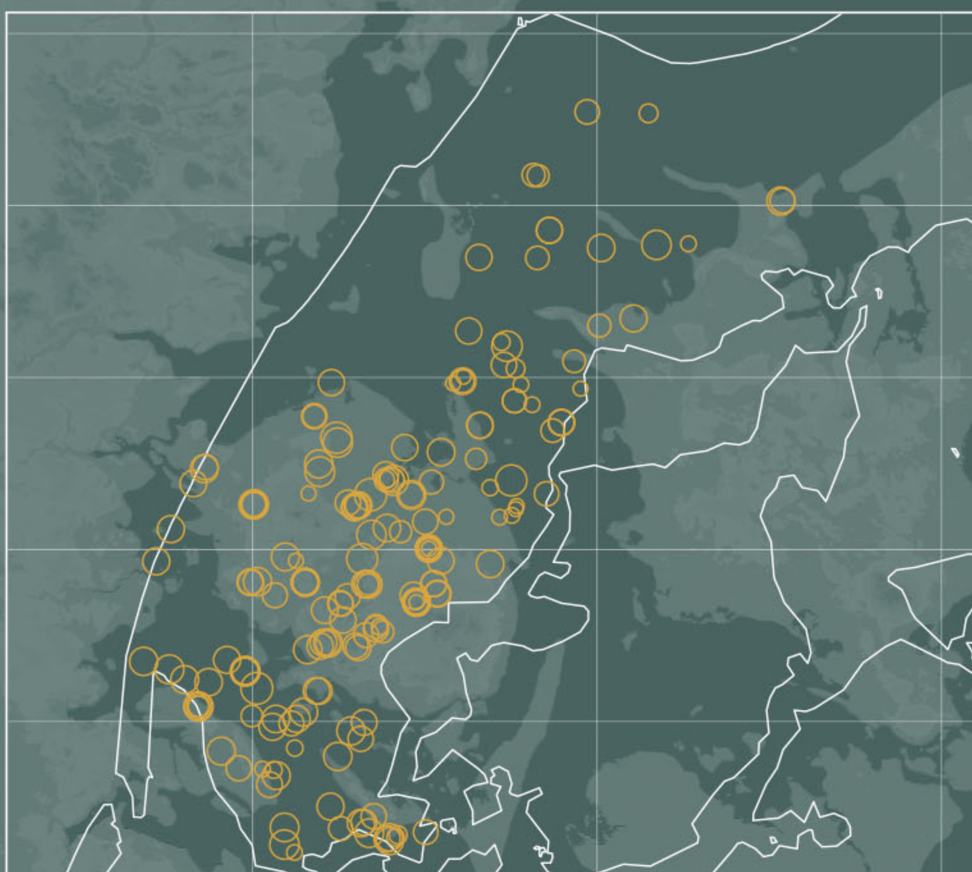
GIACOMO BILOTTI

POPULATION DYNAMICS AND LAND-USE PATTERNS

in the southwestern Baltic region during the Neolithic and the Bronze Age



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Preface of the editors

With this book series, the Collaborative Research Centre Scales of Transformation: Human-Environmental Interaction in Prehistoric and Archaic Societies (CRC 1266) at Kiel University enables the bundled presentation of current research outcomes of the multiple aspects of socio-environmental transformations in ancient societies. As editors of this publication platform, we are pleased to be able to publish monographs with detailed basic data and comprehensive interpretations from different case studies and landscapes as well as the extensive output from numerous scientific meetings and international workshops.

The book series is dedicated to the fundamental research questions of CRC 1266, dealing with transformations on different temporal, spatial and social scales, here defined as processes leading to a substantial and enduring reorganization of socio-environmental interaction patterns. What are the substantial transformations that describe human development from 15,000 years ago to the beginning of the Common Era? How did interactions between the natural environment and human populations change over time? What role did humans play as cognitive actors trying to deal with changing social and environmental conditions? Which factors triggered the transformations that led to substantial societal and economic inequality?

The understanding of human practices within often intertwined social and environmental contexts is one of the most fundamental aspects of archaeological research. Moreover, in current debates, the dynamics and feedback involved in human-environmental relationships have become a major issue, particularly when looking at the detectable and sometimes devastating consequences of human interference with nature. Archaeology, with its long-term perspective on human societies and landscapes, is in the unique position to trace and link comparable phenomena in the past, to study human involvement with the natural environment, to investigate the impact of humans on nature, and to outline the consequences of environmental change on human societies. Modern interdisciplinary research enables us to reach beyond simplistic monocausal lines of explanation and overcome evolutionary perspectives. Looking at the period from 15,000 to 1 BCE, CRC 1266 takes a diachronic view in order to investigate transformations involved in the development of Late Pleistocene hunter-gatherers, horticulturalists, early agriculturalists, early metallurgists as well as early state societies, thus covering a wide array of societal formations and environmental conditions.

In this new monograph Giacomo Bilotti deals with archaeodemography on different spatial levels over a relatively long period of time. Using data from Neolithic and Bronze Age core regions of southern Scandinavia and northern Germany, the author succeeds in systematically breaking new ground for population reconstruction based on archaeological contexts. Relative and absolute population developments can be conclusively presented from settlements to large regions. At the same time, it becomes clear which data must be available in order to carry out meaningful population reconstructions.

We are very thankful to Julia Luckner for copy editing the manuscript and for preparing the publication process with Franziska Engelbogen, Esther Thelen for her graphic editing and Nicole Taylor for coordinating the publication process. We also wish to thank Karsten Wentink, Corné van Woerdekom, and Eric van den Bandt from Sidestone Press for their engaged support in realising this volume.

Wiebke Kirleis and Johannes Müller

Contents

Preface of the author

This book explores population dynamics and land-use patterns in the south-western Baltic region during the Neolithic and Bronze Age (4100 to 500 BCE). The study of demography is highly relevant for archaeologists, as it serves as one of the main drivers of socio-cultural transformations and complex dynamics. However, studying demography in archaeology presents significant challenges, requiring careful assessment of archaeological data. In this book, I have developed a novel method to address these challenges by combining spatial statistics with archaeological data while accounting for the impact of biases.

This work is the culmination of a journey that lasted more than three years, a period filled with events. Certainly, it owes much to the support and involvement of many people, to whom I wish to express my gratitude. Firstly, my thanks go to Prof. Dr. J. Müller. His guidance over these challenging yet rewarding years has been indispensable. Similarly, I am deeply indebted to Dr. T. Kerig. His co-supervision and the engaging discussions we shared have significantly contributed to my professional growth as an archaeologist.

I am thankful to my colleagues and, more importantly, friends, Michael and Miguel. Their companionship during this journey, helping me navigate through its tumultuous waters, has been invaluable both scientifically and personally. Furthermore, I am especially grateful to every friend and colleague who generously spent their time reading parts of this manuscript, offering valuable feedback on its content and style. Nevertheless, I bear sole responsibility for any errors that remain.

My gratitude also goes out to all the friends and acquaintances who have devoted their time and attention to me over the years. Whether our paths crossed briefly or over decades, each of you has played a role in my personal and intellectual development. I am particularly grateful to those who listened, comforted me in challenging times, shared a drink, or simply engaged in conversation. You have all shaped me into the person and scientist I am today, and for that, I would not alter a single aspect of this process. Forgive me for not naming you all, but I am sure each of you knows their contribution.

