627878	Verevi	Konsa and Ots (2007)
164		6591555	581143	Kuusalu IV	Konsa and Ots (2008)
165		6589790	574540	Kivisilla	Konsa and Ots (2008)
166		6405612	705848	Meremäe II	Konsa and Ots (2008)
167		6471598	661763	Jummisaare II	Konsa and Ots (2008)
168		6475681	540167	Aluste	Konsa and Ots (2008)
169		6592376	566336	Jägala Jõesuu III	A. Kriiska, Rappu, et al. (2009)
170		6486081	560958	Aesoo I	Konsa and Ots (2009)
171		6486010	560470	Aesoo IV	Konsa and Ots (2009)
172		6484216	552258	Päästäle	Konsa and Ots (2009)
173		6480373	545497	Randivälja	Konsa and Ots (2009)
174		6478237	543993	Taali Mardi	Konsa and Ots (2009)
175		6478682	544272	Taali Paikste	Konsa and Ots (2009)

176		6480343	656268	Maramaa	Konsa and Ots (2009)
177		6486587	634656	Siniküla I	Konsa and Ots (2009)
178		6486412	634956	Siniküla II	Konsa and Ots (2009)
179		6486596	634612	Siniküla Kodasmäe II	Konsa and Ots (2009)
180		6483250	637341	Valmaotsa Hendriku	Konsa and Ots (2009)
181		6421283	621848	Ransi (Metsaääre talu)	unpublished
182		6482250	531057	Kurena	Konsa and Ots (2010)
183		6387320	651824	Saru	unpublished
184		6484654	636858	Siniküla Mukdeni	Konsa and Ots (2010)
185		6472974	631512	Saare	Lõhmus and Ots (2011)
186		6479204	635923	Valmaotsa Sooküla I	Lõhmus and Ots (2011)
187		6478319	633764	Valmaotsa Sooküla II	Lõhmus and Ots (2011)
188	1	6390767	702858	Toodsi Liidva	Lõhmus and Ots (2011)
189		6527223	627522	Kärde II	Tõrv and Ots (2012)
190	1	6529027	624499	Tooma	Tõrv and Ots (2012)
191		6485724	637387	Laeva	Kiristaja et al. (1998)
192		6482919	637712	Valmaotsa Lubjaahju	unpublished
193		6502782	652464	Ehavere	Ots and Rammo (2013)
194		6504996	626990	Pudivere	Ots and Rammo (2013)
195		6466894	643045	Härjanurme	Ots and Rammo (2013)
196		6464003	642225	Külaaseme I	Ots and Rammo (2013)
197		6464006	642800	Külaaseme II	Ots and Rammo (2013)
198		6464098	643134	Meeri Tabuli	Ots and Rammo (2013)
199		6477834	630564	Palupõhja	Ots and Rammo (2013)
200		6465112	641871	Karijärve saar III	Ots and Rammo (2013)
201		6438849	649130	Otepää Kaarnasaare	Ots and Rammo (2013)
202		6435975	645300	Pühajärve Sõsarsaar	Ots and Rammo (2013)
203		6466799	644328	Keeri Pühapalu	Rammo et al. (2014)
204		6435290	645620	Pühajärve Kolga	Rammo et al. (2014)
205		6438659	621980	Purtsi II	Rammo et al. (2014)
206		6434916	621976	Soontaga II	Rammo et al. (2014)
207		6484990	552823	Päästäle Rõõmuselja	unpublished
208		6494381	551166	Mõrdama	Rammo et al. (2014)
209		6472732	639777	Rämsi I	unpublished
210		6472846	639066	Rämsi II	unpublished
211		6486692	561963	Aesoo III	unpublished
212		6485921	559845	Aesoo II	unpublished
213		6482352	637204	Valmaotsa Valmaotsa	unpublished
214		6442483	654474	Puugi	unpublished
215		6477502	543033	Urumarja	unpublished

216		6476109	621310	Vaibla II	Johanson, Lõhmus, et al. (2007)
217		6475921	621421	Vaibla I	Johanson, Lõhmus, et al. (2007)
218		6597347	643756	Hiietalu	Sander and A. Kriiska (2018)
219		6396090	690922	Tsiistre	Konsa (2003)
220		6441632	663247	Palutaja	unpublished
221		6403720	700207	Vastseliina linnus	unpublished
222		6433947	672370	Tilleoru Kantsimägi	unpublished
223		6386151	693113	Hino	A. Kriiska and Kihno (2006)
224		6386685	693372	Siksälä Kirikumägi	A. Kriiska and Kihno (2006)
225		6445387	582751	Kaubi Kuksi	unpublished
226		6482686	620249	Lalsi Ahjuoja	unpublished
227		6478389	621763	Meleski I	Aivar Kriiska, A. Haak, et al. (2003)
228		6478368	621593	Meleski II	unpublished
229		6478503	621576	Meleski III	unpublished
230		6479737	621840	Meleski IV	unpublished
231		6592280	566521	Jägala Joa IV	Tõrv and Ots (2012)
232	1	6441347	622174	Vooremägi	Veldi and Valk (2010)
233		6505110	663195	Pedassaare I	Konsa and Ots (2009)
234		6600775	605595	Võhma Tandemäe	Saluäär and V. ä. Lang (2000)
235		6414044	669846	Järvere	unpublished
236		6472246	639831	Teilma	unpublished
237		6590785	566653	Jägala Jõelähtme	Vedru (2002)
301	1	6592625	582237	Kuusalu Oduli	A. Kriiska and Tvauri (2002)
306		6434453	644970	Kloostrisaar	Ots and Rammo (2013)
308	1	6451657	589658	Kaarli	Rammo et al. (2014)
310	1	6465277	642680	Karijärve saar II	Ots and Rammo (2013)
312	1	6472085	661527	Jummissaare I	Konsa and Ots (2008)
314	1	6492745	630715	Palu I	A. Kriiska and Tvauri (2002)
315		6492984	630407	Palu II	A. Kriiska and Tvauri (2002)
319		6491989	631367	Kunila	unpublished
319		6504955	664970	Pedassaare II	Konsa and Ots (2010)
330		6595355	643245	Jaanimäe	Sander and A. Kriiska (2018)
331		6595740	643395	Järvepõhja I	Sander and A. Kriiska (2018)
332		6595570	643415	Järvepõhja II	Sander and A. Kriiska (2018)
334		6508818	517904	Kesu II	unpublished
335		6593340	643275	Kunda Rõõmu	Sander and A. Kriiska (2018)
336		6596350	643300	Miili	Sander and A. Kriiska (2018)
337		6597263	586068	Müürissepa	Vedru (1997)
339		6596258	585887	Sepa	A. Kriiska (2001b)

341		6596202	585263	Soorinna	Vedru (1997)
342		6593551	583849	Sõitme I	Vedru (1998)
344		6457468	388527	Koki	Konsa and Ots (2006)