Lastly, and most importantly, I extend my deepest thanks to my family. Their presence has been constant, regardless of my own presence or state of mind, and their support through every phase and decision of my life, have been the bedrock of everything I have achieved. Per questo motivo, desidero ringraziarvi, in italiano, affinché tutti possano leggerlo, specialmente i miei genitori, fratelli e nonni. Spero di poter condividere ancora molti anni insieme a voi. Grazie!

1. Introduction

The aim of this work is to study population dynamics and land-use patterns in the south-western Baltic region during the Neolithic and Bronze Ages, using a multi-proxy approach, carrying out chronological modelling and spatial statistics. The geographical and temporal scope of this study is extensive, encompassing an area exceeding 90,000 km^2 and spanning over 3000 years of history, from 4100 to 500 BCE. Given this vast range, a significant degree of variation is inevitable, covering aspects such as material culture, technology, environmental conditions, and socio-economic organisation. Despite these variations, the region shows a certain degree of uniformity within specific periods. This is particularly evident in the distribution of specific types of archaeological sites, like funerary monuments (megalithic graves or burial mounds, for example), and certain material types (flint and bronze tools or weapons), indicating some sort of *koiné*.

The Neolithic is a central period in the study of humankind and palaeodemography, marking an unprecedented rise in population density. This transition from sparse hunter-gatherer groups in the Late Pleistocene-Early Holocene to over 7 billion individuals today has shaped the modern world (Turchin, 2023). Similarly, the Bronze Age is critical for understanding human behaviour as it brought together demographic expansion with technological advancements and stable long-distance connections, forming new socio-political and economic systems. Thoroughly comprehending these historical events is crucial, not only for insights into past societies but also for recognising patterns that could inform our future (Korotayev et al., 2011; Turchin, 2008). Nonetheless, such a colossal task cannot be tackled within a single PhD project. Therefore, the aim of this study is more limited (but nevertheless essential) and only tries to model and understand prehistoric demography and its variation in the south-western Baltic region.

Understanding demography is crucial for comprehending socio-cultural transformations. In recent years, several attempts have been made to reconstruct the population size of prehistoric societies (Kristiansen, 2022b; Müller, 2013a). Historically, demographic patterns have been recognised as key drivers of social change and complex dynamics (Goldstone, 1991; Korotayev et al., 2011). Thus, gaining insights into demographic trends is vital for a comprehensive understanding of these societies. Palaeodemography has gained momentum in archaeology and become a central aspect of the discipline (Crema et al., 2017; Palmisano et al., 2021; Shennan et al., 2013; Shennan and Edinborough, 2007). This is due to the fact that, compared to the processual revolution, when quantitative analyses were first introduced in archaeology, we now have a larger amount of data, a more robust methodological framework, and the necessary computational power.

Palaeodemography, while offering valuable insights, faces several challenges when compared to historical or contemporary demography. The primary challenge lies in the patchiness of data, arising from differential recovery and preservation of the archaeological record. A further issue concerns the identification of suitable proxies for prehistoric demography and their relation to each other. To mitigate these issues, a multi-proxy approach combined with formal and transparent analyses is used. Such a methodological framework allows for more nuanced analyses and dependable interpretations of the archaeological record. This study aims to reduce chronological uncertainty while maintaining absolute reconstructions, integrating radiocarbon and archaeological data. It also seeks to enhance spatial resolution compared to both the absolute reconstructions and radiocarbon models previously mentioned, allowing for a better understanding of regional variations.

This work is structured into three distinct parts, each addressing a different aspect of past population dynamics, with each section representing a methodological step (Figure 1). The first part of this research focuses on intra-site patterns, specifically examining changes within individual sites over time. Changes in household structure were analysed, studying house-size variation over time. House size was selected as a proxy for household size for its adaptability and because it circumvents the need for culturally or socially based estimates, as explained in Chapter 4.2. The second part of this work examines inter-site dynamics to understand how different sites interacted and influenced each other. These comparative analyses help to identify broader population trends and regional interactions, shedding light on how communities adapted at a larger scale. Only areas where intensive and extensive archaeological research has been conducted were considered. Lastly, larger case studies are selected to create predictive models based on site location and environmental factors. Site distribution and changes over time are carried out using Point Pattern Analyses (PPA) and cluster analysis. These models are then scaled using the results of the demographic reconstructions at the local scale, providing population estimates for broader regions. The structure is summarised and shown in Figure 1. In particular, each model was used to produce two different demographic estimates: labour-based carrying capacity and absolute demographic reconstructions. The labour-based carrying capacity represents the reconstructed maximum population within the occupied territory based on land requirements using ethno-historical information (Kerig, 2016). The absolute demographic reconstructions estimate the population living in the area during each chronological window considered.

Although interconnected to each other and all with their own intrinsic value, in this study prominence has been given to the modelling part, which makes up most of Chapter 5 and Chapter 6. This part consists of several spatial and statistical analyses on site distribution, including some chronological modelling that has never been tested before. The first section also addresses an understudied topic, at least in terms of formal statistical analyses which deserve further attention. On the other hand, the central part is mostly an account of published work used for demographic purposes. Its novelty is connected to the way that the data is integrated across space and time rather than bound to a single case study.

Data for this study encompasses all the sites that were accessible within the study region, primarily sourced from national and international archaeological site databases. For some specific case studies and reconstructions, data from the available literature were also used.

This work is structured as follows: It starts with an introductory chapter that briefly outlines the study region and its geomorphological characteristics, and describes the technical requirements necessary for replicating this work (this chapter). Chapter 2 provides the chronological framework and an extensive overview

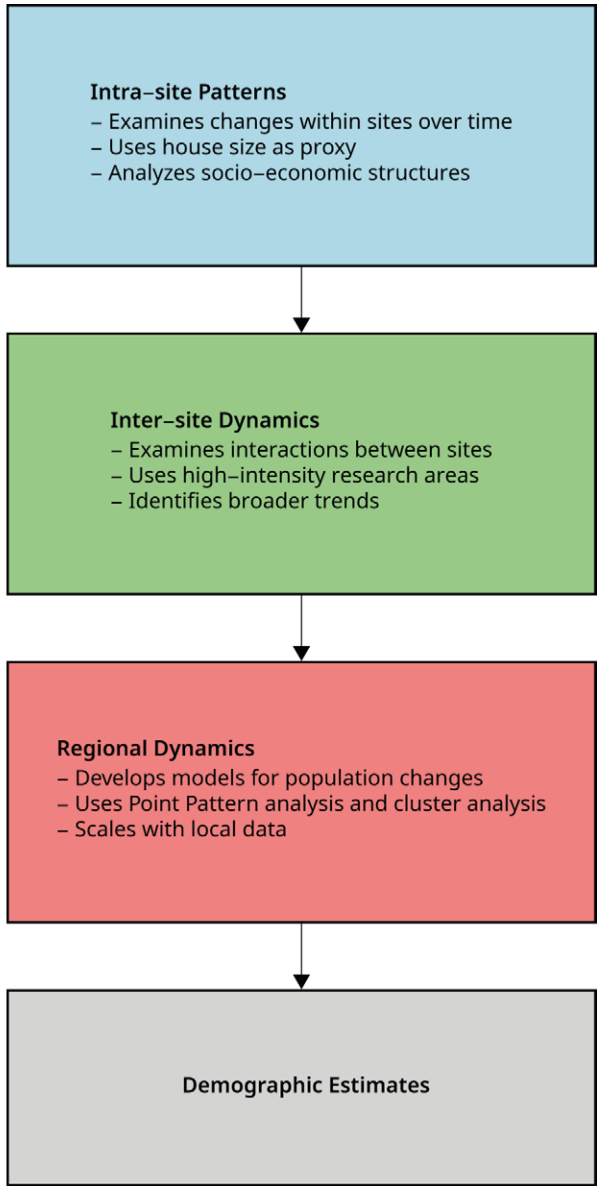


Figure 1. Diagram of the research structure of this study. Each step addresses a different scale of investigation, which are then combined into a comprehensive model.

of the state of the art in the study area. Chapter 3 is dedicated to the description of the data utilised in this study, the selection of case studies, and some data-related issues. Chapter 4 analyses the first two sections of the study, focusing on intra-site patterns and micro-regional demography. In this chapter, an account of the current state of palaeodemographic studies is also provided. The methodology employed is elaborated in Chapter 5, with particular emphasis on the modelling techniques used. Chronological modelling, PPA, and cluster analyses are discussed there. The results of the models are presented in Chapter 6, both in terms of land use patterns and demographic reconstructions, coupling the models with the results from Chapter 4. Following the previous chapter, Chapter 7 offers a structural comparison of the results with other demographic reconstructions and contextualises them within the state of the art in palaeodemography, discussing the implications of this work. The work concludes with Chapter 8, outlining the key outcomes, alongside broader considerations and future perspectives, providing a comprehensive summary of the study and its implications.

1.1 Study region

The study region includes modern-day Denmark, and parts of Sweden and Germany. Specifically, the Federal States of Mecklenburg-Western Pomerania (*Vorpommern*) and Schleswig-Holstein, the Scania (*Skåne*) county in the southernmost part of Sweden, and Denmark (Figure 2). The total surface is 94,060 km^2, with a geographical span between 53.11-57.75° N and 7.87-15.19° E (EPSG:4326). As in most archaeological studies, the borders of the regions are – at least in part – arbitrary and depend on modern administrative boundaries. Nonetheless, the region shares numerous common characteristics in terms of archaeology and environment.

1.1.1 Coordinates and reference systems

Most of the data used in this work is sourced from various institutions and agencies operating at multiple levels, ranging from local and regional to national and international levels (the European Union or world datasets). Consequently, the data exhibits a wide array of formats, not just in terms of content – such as language, descriptions, and terminologies – but also regarding spatial resolution and the coordinate reference systems used. Therefore, addressing these differences explicitly at the study's outset is essential.

Uncritical usage of spatial data can lead to significant errors and the propagation of measurement inaccuracies, potentially compromising the integrity of the final results. While completely eliminating measurement or conversion errors is not possible, it is necessary to acknowledge their presence and try to minimise their impact.

All the analyses presented here have been carried out using the ETRS89-extended / LAEA (Lambert Azimuthal Equal Area) Europe reference system (EPSG:3035). It is based on the European Terrestrial Reference System 1989, a geodetic system used for Europe, and the Lambert Azimuthal Equal Area projection. If not differently indicated, all maps included in this study are made with this reference system. Every projection is the product of a compromise and in this case, areas are preserved. Typically, projected EU data are provided in this reference system, and all other data used in this study have been transformed to match it. In particular, projection and coordinate transformation have been carried out in R using the *sf*, *terra* or *stars* packages (Hijmans, 2023; Pebesma and Bivand, 2023).

1.1.2 Landscape and geomorphology

This paragraph introduces the physical characteristics of the landscape in the study region, though for a more detailed understanding of the local geomorphology, I refer to the specialised literature.

Scandinavia's landscape, influenced by climate shifts and melting ice caps, has evolved significantly from the Atlantic to the Subboreal period. By the Early Neolithic, the landscape resembled its current form, though with a higher sea level in the north and significantly higher in central and northern Scandinavia (Risberg and Regnell, 2006). Marine transgressions occurred between 7000-5500 BP, with the Oresund area reaching about 5 m above the current sea level around 5500 BP before dropping to modern levels. Sea level changes, particularly during the Mesolithic period, significantly impacted settlement patterns and human behaviour (Risberg and Regnell, 2006).

The study area is characterised by low elevation terrain, morainic hills from past glaciations, wide plains and sandy coastal landscapes. Dunes are common in coastal areas of northern Jutland. During the last glaciations, the older bedrock was reworked and during the deglaciations strong alluvial sedimentation resulted in the creation of the wide plains (Seppälä, 2008). In some cases, especially in western Scania, the