A.2 Narva stage sites

		X	Y	SITE NAME	REFERENCES
2	3	6594258	643993	Kunda Lammasmägi	Sander and A. Kriiska (2015)
3	1	6478700	688748	Akali	L. Jaanits (1955)
5		6466349	422676	Kõnnu	L. Jaanits (1979)
6	1	6419057	684848	Kääpa	L. Jaanits (1955)
7	1	6530122	396945	Kõpu IA	A. Kriiska (1995a)
10	2	6588896	739099	Narva-Joaorg	L. Jaanits (1955)
35		6530589	396103	Kõpu XIV	Kiristaja et al. (1998)
38	2	6407664	455335	Ruhnu II	A. Kriiska and Saluäär (2000a)
40	2	6406579	456063	Ruhnu IV	A. Kriiska and Saluäär (2000a)
52	2	6481455	621840	Kivisaare	A. Kriiska and Johanson (2003)
60	1	6470435	535312	Sindi-Lodja III	A. Kriiska and L. Lõugas (2009)
238		6602569	601104	Vihasoo III	Aivar Kriiska (1996)
239		6592531	555802	Kroodi	L. Jaanits (1968)
240		6530531	396045	Kõpu XIII	Timo Jussila and Aivar Kriiska (2004)
241		6531214	397531	Kõpu XVI	Timo Jussila and Aivar Kriiska (2004)
242	1	6595404	734049	Riigiküla I	Гурина (1967)
243	1	6595572	733908	Riigiküla II	Гурина (1967)
244	1	6595243	734088	Riigiküla III	Гурина (1967)
245	1	6595124	734009	Riigiküla IV	A. Kriiska (1995b), A. Kriiska (1996)
246		6595091	733962	Riigiküla V	A. Kriiska, Miller, et al. (1999)
247		6595055	733900	Riigiküla VI	A. Kriiska, Miller, et al. (1999)
248		6594958	733851	Riigiküla VII	A. Kriiska, Miller, et al. (1999)
249		6594912	733811	Riigiküla VIII	A. Kriiska, Miller, et al. (1999)
250		6594697	733714	Riigiküla IX	A. Kriiska, Miller, et al. (1999)
251		6594627	733686	Riigiküla X	A. Kriiska, Miller, et al. (1999)
252		6594544	733637	Riigiküla XI	A. Kriiska, Miller, et al. (1999)
253		6594477	733595	Riigiküla XII	A. Kriiska, Miller, et al. (1999)
254		6594054	733484	Riigiküla XIII	unpublished
255		6593937	733375	Riigiküla XV	unpublished

256		6504737	664138	Pedassaare III	Konsa and Ots (2009)
281	1	6417994	680342	Villa II	A. Kriiska and Tvauri (2002)
285	1	6542222	682594	Rannapungerja I	Roio et al. (2016)
317	1	6531865	670601	Kalmaküla I	unpublished
318	1	6531987	670540	Kalmaküla II	Konsa and Ots (2009)
323	1	6519046	672520	Omedu Jõekääru	Roio et al. (2016)
324	1	6519619	672329	Omedu Jõesuu	Roio et al. (2016)
325	2	6519301	672927	Omedu paadisadam	Roio et al. (2016)
326	2	6542115	682668	Rannapungerja II	Roio et al. (2016)
327	1	6542216	683005	Rannapungerja III	Roio et al. (2016)

A.3 Comb ware stage sites

		X	Y	SITE NAME	REFERENCES
2	2	6594258	643993	Kunda Lammasmägi	Indreko (1948b)
3	1	6478700	688748	Akali	L. Jaanits (1955)
4	1	6479341	686642	Kullamägi	L. Jaanits (1955)
6	2	6419057	684848	Kääpa	L. Jaanits (1968)
8		6530122	396945	Kõpu IB	Timo Jussila and Aivar Kriiska (2004)
10	3	6588896	739099	Narva-Joaorg	Л. Ю. Янитс (1959b)
11	1	6459163	396666	Naakamägi	Л. Ю. Янитс (1959b)
52	3	6481455	621840	Kivisaare	A. Kriiska and Johanson (2003)
60	2	6470435	535312	Sindi-Lodja III	A. Kriiska and L. Lõugas (2009)
190	2	6529027	624499	Tooma	Tõrv and Ots (2012)
232	2	6441276	622116	Vooremägi	Veldi and Valk (2010)
242	2	6595404	734049	Riigiküla I	Гурина (1967)
243	2	6595572	733908	Riigiküla II	Гурина (1967)
244	2	6595243	734088	Riigiküla III	Гурина (1967)
245	2	6595124	734009	Riigiküla IV	A. Kriiska (1995b), 1996
257	1	6597383	730937	Narva-Jõesuu I	A. Kriiska and K. Nordqvist (2010)
258		6597288	730916	Kudruküla	Янитс (1980)
259		6467607	384020	Loona	Л. Ю. Янитс (1959b)
260		6484454	383785	Undva	L. Jaanits (1955)
261		6531256	397860	Kõpu X	Timo Jussila and Aivar Kriiska (2004)

262		6529523	397395	Kõpu XI	Timo Jussila and Aivar Kriiska (2004)
263		6533205	397914	Kõpu XII	Timo Jussila and Aivar Kriiska (2004)
264		6529488	397787	Kõpu XV	Timo Jussila and Aivar Kriiska (2004)
265		6437624	711625	Laossina	A. Kriiska and Tvauri (2002)
266		6433984	714578	Väike-Rõsna	Kiristaja (2009)
267		6431850	714035	Pedäjäsaar	Kiristaja (2009)
268		6602829	598180	Rahunurme	A. Kriiska and Tvauri (2002)
269		6592640	565809	Jägala Jõesuu I	Spreckelsen (1925)
270	1	6497751	475290	Kaseküla	A. Kriiska, L. Lõugas, and Saluäär (1998)
271		6477619	518571	Malda	A. Kriiska and Saluäär (2000b)
272		6477274	518384	Lemmetsa II	A. Kriiska and Saluäär (2000b)
273	1	6475900	518861	Lemmetsa I	A. Kriiska and Saluäär (2000b)
274		6471260	535546	Jõekalda	A. Kriiska and L. Lõugas (2009)
275		6458128	540524	Metsaääre III	A. Kriiska (2001a)
276		6419216	610939	Valgjärv	Selirand (1986)
277	1	6468836	614734	Valma	Л. Ю. Янитс (1959a)
278	1	6415426	676915	Tamula I	Indreko (1948a)
279		6415178	674797	Vagula	Kiristaja et al. (1998)
280	1	6418068	680665	Villa I	Л. Ю. Янитс (1959b)
281	2	6417994	680342	Villa II	A. Kriiska and Tvauri (2002)
282		6442330	621779	Kalasaare	unpublished
283	1	6588628	542279	Tallinna Vabaduse väljak	Kadakas et al. (2010)
284		6592661	566088	Jägala Jõesuu V	Khrustaleva et al. (2020)
285	2	6542222	682594	Rannapungerja I	Roio et al. (2016)
286	1	6597310	730821	Narva Jõesuu IIA	Aivar Kriiska and Kerkko Nordqvist (2012)
287	1	6597220	730725	Narva Jõesuu IIB	Aivar Kriiska, D. V. Gerasimov, et al. (2016)
288	1	6597154	730700	Narva Jõesuu III	Aivar Kriiska, D. V. Gerasimov, et al. (2016)
289	1	6597382	731006	Narva Jõesuu IV	Aivar Kriiska, D. V. Gerasimov, et al. (2016)
317	2	6531865	670601	Kalmaküla I	Konsa and Ots (2009)
318	2	6531987	670540	Kalmaküla II	Konsa and Ots (2009)
320		6602883	600972	Vihasoo IV	Aivar Kriiska (1996)
321	1	6510413	514989	Ojapere II	unpublished