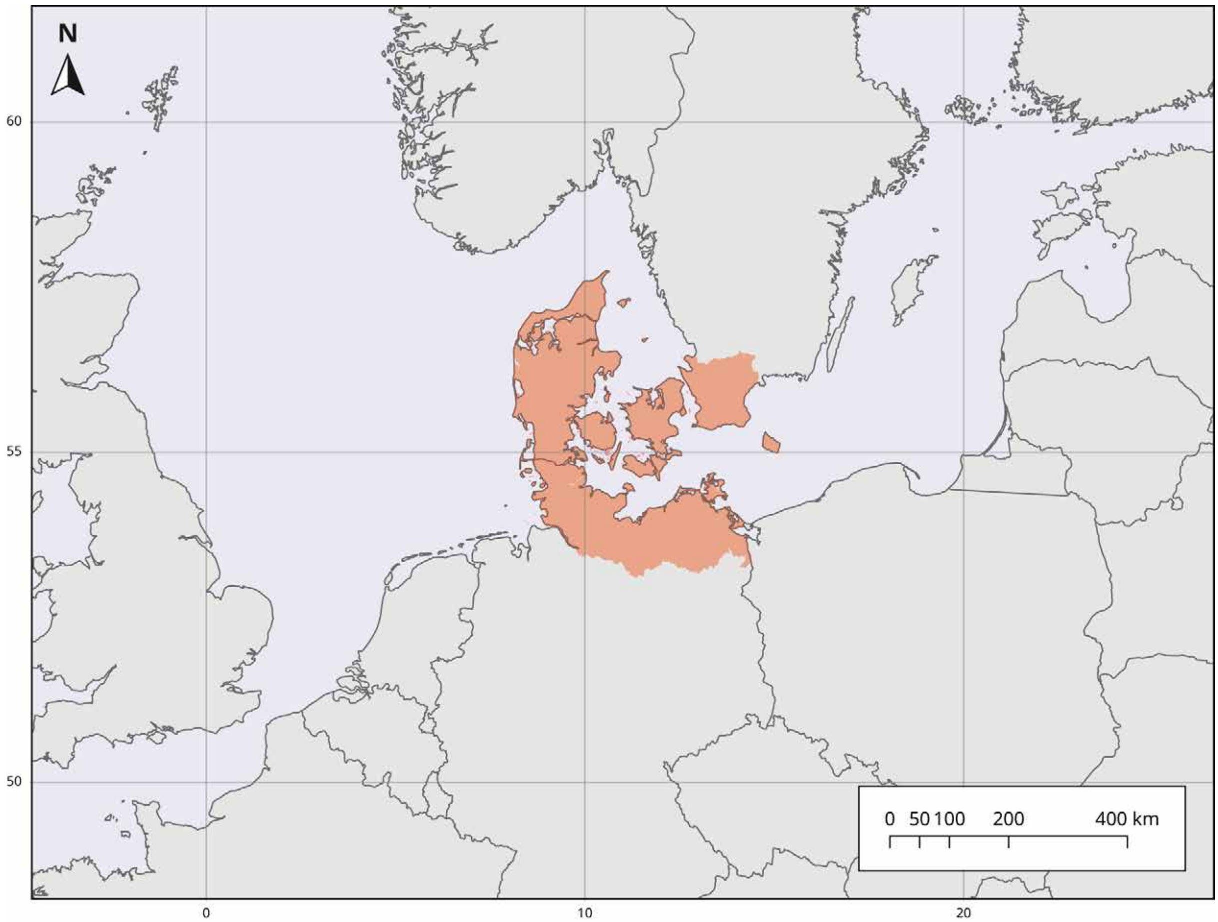


Figure 2. Map of the study area subject of this study. The area is highlighted in red, while a map with the borders of modern-day countries is shown in the background. The country outline was obtained via the rnaturalearth R package (Massicotte and South 2023). Coordinates in WGS84 EPSG: 4326.

coastline is characterised by cliff-like structures. Several lakes of glacial origin are recorded but their number is considerably lower than other parts of Scandinavia (Seppälä, 2008).

The highest point in the study area is found in Scania, reaching an elevation of 212 metres above sea level. It is located in Söderåsen, which is the north-west – south-east ridge that separates south-western and north-eastern Scania. Geologically, it represents a horst-type relief that separates the Precambrian bedrock of Fennoscandia from the platform sediments of central Europe (Lidmar-Bergstrom et al., 1991). Scania's northern and eastern regions feature a more rugged and forested landscape (see Chapter 3.1.2). The lowest point in the region is the Lammefjorden in Zealand, at – 7 m asl. However, it was previously an arm of a fjord that had been dyked and drained during the 19th and 20th centuries. Some other low-elevation areas are found in Scania, around the lake area near Kristianstad or in Wilstermarsch, in western Schleswig-Holstein.

The study region's proximity to the sea is a defining characteristic, with most points within 100 km of the coast, but reduced to around 50 km in Scania and Denmark. This strong relation is further enhanced by the several kilometres of shorelines and the presence of numerous islands. Most of them are located in the Danish strait, between the Kattegat and the Baltic Sea. The largest islands in the region are Zealand (*ca.* 7000 km^2), the North Jutlandic Island (*ca.* 4700 km^2), Funen (3100 km^2), Lolland (1200 km^2) and Rügen (900 km^2). Although there are many rivers in the study region, only few of them have a considerable length or discharge (Figure 3). The most important river in the region is the Elbe, flowing along the south and south-western border of the study area.

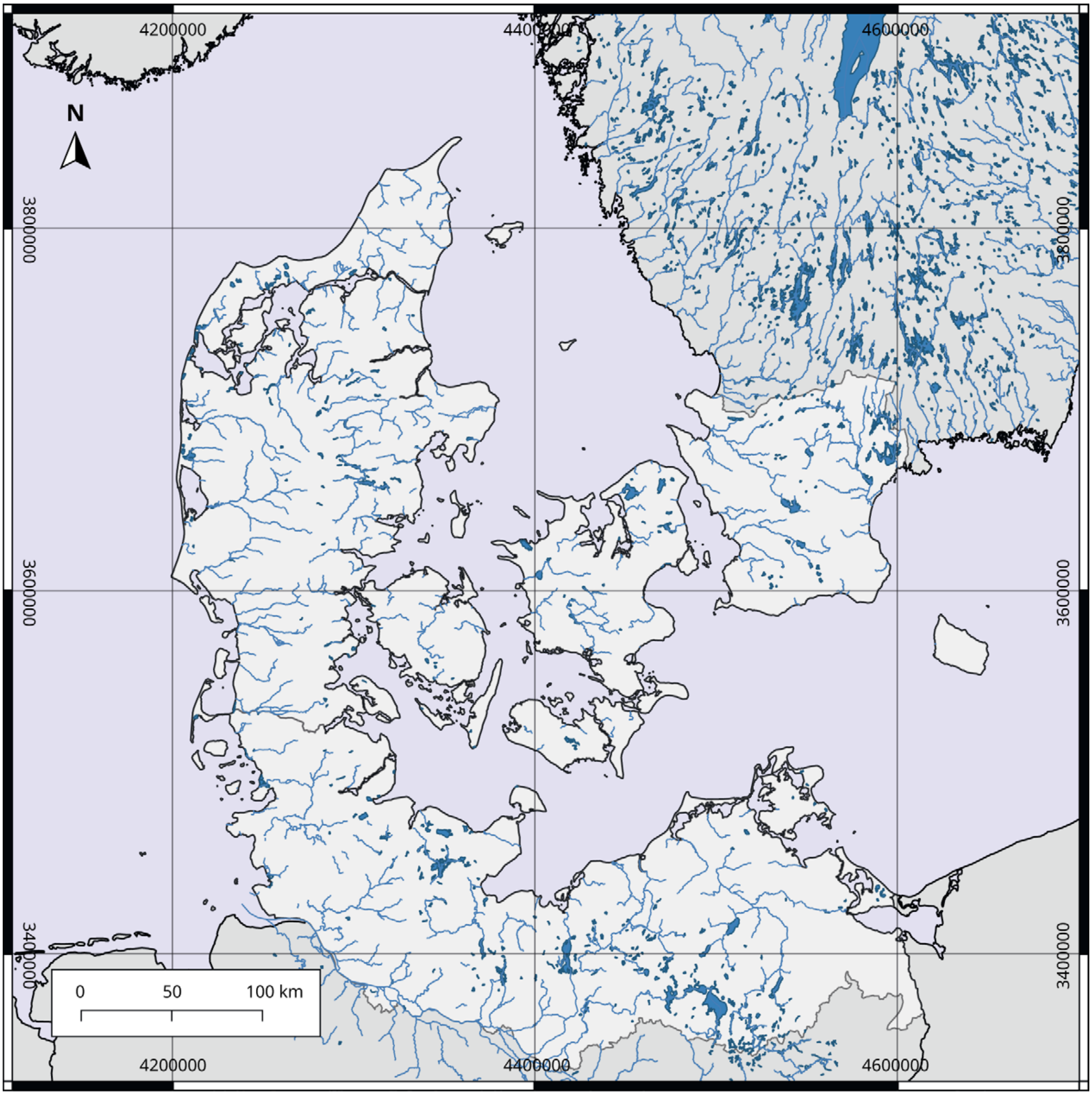


Figure 3. Rivers and lakes in the study region. Only rivers with a Strahler number above 3 and lakes with an area above 50 ha are shown. Data from EU-Hydro River Network Database (DOI: 10.2909/393359a7-7ebd-4a52-80ac-1a18d5f3db9c).