322	1	6510056	515507	Ojapere III	unpublished
323	2	6519092	672388	Omedu Jõekääru	Roio et al. (2016)
324	2	6519619	672329	Omedu Jõesuu	Roio et al. (2016)
325	1	6519301	672927	Omedu paadisadam	Roio et al. (2016)
326	3	6542115	682668	Rannapungerja II	Roio et al. (2016)
327	2	6542216	683005	Rannapungerja III	Roio et al. (2016)
328		6545844	697220	Alajõe I	Roio et al. (2016)
329		6537583	675854	Avijõe suue	Roio et al. (2016)

A.4 Corded ware stage sites

		X	Y	SITE NAME	REFERENCES
3	1	6478700	688748	Akali	L. Jaanits (1955)
4	2	6479341	686642	Kullamägi	Л. Ю. Янитс (1959b)
6	3	6419057	684848	Kääpa	L. Jaanits (1966)
7	2	6530122	396945	Kõpu IA	A. Kriiska (2004)
10	4	6588896	739099	Narva-Joaorg	L. Jaanits (1966)
11	2	6459163	396666	Naakamägi	L. Jaanits (1966)
21		6488965	404713	Võhma I	A. Kriiska (1998)
47	2	6480655	621509	Siimusaare	Л. Ю. Янитс (1959b)
52	4	6481455	621840	Kivisaare	A. Kriiska and Johanson (2003)
54	2	6483984	637510	Valmaotsa II	A. Kriiska and Tvauri (2002)
60	3	6470435	535312	Sindi-Lodja III	A. Kriiska and Tvauri (2002)
63	2	6467926	644648	Keeri III	Johanson, Kadakas, et al. (2014)
77		6544856	690988	Uusküla	Roio et al. (2016)
97		6593762	734983	Vasa	A. Kriiska, K. Nordqvist, Khrustaleva, et al. (2019)
105	2	6487674	634480	Siniküla Vati II	Konsa and Ots (2004)
106	2	6500200	635175	Tammiku	A. Kriiska and Tvauri (2002)
133		6591357	699549	Toila	unpublished
151		6515566	668171	Küti Viidike	unpublished
188	2	6390767	702858	Toodsi Liidva	Lõhmus and Ots (2011)
190	3	6529027	624499	Tooma	Tõrv and Ots (2012)
242	3	6595404	734049	Riigiküla I	Гурина (1967)
243	3	6595572	733908	Riigiküla II	Гурина (1967)
245	3	6595124	734009	Riigiküla IV	A. Kriiska (1995b), 1996
257	2	6597383	730937	Narva-Jõesuu I	A. Kriiska and K. Nordqvist (2010)

270	2	6497751	475290	Kaseküla	A. Kriiska, L. Lõugas, and Saluäär (1998)
273	2	6475900	518861	Lemmetsa I	A. Kriiska and Saluäär (2000b)
277	2	6468836	614734	Valma	Л. Ю. Янитс (1959a)
278	2	6415426	676915	Tamula I	L. Jaanits (1966)
280	2	6418068	680665	Villa I	Л. Ю. Янитс (1959b)
283	2	6588628	542279	Tallinna Vabaduse väljak	Kadakas et al. (2010)
286	2	6597310	730821	Narva Jõesuu IIA	Aivar Kriiska and Kerkko Nordqvist (2012)
287	2	6597227	730725	Narva Jõesuu IIB	A. Kriiska, K. Nordqvist, D. Gerasimov, et al. (2015)
288	2	6597154	730700	Narva Jõesuu III	A. Kriiska, K. Nordqvist, D. Gerasimov, et al. (2015)
289	2	6597382	731006	Narva- Jõesuu IV	A. Kriiska, K. Nordqvist, D. Gerasimov, et al. (2015)
290		6474562	442589	Asva	Indreko (1939); L. Jaanits (1966)
291		6486400	436732	Kuninguste	V. Lõugas (1974)
292		6478380	587893	Madi	A. Kriiska and Tvauri (2002)
293		6545463	680732	Lemmaku	A. Kriiska and Tvauri (2002)
294		6561845	693306	Jõuga	V. Lõugas and Selirand (1989)
295		6594023	733388	Riigiküla XIV	Aivar Kriiska (2000)
296		6600650	606135	Kadrina Võhma I	Ots, Allmäe, et al. (2003)
297		6600729	607148	Ilumäe II	V. Lang and Konsa (1998)
298		6600997	606733	Ilumäe IV	V. Lang and Konsa (1998)
299		6597198	586530	Muuksi I	Vedru (1996)
300		6597252	585969	Muuksi II	Vedru (1996)
301	2	6592625	582237	Kuusalu Oduli	Vedru (1999)
302		6591561	560910	Võerdla I	V. Lõugas and Selirand (1989)
303		6593052	562209	Rebala	V. Lang, Ilves, et al. (2001)
304		6586362	553872	Lagedi	V. Lang (1996)
305		6591338	551268	Iru	Vassar (1939); V. Lang (1996)
307		6434453	644970	Kloostrisaar	Johanson, Kadakas, et al. (2014)
308	2	6451657	589658	Kaarli	unpublished
309		6433818	644783	Pühajärve Lepassaar	Johanson, Kadakas, et al. (2014)
310	2	6465277	642680	Karijärve saar II	Ots and Rammo (2013)
311		6588216	542263	Tallinna Mülleri Põld	Bernotas et al. (2017)
312	2	6472085	661527	Jummissaare I	Konsa and Ots (2008)
313		6407063	456188	Ruhnu Valgi	Konsa and Ots (2009)
314	2	6492745	630715	Palu I	unpublished
316		6469842	662660	Veibri	A. Kriiska and Tvauri (2002)

321	2	6510413	514989	Ojapere II	unpublished
322	2	6510056	515507	Ojapere III	unpublished
323	3	6519046	672520	Omedu Jõekääru	Roio et al. (2016)
326	4	6542115	682668	Rannapungerja II	Roio et al. (2016)
333		6470303	665713	Kabina II	Konsa and Ots (2007)
338		6457413	582218	Sammaste	unpublished
340		6587377	549331	Soodevahe	Paavel et al. (2016)
343		6519938	512153	Teenuse IX	unpublished