The land-use suitability across the study area is not uniform. In particular, the most agriculturally favourable regions, following modern-day classification and standards, are found in the eastern Cimbrian peninsula, the Danish Isles, and parts of Mecklenburg-Western Pomerania. In these areas, the main soils are luvisols, which are considered excellent arable soils (Figure 4; Zech et al., 2014). The combination of moderately acidic topsoils and subsoils with higher pH values enables the availability of all essential plant nutrients. However, long-term cultivation requires intensive fertilisation (Zech et al., 2014). On the other hand, the western part of the Cimbrian peninsular is much less fertile and less suitable for agriculture, as it is characterised by podsols, which are considered low-yielding soils because they are sandy, nutrient-poor and acidic, limiting optimal crop growth (WRB, 2022; Zech et al., 2014). This region also marks the limit of the Weichselian glaciation and the extent of morainic soils, which are generally more fertile (Lidmar-Bergstrom et al., 1991). In other areas, such as north-western Jutland, the main soil type is regosols, which have better agricultural properties than podsols but have lower nutrient content and higher

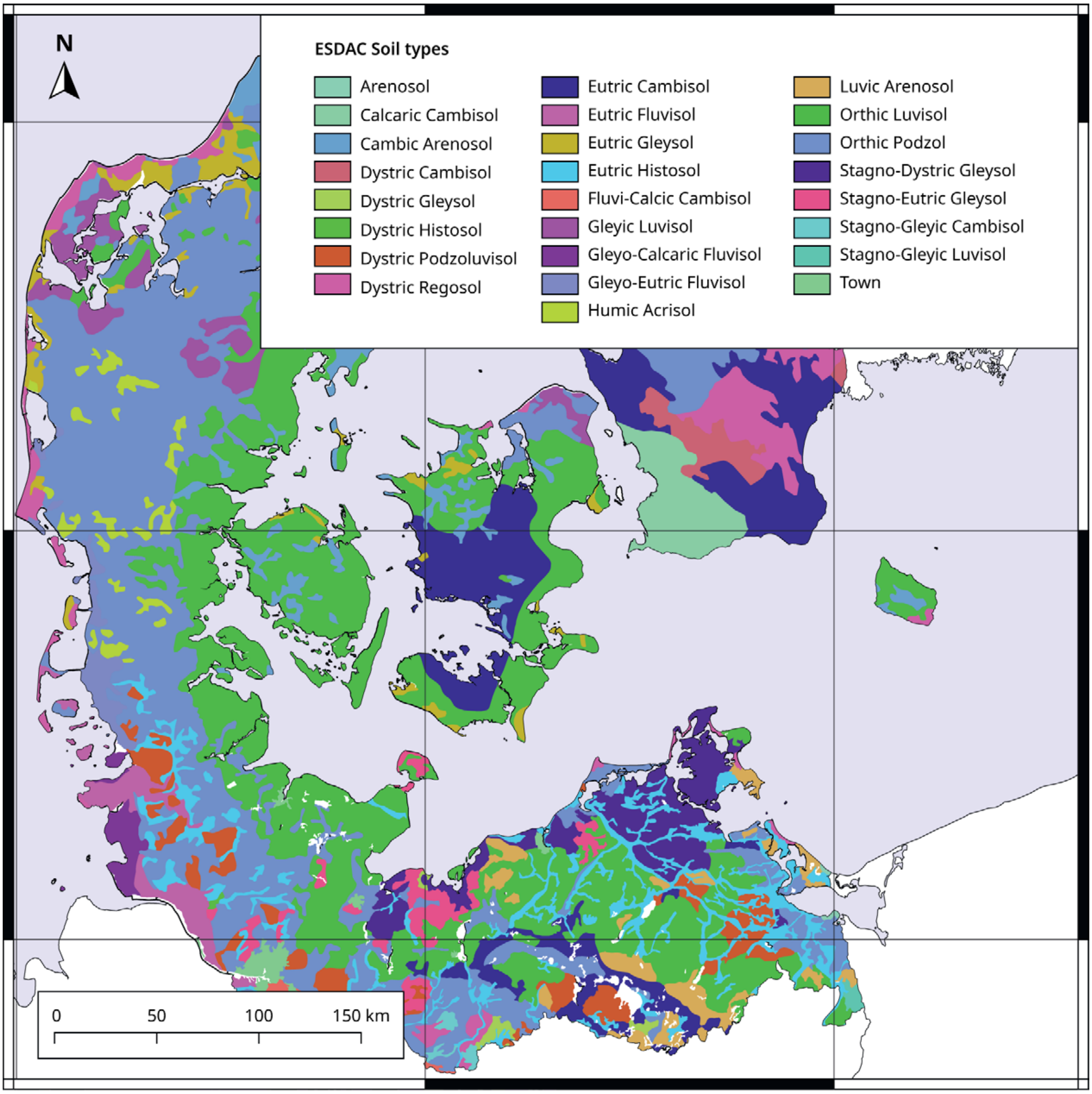


Figure 4. Soil map of the study area. Data from the European Soil Data Centre (ESDAC) (https://esdac.jrc.ec.europa.eu/).

erodibility compared to luvisols (Amelung et al., 2018). The predominant soils in Scania are cambisols, which have a varible agricultural suitability, depending on several factors such as soil depth and base saturation. However, they are generally suitable for pasture (Amelung et al., 2018; Zech et al., 2014).

Most of the study region falls within the so-called nemoral zone, characterised by temperate climate and winter freezing (Pfadenhauer and Klötzli, 2020). According to Walter's classification system, these regions are characterised by deciduous and temperate forest with frost resistance (Breckle and Walter, 2002). Annual temperature records from Fennoscandia indicate the coldest periods in the Holocene occurred around the 8.2 ka event (8200 BP) and during the Little Ice Age, between 500 and 100 years ago (Seppä et al., 2009). Cold anomalies were also identified between 3800 and 3000 BP, roughly corresponding to the Early Bronze Age, while the warmest period, known as the Holocene Thermal Maximum, was between 8000 and 4800 BP (*ca.* 6000-2800 BP; Antonsson et al., 2008; Seppä et al., 2009). These climatic variations are linked with oceanic and atmospheric circulation changes in the North Atlantic and northern Europe (Seppä et al., 2009). For instance, central Sweden's annual average temperature was 2.0-2.5°C higher than today's between 6000 and 4000 BP, although in July they were only 1.5°C above present day levels, aligning with global temperature reconstructions from Greenland ice cores (Dahl-Jensen et al., 1998). Colder periods during the Holocene Thermal Maximum were observed around 7000 BP (Mesolithic) and 5300 BP, during the Early – Middle Neolithic transition. However, this pattern is only observed in the annual averages and not in summer temperatures (Seppä et al., 2009). Central European evidence and glaciochemical proxies from Greenland suggest a cooling around 5800-5100 BP, possibly linked to a decrease in westerly circulation (Mayewski et al., 1997; Moros et al., 2004; O'Brien et al., 1995).

Post-5000 BP, palaeoclimatic reconstructions show a general cooling trend in average temperatures, with deviations such as those around 5000-4000 BP (Middle to Late Neolithic) and 3000-1000 BP (Late Bronze Age – Early Iron Age; Seppä et al., 2009). The end of the Holocene Thermal Maximum is marked by high temperatures and low humidity, particularly in Fennoscandia's continental areas, with significant reductions in lake levels or drying (Hammarlund et al., 2003; Seppä et al., 2009). The second period of warmth coincides with geological and climatological evidence from central Europe and the Alps, indicating widespread warm and dry conditions. Its peak around 2000 BP saw an average temperature increase of 2.3°C (Dahl-Jensen et al., 1998; Seppä et al., 2009). Warm periods are typically associated with dry conditions, while cold periods were humid, partially influenced by key atmospheric circulation processes in northern Europe. The warm, dry mid-Holocene period is associated with predominantly anticyclonic summer circulation (Antonsson et al., 2008). Deviation from this trend, such as the 3800-3000 BP cool period, are likely influenced by changes in dominant circulation type (Seppä et al., 2009).

1.2 Technical requirements

The present work was conducted on a Lenovo ThinkPad P16 Gen 1, equipped with a 64-bit architecture and 24 cores. It features a 12th Gen Intel(R) Core (TM) i7-12800HX processor. The machine has a memory capacity of approximately 125 GB (128507 MB). For the operating system, Ubuntu 22.04.3 LTS (Jammy) was used. The analyses were carried out using R version 4.3.1 (2023-06-16), 'Beagle Scouts'. RStudio version 2023.06.1+524, 'Mountain Hydrangea' Release (dated 2023-07-07) for Ubuntu Jammy, was utilised as the integrated development environment (Posit team, 2023; R Core Team, 2023). The code is adapted for Linux OS, but it can be easily modified to run on all operating systems with minimal adjustments, which are indicated within the code.

To perform some of the analyses in this study, a version of GRASS GIS is required (Geographic Resources Analysis Support System software; GRASS Development Team, 2023). Specifically, version 8 is necessary; I used GRASS GIS 8.3.1 in this case. Rather than using GRASS GIS as standalone software, its functions were accessed in R through the *rgrass* package (Bivand, 2023). Nevertheless, older versions of GRASS GIS can also be used, provided that the software is operated separately and its results are then imported into R. Similarly, installation of SAGA-GIS (System for Automated Geoscientific Analyses Geographical Information System software) is essential, with version 8.2.2 being used here. However, any release newer than version 2.3.1 suffices (Conrad et al., 2015). For interfacing with R, the *Rsagacmd* package was utilied (Pawley, 2023). The integration and use of these software tools and packages with R are described in the specific scripts where the analyses are conducted.

The R code used to produce this thesis is accessible on GitLab at the following link: https://gitlab.com/bilottigiacomo/pswb-demo-appendix. The provided scripts allow the reader to reproduce all the analyses or to adapt them for their own purposes. This is possible provided data accessibility, which is generally possible, apart from a few databases. In case of open data, instructions on where and how to download them are provided. This work has been composed in Quarto, an open-source scientific and technical publishing system, available at https://quarto.org/.

2. State of the archaeological research in the region

This chapter provides an overview of the current state of the archaeological research in the region. The different periods are briefly discussed, referencing pertinent scholarly works. The initial part of this section establishes the chronological framework of the thesis, detailing both absolute and relative chronologies. Subsequently, I outline the overarching trends and patterns identified in the region. Finally, a more detailed examination of each sub-phase is provided.

2.1 Chronology

The absolute chronological framework of this study spans from 4100/4000 BCE to 500 BCE, aligning with the 'Nordic' Neolithic and Bronze Age in relative terms. The relationship between relative and absolute chronology, as well as the introduction of technologies defining period subdivisions, is not straightforward. Therefore, the chronology proposed here simplifies reality, serving as a reference for timing the findings analysed in this study. The relative chronology for the region primarily relies on pottery and, depending on the period, stone and metal objects. The Neolithic chronology used in this study is shown in Table 1 and follows Müller (2017a). For the Bronze Age, I refer to the widely accepted, though revised, Montelius periods (Montelius, 1885; Thrane, 2013). The various sub-phases are briefly outlined in this section, with a more detailed description of each time window in subsequent paragraphs. All dates mentioned, unless specified otherwise, are calibrated.

Research history sometimes requires additional attention due to differences in scholarly traditions and countries. In instances of conflicting chronologies in the available literature, I will mention them for clarity, relying on absolute dating whenever possible to mitigate this issue.

Four main pottery traditions are identifiable within the Neolithic period. In northern Germany, these are termed Early, Middle, Younger, and Late Neolithic (Table 1). In Scandinavian literature, Middle and Younger Neolithic are referred to as Middle Neolithic A and B, respectively. For clarity, I will sometimes associate the two terms, but I use the former term.

The following sub-phases are used during the Neolithic (after Müller and Peterson, 2015):

- Early Neolithic I (EN I, *ca.* 4100-3500 BCE). Characterised by the emergence of Funnel Beaker (TRB, from the German *Trichterbecher*) ceramics in diverse regional groups such as Wangels/Flintbek, Volling, and Svalekint. Pottery styles

cal BCE	Period	S Jutland / Mecklenburg	Zealand / Scania	N Jutland
4200-4000	Late Mesolithic	Late Ertebølle		
4000-3800	EN Ia	Wangels / Flintbek	Svaleklint	Volling
3800-3500	EN Ib	Satrup / Siggeneben-Süd	Oxie / Svenstorp	Oxie / Volling
3500-3300	EN II	Wolkenwehe 1	Fuchsberg / Virum	Fuchsberg
3300-3200	MN Ia	Wolkenwehe 2	Troldebjerg	
3200-3100	MN Ib		Klintebakke	
3100-3000	MN II	Oldenburg	Blandebjerg	
3000-2900	MN III – IV	Bostholm	Bundsø / Lindø	
2900-2800	MN V	KA	Store Valby	
2800-2600	YN 1	Early Single Grave Group		
2600-2400	YN 2	Middle Single Grave Group		
2400-2200	YN 3	Late Single Grave Group		
2200-2000	LN 1	Early Dagger Group		

Table 1. Chronology of the Neolithic period in the region. Table after Müller (2017a).

range from simple, undecorated funnel beakers to more elaborate decorations. This period can be further divided into sub-phases Ia and Ib.