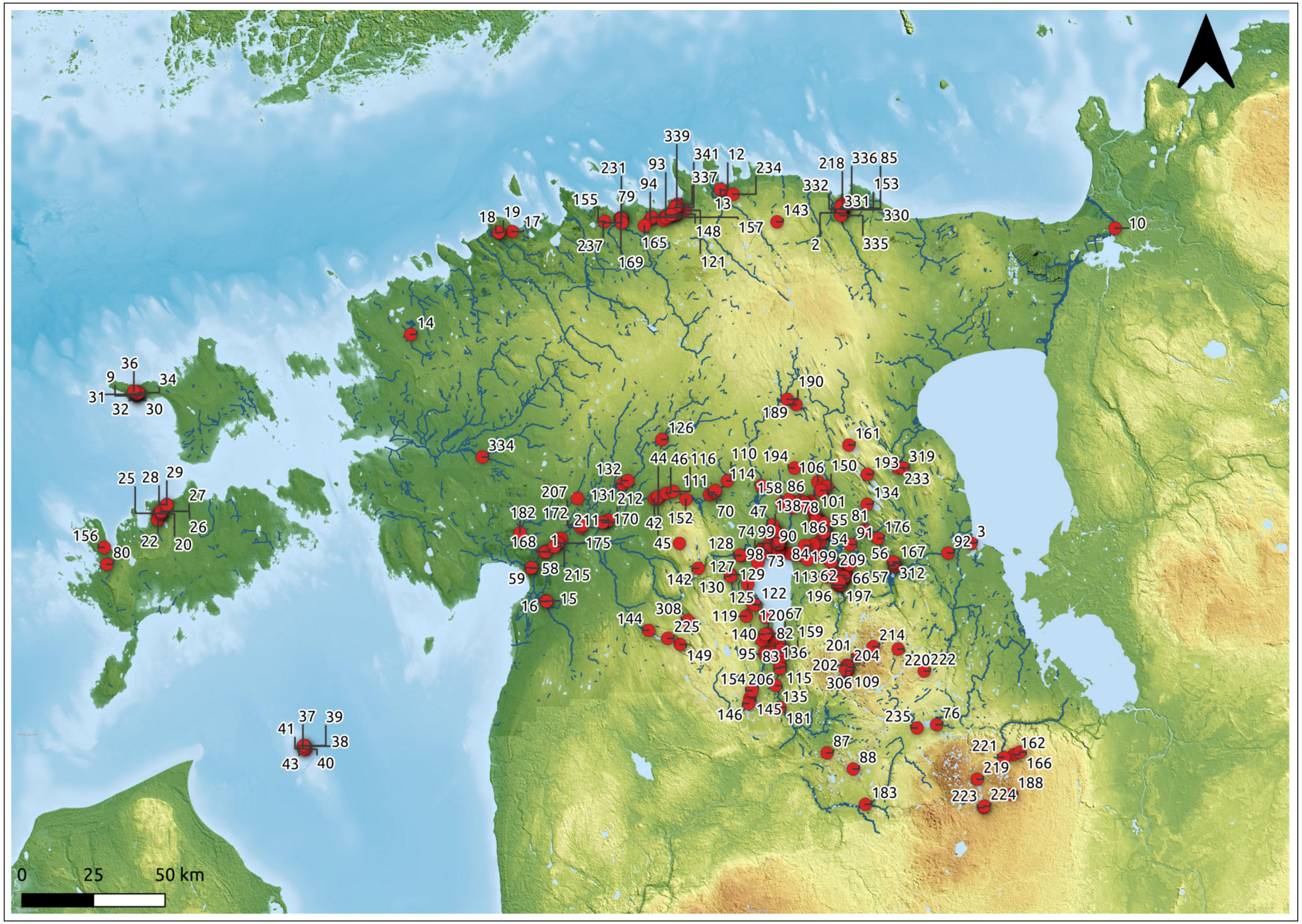


Figure A.1: **Prepottery Mesolithic settlement pattern. Author: Kaarel Sikk. Topographic map: Estonian Land Board (2020)**

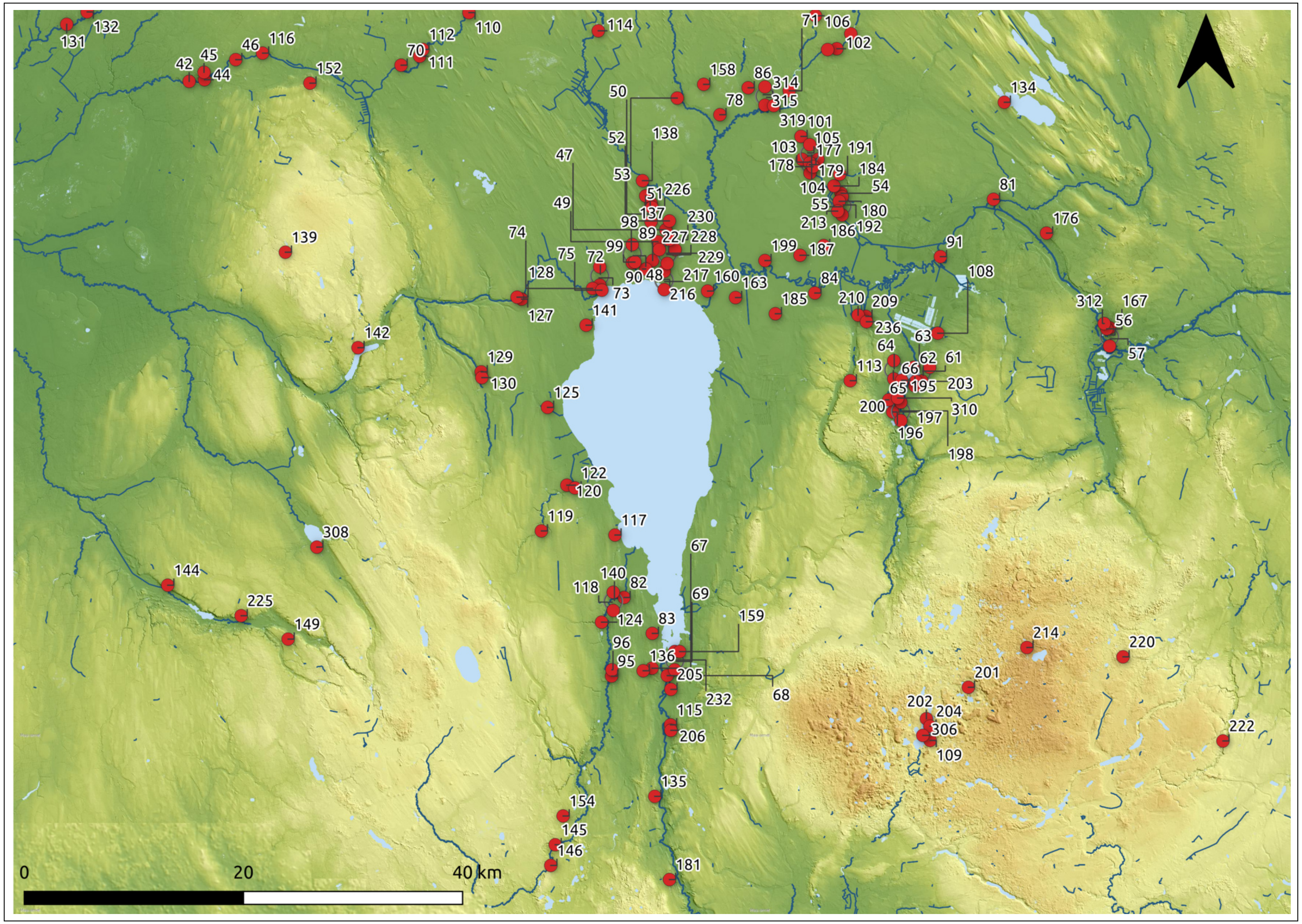


Figure A.2: **Prepottery Mesolithic settlement pattern in the region close to lake Võrtsjärv. Author: Kaarel Sikk. Topographic map: Estonian Land Board (2020)**