- Early Neolithic II (EN II, *ca.* 3500-3300 BCE). Marked by varied decoration patterns (*e.g.* Fuchsberg and Virum groups) and the construction of the first megaliths and enclosures.
- Middle Neolithic (MN, I to V, *ca.* 3300-2800 BCE). Continuation of megalith construction and the TRB society, with further intensification of ornamentation. The MN is divided into shorter phases: MN I (3300-3100 BCE), MN II (3100-3000 BCE), MN III/IV (3000-2900 BCE), and MN V (2900-2800 BCE).
- Younger Neolithic (YN, I to III, *ca.* 2800-2200 BCE). The periods correspond to the appearance of the Single Grave society, which is evident from marked changes in pottery design. Among the new characteristic elements of material culture there are flat-bottomed beakers with corded decoration and new types without typological links to late Funnel Beaker. Burials and settlement practices also change greatly.
- Late Neolithic (LN, I and II, *ca.* 2200-1700 BCE). The transition into LN is smooth and marked by a continuation of Single Grave traditions, with shifts in material culture. Bell Beakers play an important role in both domestic and burial sites and the LN pottery tends towards simpler, undecorated forms. The transition between LN I and II is generally set around 1900 BCE. Early metal imports are found during this phase. In some cases, the LN is articulated differently (*e.g.* Brink, 2009a) while in the south-eastern fringes of the study region the Bronze Age starts around 2200 BCE (Jockenhövel, 2013). However, as no case studies are coming from this area it will not be taken into account.

The Bronze Age (BA) lasts more than 1000 years and there are many changes occurring during this period (*ca.* 1700-500 BCE). The transition from the Neolithic is often gradual, with the earliest Bronze Age sometimes difficult to distinguish. For this reason, the beginning of the BA is subdivided in periods Ia and Ib, with the former period (*ca.* 1700-1600 BCE) closer to the LN tradition. The relative chronology is based on Montelius's six periods, albeit modified using various proxies, such as typology, and, when possible, dendrochronology (Montelius, 1885; Thrane, 2013). The corpus of publications is more extensive and precise for the Early Bronze Age (EBA periods I – III, each 200 years long spanning between 1700 and 1100 BCE) than for the following period IV – VI of the Late Bronze Age (LBA, 1100-500 BCE).

2.1.1 The Funnel Beaker Group: Early and Middle Neolithic

The process of neolithisation involved the domestication of livestock and crops, which became central to human diet and labour (Coward et al., 2008; Kerig, 2016). Recent decades have seen the unfolding of patterns of diffusion and regional differences, with a continuous flow of new and precise data (Colledge and Conolly, 2007; Gron and Sørensen, 2018). This transition began between 12,000 and 11,000 years ago, aligning with the end of the last ice age and the onset of the Present Interglacial Period (Larson et al., 2014). Contrary to some earlier perspectives, it has been shown that domestication was a complex and prolonged process (Larson et al., 2014; Price and Bar-Yosef, 2011). Originating in the Levant, Neolithic practices reached central Europe via south-east Europe around 7500 BP (*ca.* 5500 BCE), introduced by the *Linearbandkeramik* society. However, the expansion of farming halted for over a millennium, until around 4000 BCE, before reaching the North European Plain and southern Scandinavia (Rowley-Conwy and Legge, 2015). The arrival of farming in the study region marks the beginning of a distinct archaeological group, known as Funnel Beaker society (TRB), which reached southern and central Sweden (Sørensen, 2014). It appears that the limits of this initial expansion were defined by the distribution of arable land, halting at the boreonemoral-southern/middle boreal border (Sørensen, 2014: 72). Funnel Beaker societies occupied parts of central and northern Europe for a very long period, spanning from 4100 to 2800 BCE (Müller, 2017b).

Various factors, such as population growth, social dynamics, and resource availability, have been proposed to explain this expansion (Fischer, 2002). The spread of the TRB society and its Neolithic lifestyle was relatively rapid, as indicated by archaeological and radiocarbon data (Artursson et al., 2003; Kihlstedt, 1996; Persson, 1999). Already between 4000 and 3800 BCE Funnel Beaker society appears to be established with a well-developed social structure (Artursson et al., 2003). Theories explaining these shifts can be classified into three main categories: migrationism, indigenism, and integrationism, mirroring the concepts proposed for the Neolithic Transition in the rest of Europe, and attributing various degrees of integration to the local foragers (Artursson et al., 2003; Gron and Sørensen, 2018). However, recent genetic evidence shows a clear difference between the local Ertebolle group and farmers, with the latter sharing genetic similarities with central European agriculturalists (Allentoft et al., 2024; Malmström et al., 2009; Malmström et al., 2015; Mittnik et al., 2018). Currently, the process of neolithisation in the region follows a scheme divided in three phases: contact (4400-4000 BCE), introduction and negotiation (4000-3700 BCE), and homogenisation (post 3700 BCE; Gron and Sørensen, 2018; Müller, 2011a; Zvelebil and Rowley-Conwy, 1984).

Although the neolithisation dates to the turn of the 4th millennium BCE, some contacts between the Late Ertebolle and farming communities were already ongoing since the second half of the 5th (Gron and Sørensen, 2018). One of the earliest examples is a pit filled with TRB material from Flintbeck (Schleswig-Holstein) dated to 4300-3900 BCE (Gron and Sørensen, 2018; Mischka, 2011; Zich, 1992). Moreover, charred cereals have been found in two sites in Scania (Hyllye 165:79 and Oxie 50:1), also dating to the centuries around 4300-3900 BCE (Sørensen, 2014). From 4000 BCE, dated evidence of domesticated animals and cereals become widespread, the TRB flint toolset replaces the Mesolithic tradition, and a new type of house (two-aisled) appears (Artursson et al., 2003; Gron and Sørensen, 2018; Sørensen, 2014). Deposition, previously only sporadic, now becomes systematic, mostly concerning pointed-butted axes and funnel beakers (Gron and Sørensen, 2018; Sørensen, 2014). The diet shifts almost entirely from marine to terrestrial foods, though some uncertainties exist due to reservoir effects on radiocarbon dating (Fischer et al., 2007). By 3800 BCE, the diet was predominantly terrestrial and the distribution of EN sites and pointed-butted axes, dated to the first phase of the EN I (4000-3700 BCE), suggests a preference for easily workable soils and inland areas where Mesolithic occupation was limited (Gron and Sørensen, 2018; Sørensen, 2014). However, this aspect may be prone to a bias, as favourable arable soils may also have been preferred in modern times and therefore yielded more discoveries of sites or scattered finds (see Bilotti, 2023 for a discussion). Despite these changes, some continuity with the Late Mesolithic is evident, such as similarities between early TRB flint artefacts and those of the Ertebølle period, and the persistence of some lithic industries (Fischer, 2002; Gron and Sørensen, 2018). Similarities in pottery and the continued occupation of several Ertebølle period kitchen middens in the EN, without notable changes in faunal assemblages, are particularly evident in Northern Jutland, where geography favours marine resource exploitation (Gron and Sørensen, 2018).

2.1.1.1 The Early and Middle Neolithic landscape

Pollen diagrams show a similar picture of the transition, possibly underlining demographic trends. In pre-Neolithic times (4700-4100 BCE), evidence of human activity in northern Europe was limited, with dominant closed mixed oak woodlands and low levels of anthropogenic indicators (Feeser and Dörfler, 2015). Around 4500 BCE, some changes in woodland composition in northern Germany may suggest initial human impact, but direct archaeological evidence is missing (Feeser and Dörfler, 2015). The situation in Denmark, as illustrated by the results in Dallund Sø (Funen), reveals a landscape predominantly covered by deciduous forests, indicating a forested environment with minimal human influence (Rasmussen, 2005). Low human activity is further supported by sparse erosional deposits in the lake, indicating a low accumulation of minerogenic matter in the sediment layers (Rasmussen and Bradshaw, 2005).