Figure A.3: **Narva stage Mesolithic settlement pattern. Author: Kaarel Sikk. Topographic map: Estonian Land Board (2020)**

Figure A.4: **Comb Ware settlement pattern. Author: Kaarel Sikk. Topographic map: Estonian Land Board (2020)**

Figure A.5: **Corded Ware stage settlement pattern. Author: Kaarel Sikk. Topographic map: Estonian Land Board (2020)**

Appendix B

ODD+D protocol overview of the ABM model of CPF settlement choices

I **Overview**

i **Purpose**

a **What is the purpose of the study?** To test the robustness of CPF model to initial spatial configuration and evaluate its theoretical explanatory power of settlement pattern formation processes. The theoretical model is developed so it can also later be used as a baseline model for experimenting research questions with explicit empirical case studies. This research could involve testing formalised hypotheses and identifying emergent properties of settlement pattern formation.

b **For whom is the model designed?** For archaeologists and other scientists studying hunter-gatherer mobility and residential choice through modelling approaches

ii **Entities, state variables and scales**

a **What kinds of entities are in the model?** The agents in the model are human groups. The environment represents a resource distribution landscape.

b **By what attributes (i.e. state variables and parameters) are these entities characterised?** Agents in the model have an explicit location and a population, which is constant (20) in the presented simulation experiments. They possess a state variable for the time an agent is expecting to stay at its next location (EXPTIME). Each cell (i) in the environment has a state variable ENERGY which represents the potential net return rate of energy (R_i). It is the amount of energy that can be foraged from it during a day by an agent. As the net return rate depletes after resource use we store an additional ACTIVE-ENERGY variable to store currently available energy. The model includes global variables which are used during the simulation. The first one is the fixed time costs of disassembling the old and setting up the new camp. It does not involve the moving process itself and thus is not related to distance. It is a defined separate global variable (MOVE-START-COST). Another global variable used for generating the environment is the mean energy rate of the environment (MEAN-ENERGY-RATE-KM), which defines the abundance of energy available.

c **What are the exogenous factors / drivers of the model?** The environment is generated by an external model configuration which determines its general characteristics. Configuration variables are selected so that the summed energy rate of the environment will not be depleted by an artificial population and will achieve a stable equilibrium state.

d **What are the temporal and spatial resolutions and extents of the model?** The environment is represented by 100x100 grid, each of which is equivalent to 1 square kilometer. One step in the model run is the equivalent of one week.

e **If applicable, how is space included in the model?** Environment is presented explicitly in space and agent decisions take into account distances in space.

iii **Process overview and scheduling**

a **What entity does what, and in which order** In the beginning the environment is created based on a Monte-Carlo process and is then calibrated to match the configuration variables. At every turn agents are run in random order and consume resources around them, which changes the ACTIVE-ENERGY variable of the environment. At every four turns (to optimize model runs) resources are restored at a certain rate. At every turn agents evaluate the time costs of meeting requirements at the current location during an expected duration of stay and weight it against similar costs in alternative site locations. If any alternative location offers more optimal time use the agents moves to best (least time costs) alternative location.

II **Design Concepts**

i **Theoretical and empirical background**

a **Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?** The energy return rates in the environment are based on environmental data and ethnographic observation. The depletion of resources in the environment is mostly based on theory but also on some ethnographic studies. As the data is not sufficient the mechanism is not calibrated to it. The environment configurations are generated using Monte-Carlo methods and are not calibrated to resemble real landscape configurations as the data is not available. Every location has an utility value assigned, which comes from Central Place Foraging theory (Kelly, 2013). Every cell has an utility value - an energy rate which can be accessed from a cell both locally and by logistic mobility to other cells in the logistic range.

b **On what assumptions is/are the agents' decision model(s) based?** The decision model of mobility and settlement choice is based on mobility theory from the Central Place Foraging model (Kelly, 2013) which is a special case of Optimal Foraging theory. The theory asserts that a human group moves its settlement if it finds an alternative location which promises better returns during a certain period of time.

c **Why is /are certain decision model(s) chosen?** The goal of the model is test the effect of varying spatial configurations of the environment to mobility patterns produced by CPF. As the goal of the simulation is to isolate the spatial effect of the CPF, no other possible factors (suitability of locations, socio-cultural dynamics) were included.

d **If the model / submodel (e.g. the decision model) is based on empirical data, where do the data come from?** The model is not based on empirical data.

e **At which level of aggregation were the data available?** The model is not based on empirical data.

ii **Individual Decision Making**

a **What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled?**

Are multiple levels of decision making included? Agents decide on the location for their settlement site.

b **What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria?** Agents select a site location with maximum returns by means of logistic mobility during a fixed period of time including movement time to new location.

c **How do agents make their decisions?** Agents compare the time costs of satisfying their needs by staying at one location and choose the optimal location.

d **Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?** The environment configuration and other agents' locations determine agents' decisions.

e **Do social norms or cultural values play a role in the decision-making process?** No

f **Do spatial aspects play a role in the decision process?** Energy resources are spatially explicitly distributed. The concept of distance is used in calculating mobility costs.

g **Do temporal aspects play a role in the decision process?** The expected time of stay at one location has significant impact on the decision-making.

h **To which extent and how is uncertainty included in the agents' decision rules?** Uncertainty is not included in the decision rules.

iii **Learning**

a **Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?** The agents' learning process considers finding an optimal time of stay (t, agent variable EXPTIME). The time is calculated as a mean of durations of two previous stays. The durations are the result of considering local conditions better than any alternatives.

b **Is collective learning implemented in the model?** Collective learning is not implemented.

iv **Individual Sensing**

a **What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the**

sensing process erroneous? Agents in the model have complete information about the ENERGY and ACTIVE-ENERGY values of each cells in their residential range.

b **What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?** Agents do not sense any state variables of other agents.

c **What is the spatial scale of sensing?** The spatial scale is residential move range.

d **Are the mechanisms by which agents obtain information modelled explicitly, or are individuals simply assumed to know these variables?** Agents are assumed to know variables.

e **Are the costs for cognition and the costs for gathering information explicitly included in the model?** Cognition costs are not included in the model.

v **Individual Prediction**

a **Which data do the agents use to predict future conditions?** Agents use variable ACTIVE-ENERGY for predicting future energy rates.

b **What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?** Agents are using a model of resource depletion for predicting future conditions.

c **Might agents be erroneous in the prediction process, and how is it implemented?** Agents' predictions are correct only assuming their own resource use, but they do not predict activities of other agents.

vi **Interaction**

a **Are interactions among agents and entities assumed as direct or indirect?** Agents directly interact with the environment and indirectly with each other: two agents can't occupy the same cell.

b **On what do the interactions depend?** Interactions depend on spatial proximity of agents and environment cells.

c **If the interactions involve communication, how are such communications represented?** Entities do not use communication.

d **If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?** Model does not have interaction network.

vii **Collectives**

a **Do the individuals form or belong to aggregations that affect and are affected by the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?** Collectives are not included in the model.

b **How are collectives represented?** Collectives are not included in the model.

viii **Heterogeneity**

a **Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?** Entities are heterogeneous having different expectations of length of stay at one location.

b **Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?** Decision-making is heterogeneous depending on the EXPTIME variable and on agents' location.

ix **Stochasticity**

a **What processes (including initialisation) are modelled by assuming they are random or partly random?** Environment generation and spatial placement of agents is partly random.

x **Observation**

a **What data are collected from the ABM for testing, understanding and analysing it, and how and when are they collected?** During every simulation run the variables I-UTIL and I-RESOURCE which represent the spatial autocorrelation of respectively utility value and resource distributions are collected. Agents' expected duration of stay at one location is collected and statistics about mobility are collected (MOVESPERYEAR, LOGMOBTURN, MOVELEN).

b **What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)** Model run shows that mobility characteristics have a non-linear relation with mean energy rate of the environment and moving costs of a settlement. Spatial configuration of the environment has an impact on mobility.

III **Details**

i **Implementation Details**

a **How has the model been implemented?** The model has been implemented in Netlogo version 6.04 (Wilensky, 1999) modelling environment.

b **Is the model accessible, and if so where?**
The scripts reported in this paper have been deposited in the Zenodo repository, (https://doi.org/10.5281/zenodo.3709457). Model is published in Github public repository as a work in progress (https://github.com/vinnetu/OFTpatterns/).

ii **Initialisation**

a **What is the initial state of the model world, i.e. at time t=0 of a simulation run?** Environment is generated as a Monte-Carlo process and calibrated using configuration variables and agents are placed at random spatial positions in the environment.

b **Is the initialisation always the same, or is it allowed to vary among simulations?** Initialization process is the same.

c **Are the initial values chosen arbitrarily or based on data?** Initial values are chosen arbitrarily.

iii **Input Data**

a **Does the model use input from external sources such as data files or other models to represent processes that change over time?** The model does not use input data.

iv **Submodels**

a **Environment generation** A surface of normally distributed cell values (ENERGY) was generated through a Monte-Carlo process using standard deviation given as a input parameter (STD-ENERGY). The surface was then smoothed to increase autocorrelation according to an input smoothing parameter using the diffuse function of NetLogo. As the STD-ENERGY value is sometimes bigger than MEAN-ENERGY-RATE-KM the values of cells are cut off at minimal and maximal threshold values and the whole distribution is normalized so that the mean energy rate still corresponds to the global configuration variable. As a result an environment is generated and variables I-RESOURCE and I-UTIL are calculated as global Moran's I values of local and accessible return rate distributions. The four variables describing environment are used for comparison with observation variables of mobility. During experiments the initial input configuration variables are chosen so that the overall energy of the environment is not depleted by agents but agents still have a reason to move.

b **Resource depletion** The process of resource depletion has not been studied in enough detail to create an empirically calibrated model. Only work analysing the diminishing return of hunter-gatherer foraging processes informs us that the gain curve has a general sigmoid or asymptotic shape (Venkataraman et al., 2017).
To reproduce a similar dynamic we created the following heuristic process. Every agent has to satisfy its need for resources, so at every turn a cell which has the best return rate from the base will be used for foraging. During the process the ACTIVE-ENERGY variable is decreased by the depletion rate (D) times energy taken from the cell. The depletion rate configuration variable used in the system is set to a constant value of 2/3. The experiments showed that using the value of the mobility results are in the same range as empirical observations, helping us avoid anomaly of scale.
Experiments also confirm that the depletion dynamics created in this way is a close enough approximation to the differential equation that agents use for predicting utility values for potential locations.

c **Resource recovery** Over time energy rates of cells gradually recover. As there is no data to base recovery rate on, we assume that the resources will recover over one year. Although in practice recovery rates in different resources are obviously different we consider this to be a usable heuristic in our system as it is a period during which nature completes a seasonal cycle and we can also observe hunter-gatherer mobility cycles.

Appendix C

ODD protocol overview of the ABM model of settlement pattern formation presented in Chapter 5

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm, Berger, Bastiansen, et al., 2006), as updated by Grimm, Railsback, et al. (2020).

C.1 Purpose and patterns

This model deals with settlement patterns formation from a socio-ecological system perspective. It explores patterns as emergent phenomena resulting from populations' adaptations to their environment. The emerging spatial population distributions are reflected in archaeological empirical material and contemporary population data.

The purpose of this model is to study how social and environmental attractions lead to variations in observed population agglomeration or dispersion. It questions the relative role of environmental determinism and social processes in individual location choice processes and emergence of settlement systems. The higher-level purpose of the model is to develop a framework for interpreting archaeological settlement systems that appear at the aggregate level and to relate them to both social (e.g. agglomeration) and environmental (e.g. ecosystem services; (Program), 2005) effects that apply to groups of human individuals.

Emerging patterns are observable from archaeological material. In effect, spatial characteristics of settlement systems, like clustering, are derived from inductive modelling where environmental conditions of settlement sites are used as predictors. Various inductive models (see Judge and Sebastian, 1988; Kvamme, 2005; Verhagen and Whitley, 2012) have been created based solely on environmental data to explain principles of settlement locations and predict unknown archaeological sites.

But those models require explanatory frameworks to interpret data. For example, it has been observed that model performance and environmental determinism both seem to decrease with the move from hunter-gatherer systems to agrarian and further to urban systems (Sikk, Caruso, et al., 2022). Another observable pattern is the historical development of population agglomeration leading to current urban settlements formation. Predictive models are also static and take environmental conditions at one point in time as given. As soon as social effects are considered, population dynamics and path-dependency gain in importance. Therefore there is a need for a more general and dynamic framework where both social and environmental effects are modelled. Such a framework is more likely to encompass those transitions (hunter-gatherer to agrarian to urban).

The goal of the model is to explore the effect of socio-ecological strategies on emerging spatial settlement patterns. The strategies are related to environmental attraction space and to levels of social organisation that provide access to various cultural and ecosystem services ((Program), 2005).

C.2 Entities, state variables, and scales

The following entities are included in the model: agents representing population units grid cells that represent geographical locations and the global environment that represents a socio-ecological system with a specified adaptation strategy (technological means, culture, climate, natural environment etc.) and landscape with specific spatial configuration.

Population units (agents) are defined as generic human groups who make settlement location choices together. The chosen unit is capable of making mobility decisions. Its size and type typically depends on the spatial scale of the problem. For this theoretical model, population size is not specified. The distinctive state variable for population agents is their geographical location.

Cells that form a 50x50 grid represent a discretization of geographical space. Every cell has a series of state variables, which are used to compute an average utility value of the area.

The environment (observer) is a single entity controlling global variables describing higher level spatial characteristics of the region and location choice characteristics shared by all agents.

As the model is not intended to represent a specific real system but for theoretical exploration it can be also used to explore the effects of scale since there is varying spatial autocorrelation in the landscape and distance dependent interactions. The

Variable	Type	Description
location	Real, static	Cell location using the NetLogo's built-in coordinate system
UT-ENV	Real, staticrange 1 – 100	Static environmental utility value associated with the given location on the landscape
UT-SOCIAL	Real, dynamicrange 1 – 100	Dynamic social utility value
UT-RANDOM	Real, dynamicrange 1 – 100	Random utility value
UT-FULL	Real, dynamicrange 1 – 100	Combined utility value as perceived by agents of a given eco-cultural system

Variable	Type	Description
LS-LAMBDA	Real, static in range 0 – 1	Spatial autocorrelation coefficient of spatial distribution of environmental utility values.
DENSITY-PREFERENCE	Real, static in range 0 – 100	The normalised population density preferred by agents.
COEF-SOCIAL	Real, static in range 0 – 1	The importance of social utility in comparison to environmental utility (defines weights).
COEF-RANDOM	Real, static in range 0 – 1	The rate of exogenous randomness in the utility value used to test model robustness (defines weights).

measures and scopes are thus not strictly fixed. The general scope of the environment is to represent a region inhabited by a population with shared socio-ecological practises. An example cell size could correspond to 1 km2 and the whole region could then represent 2500 km2.

Time in the model is discrete and one tick represents a time period that takes for a population unit to live in a selected location and move. The model is independent on the time scale as it is on the spatial scale. It is not aimed to hint onto the time range of the historical processes but to study the relation between individual choices, emerging spatial patterns and their feedbacks in a generic manner. Both the spatial and temporal scales can later be fitted to specific empirical data and periods.

C.3 Process overview and scheduling

C.3.1 Processes

The model is developed to explore the formation of settlement systems as a result of consecutive settlement choice events carried out by population units. The emerging settlement system is the spatial adaptation of the population to the environment. The main process in the model is based on the mechanism of direct objective seeking. The choice set is the amount of cells within a defined neighbourhood range (default of 10 cells distance). Agents are then choosing a location with the maximum utility value and moving to the location, if it is not the current location already.

C.3.2 Schedule

After initialisation (see Initialisation) the model is run step-by-step until reaching a steady state or until the model is externally stopped. A steady state is considered to be reached when the main observed variable (mean selected utility) has stayed for 5 timesteps within 5% of the value range.

The following processes are run within each timestep. For every of the n agent (main loop)

- Update utility values of all locations. Technically this is done only for those cells that potentially changed because of previous movers (including within the time step). Utility is based on the environmental, updated social and random utilities, and on the model parameters (see next section)
- Decision to stay if the occupied cell offers the highest utility. Otherwise the agent moves to the location with maximum utility if vacant. It the best place is not vacant, agents move to the second, or third, ... i.e. n-th best place

- Recalculate social utility of all cells impacted by the agent's move (submodel SM1)
- Compute control variables of the system, if within 5% range over the last 5 steps, consider steady state is reached and stop simulation.

C.4 Design concepts

C.4.1 Basic principles

The settlement choice in archaeology has long been considered to be influenced by relatively static environmental attractions, dominated by resources. But there are also implied directly unobservable social contexts influencing the process. Those relations have so far been mostly described in the context of archaeological locational modelling that indicate patterns of varying environmental determinism and its hypothetical relations to social factors. We are building our model on knowledge from archaeological locational modelling. In this model we use a direct objective seeking behaviour modelling. We assume the possibility of constructing an abstract utility function, that represents how individuals (groups of) select a location from a choice set of locations.

Although not observed directly, there exists theory that a proportion of the utility values of the locations as perceived by inhabitants are to a certain proportion determined by direct environmental access and to an extent determined by social organisation (Judge and Sebastian, 1988). In our model we use the model parameter COEF-SOCIAL to set those proportions (the environmental coefficient assumed to be its complement). In addition to environment and social effects, we use a randomness factor. We construct the utility function as a weighted sum of those three abstract utility values (environmental, social and random)

First, the environmental, natural landscape based utility is a proxy for a series of ecosystem services. Examples could include dry and safe location for dwelling, direct access to water and soil for growing food, quality of soils, etc. The social services include a combination of attraction-repulsion to other population units, reflected through a preferred density.

Second, the social utility is meant to approximate access to both resources and services,systematically or culturally organised by the society (security, child care, mating opportunities and so on).

Third, a random value is included in the model to account for modelling error, unknown variations in population characteristics or space, and possible time varying exogeneous effects. It is used to test the robustness of the model results and explore possible randomly induced path-dependencies.

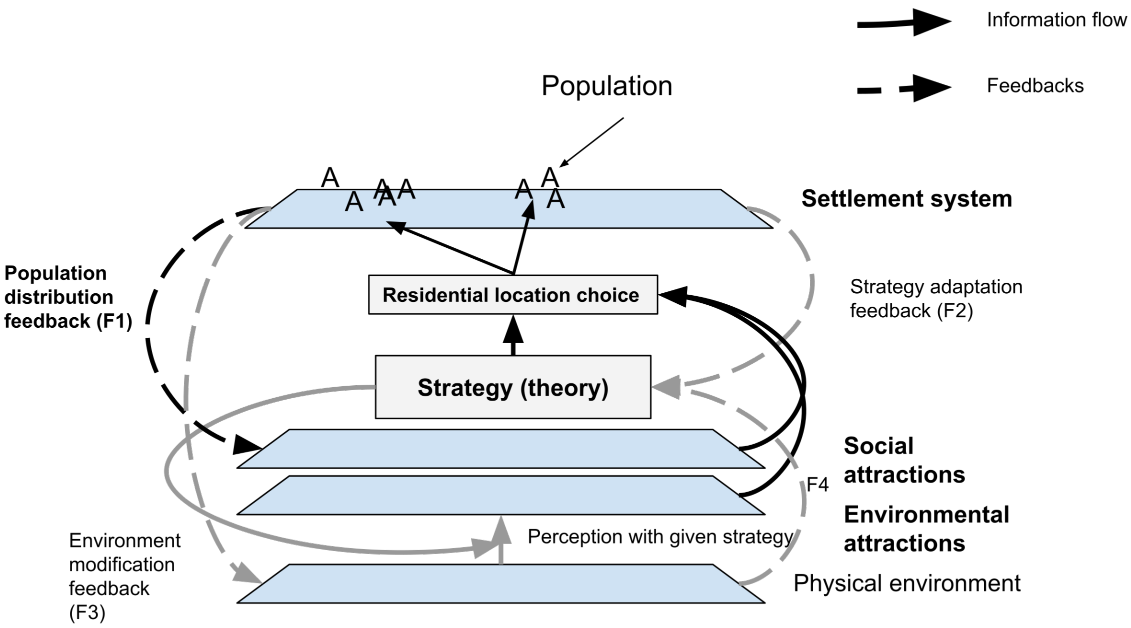


Figure C.1: Information flows and feedback studied using the model in the context of general model of settlement system formation (Chapter 1)

C.4.2 Emergence

The emergence in the model arises from agents' strategies that lead to new spatial and statistical patterns. It is assessed from the evolution through time of a simulation and across simulations using different parameters (sensitivity analysis). In particular spatial patterns can be qualitatively assessed from the spatial distribution of agents and utilities, and the aggregate model outcomes, e.g. level of clustering (nearest neighbour index), utility values range at steady state, etc. related to changes in the input parameters.

C.4.3 Adaptation

The model represents spatial adaptation, that means individual agents adapt to changes in the environment by relocation. Relocation is based on utility maximisation: agents seek the best possible location for residence. The choice set is limited within a certain distance from the previous location(10 cells distance).

C.4.4 Objectives

Each agent pursues the same objective represented by maximising their utility. The objective represents a socio-cultural strategy where both the environment and the location of other agents are taken into account in the decision. The value (utility) of a location for habitation is defined by a social, environmental and a random component denoted by U_{social}, $U_{environement}$ and U_random. A utility level is associated with every cell and computed as a weighted sum of each component. The main parameter of the weighted sum represents the relative importance of the social vs the environmental part of the decision. COEF-SOCIAL is the weight associated to the social utility and $1 - COEF - SOCIAL$ is associated to the environment So each cell i has utility $U_i = COEF - SOCIAL * U_{social} + (1\breve{}COEF - SOCIAL) * U_{environment}$

For exploring the robustness of the model to preference idiosyncrasies and unobserved elements of the landscape or behaviour, we add a random coefficient, COEF-RANDOM, used in a similar way as $coef_{social}$ this time to weigh the random against the deterministic part of the utility: $U_i = COEF - RANDOM * U_{random} + (1\breve{}COEF - RANDOM) * (COEF - SOCIAL * U_{social} + (1\breve{}COEF - SOCIAL) * U_environment)$

$U_environment$ and U_random are exogenously defined (see initialization). U_social is endogeneous and calculated from the density of the population (see submodel SM1).

Learning of individual agents is not implemented in this model design.

C.4.5 Prediction

The agents are not forward looking but observe the landscape and location of other agents as it is when it is their time to (potentially) move. By relocating to the cell with the maximum utility around, we can say they go to the best predicted cell. However this can change in later stages and this is not accounted for. Their time horizon is limited to the next iteration. As an observer of the landscape we can't very well predict the emerging spatial patterns - this is the reason for simulating. Given the number of agents and the size of the space, there is a benchmark clustering level based on a random spatial distribution (theoretical nearest neighbour index). In dynamic terms, it is also expected that the reshuffling of agents through time leads to increased utility values, i.e. benefits of adaptation. Sensing. Agents sense the utility values of locations in their neighbourhood range that are used for calculating the attraction to a given cell. They also sense the number of agents already inhabiting those cells, to avoid them if the population limit (defaults to 1 agent per cell) is already full and also local population density on cells.

C.4.6 Interaction

Agents have two indirect spatial interactions with each other. They work through sensing the population density and selecting its residential location based on it. The interactions also help to avoid population densities that are above maximum possible (several agents on one cell).

C.4.7 Stochasticity

The model has several stochastic components: the environmental utility distribution, the initial placement of agents (for both see Initialisation) and the random component of the utility function (see above).

C.4.8 Collectives

Collectives in the model implicitly emerge as population clusters under certain global model conditions. All the agents in the system are identical so their belonging to a certain group can be decided visually. Clustering as an emergent property itself is measured as one of the system states.

Collectives interact with each other indirectly through their population densities and agent's preference of certain population densities. In case of density maximisation larger agglomerations

C.4.9 Observation

The following variables are observed:

C.5 Initialization

The model is started with the initialisation, which includes the following steps:

- placement of agents in the environment
- generating environmental utility values of every cell through a sub-model (SM1) using variable LS-LAMBDA.
- generating social utility values of every cell using sub-model (SM2)
- generating random utility values of every cell

Name	Description
NNI	Nearest Neighbour Index measure of agents clustering
MEAN-UT-ENV*	Mean selected environmental utility taken from the distribution of utilities in agents locations, a proxy to environmental determinism in the model
STDEV-UT-ENV*	Standard deviation of selected environmental utility
MEAN-UT-FULL*	Mean selected combined utility, the utilities in agents locations, a proxy to agent "happiness" in the model
STDEV-UT-FULL*	Standard deviation of combined utility, taken from the distribution of; a proxy to agent "happiness" in the model
MORAN-FULL	Moran's I measure of the combined utility distribution in space

C.5.1 Initialisation of agents

The set of agents (default N = 100) represent a population with a given socio-ecological strategy that goes through a process of adaptation to the environment. In the initial state the agents are placed in the environment on random locations using Netlogo's default functionality.

C.5.2 Landscape initialization

The initial state of the model at the time t=0 represents an hypothetical attractions environment consisting of a 50 x 50 lattice and agents randomly placed in it. Model landscape is generated by initialising three different variables of each cell. Those variables are environmental utility (UT-ENV), social utility (UT-SOCIAL) and random utility (UT-RANDOM) representing the physical and social environments attractiveness for habitation and random effect.

Environmental utility (UT-ENV) is initialised as a neutral landscape model using an algorithm to generate a stochastic N * N grid with a fixed, approximate Moran's I spatial autocorrelation measure. The measure is set by the global model variable LS-LAMBDA. Landscape initialisation is run through loading pre-generated data (10 models for every Moran's I value with precision of second decimal place) using a Python script. Pre-generation is done because of the lack of existing functionality in

NetLogo and performance reasons. The value distribution is then normalised to the range 1 – 100.

Social utility is generated every turn through a submodel SM1 which compares expected density with local population (agents) density and normalises the results to a specific range.

Random utility values are set up by giving a random value in range 0..100 to every cell.

C.6 Input data

The model does not use input data to represent time-varying processes.

C.7 Submodels

C.7.1 SM1, social utility calculation.

For calculating the social utility of each cell local population density is calculated for the surrounding neighborhood of the cell (agents in radius of variable neighborhood area; default neighborhood = 10 cells). The density value is then normalised to value range 0 – 100 and the difference between models preferred density and local density is calculated. The difference is then normalised from 1 – 100 resulting in a social utility value of the cell.

$UT-SOCIAL = normalised(100-abs(normalised(preferred_density)-local_density))$

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