With the onset of the Neolithic, significant changes in woodland composition are observed, particularly the decline of elm (*Ulmus*), ash (*Fraxinus*), and lime (*Tilia*) trees, and the rise of hazel (*Corylus*) and willow (*Salix*) (Feeser and Dörfler, 2015). Decline in elm is a widespread observation in north and west Europe and is generally attributed to the spread of a disease affecting this tree around 3800 BCE (Parker et al., 2002; Peglar and Birks, 1993). However, in eastern Schleswig-Holstein and Mecklenburg, this decline is associated with the presence of charcoal, which can be linked to human activity (Feeser et al., 2012). Nonetheless, large-scale open habitats and clear signs of agricultural activity from this period are still very limited (Feeser and Dörfler, 2015; Kirleis, 2022). A similar decline in elm during the Early Neolithic in Denmark is similarly interpreted as a combination of pathogen impact and human interference (Rasmussen, 2005). However, at Dallund Sø there is no clear evidence of archaeological sites that can support this inference (Rasmussen, 2005). Conversely, an increase in *Corylus*, *Quercus*, and *Alnus* pollen is also observed, indicating changes in forest structure (Rasmussen, 2005).

The results from pollen diagrams in Scania are rather similar, with charcoal dust associated with human activities (slash-and-burn) dated to *ca.* 4000 BCE and increasing concentrations of ribwort and birch, sometimes associated to a fallow agricultural strategy (Digerfeldt and Welinder, 1989; Sørensen, 2014). Early farming in Sweden is also supported by radiocarbon samples of cultivated cereals dated to *ca.* 4000 BCE (Hinz et al., 2012; Regnell and Sjögren, 2006). Lastly, cattle seems to have been important in this region from the beginning, as nitrogen isotopic values indicate that animal manure was used in Stensborg (Sweden) during the EN Ib and that cattle were reared year-round in open environments rather than forests (Gron et al., 2015, 2017; Gron and Rowley-Conwy, 2017). Dietary and isotopic analyses also show long-distance cattle movement, possibly indicating small, isolated herds, that needed to be moved across long distances for breeding (Gron et al., 2016). Despite evidence for a widespread Neolithic lifestyle, the impact of the new population was still relatively low, with farming conducted on a small scale and without extensive forest clearance. Traces of early animal husbandry are also recorded in Danish and northern German contexts, with some cases from northern Germany dated to a very early transitional phase (Sørensen, 2014: 86).

After 3750 BCE, *Plantago lanceolata* becomes a prominent feature in all pollen profiles across northern Germany (Feeser and Dörfler, 2015). Other anthropogenic indicators like *Poaceae* and *Rumex* also increase from this period onwards, as does cereal-type pollen. In addition, there are noticeable regional variations in arboreal species, with a decrease in *Betula* and an increase in *Fagus* (Feeser and Dörfler, 2015). These patterns suggest the establishment of permanent open areas, likely linked to novel land-use practices by farming populations, who cultivated cereals on larger fields with fallow periods, resulting in a high content of grass species (Feeser et al., 2012). Feeser et al. (2012) interpret these changes as indicative of technical advancements like the ard plough, whose marks have been identified in various parts of the Baltic Sea basin, generally dated to the latter half of the Early Neolithic I (Mischka, 2011; Niesioowska-Śreniowska, 1999; Thrane, 1989). The expansion of agricultural practices appears to peak around 3500 BCE, and at approximately 3300 BCE an increase in mixed oak forest taxa is noted, while pollen from non-arboreal species diminishes (Feeser and Dörfler, 2015). This trend is interpreted as a reflection of reduced land-use activities and the subsequent regeneration of forests (Feeser and Dörfler, 2015). This coincides with a period of climatic deterioration, marked by a notable decrease in summer temperatures from 3350 to 3000 BCE, as corroborated by sedimentological studies conducted in the region (Dreibrodt et al., 2012). However, regional variations are evident, with eastern Schleswig-Holstein exhibiting a brief phase of renewed activity between 3200 and 3125 BCE (MN Ib), unlike western Mecklenburg – potentially reflecting differences in regional vulnerability or land-use strategies (Feeser and Dörfler, 2015). Then, around 3000 BCE (MN III/IV), arboreal taxa decline again, and non-arboreal pollen increases, likely signalling woodland clearance and human activities (Feeser and Dörfler, 2015). Around 2900 BCE (MN V), the anthropogenic indicators revert to pre-3300 BCE levels (Feeser et al., 2019; Feeser and Dörfler, 2015).

Around 3530 BCE, a distinct peak in *Betula* pollen is observed in the Funen pollen diagram (Rasmussen, 2005) shortly followed by the first evidence of cereal cultivation (3460 BCE), indicated by the presence of *Avena/Triticum*-type grain. *Plantago lanceolata* suggests the start of animal husbandry in the area by 3320 BCE (Rasmussen, 2005). Overall, EN pollen diagrams from Funen correspond with the archaeological record and those from Germany, showing an increase in site intensity in the latter half of the EN I, linked by the literature to megalithic grave construction and the first traces of the ard plough (Feeser and Dörfler, 2015; Rasmussen, 2005; Thrane, 1989). A later reduction in human impact on the landscape seems also visible in pollen diagrams from southern Sweden and in particular from the Ystad area (Berglund et al., 1991). This phase, termed the 'Middle Neolithic forest regeneration phase', is associated with a decline in human population and a concentration of settlements in coastal areas (Friman and Lagerås, 2023).

Nevertheless, following this initial period of low impact and possibly partial coexistence with earlier settlers, a more cohesive TRB group emerged during the EN Ib – II (post-*ca.* 3700 BCE). This is the time when the first megalithic graves are built, which probably implied a more organised and populous society and a more open landscape (Persson and Sjögren, 1995). Before the construction of these monuments, TRB communities where building earthen long barrows, monumental constructions that were less labour-intensive than dolmens and passage graves (Sørensen, 2014). This shift in construction has also been explained in terms of changes in demographics and technologies after 3600 BCE (plough, wheel, improved sea-faring techniques), causing changes in the social structure, the decision-making chain, and the mobilisation of workforce (Müller, 2019).

Radiocarbon and pollen data show that a boom in human occupation occurred during this phase and in particular during the MN I. This partially reflects the flint axes distribution, with the thin-butted axes, dated to the second part of the EN I to the MN II covering a wider area compared to the older point-butted axes (Sørensen, 2014: 176; see Figure 10 for Scania).

2.1.1.2 Settlements and houses during the TRB

The transition from the Late Ertebølle to the Early Funnel Beaker period is characterised by a notable shift in house structure, with the previously prevalent small huts being generally replaced by larger two-aisled houses (Artursson et al., 2003; Müller, 2013c). The Mesolithic huts were usually round or D-shaped with an area under 20 m^2, although some larger structures reaching up to 70 m^2 have also been found (Sørensen, 2014). Besides a change in house construction, the new structures tend to be located more inland and on arable land, whereas Mesolithic sites were generally located in coastal environments or at lake shores (Sørensen, 2014: 178).

The house size of TRB houses varied considerably, ranging from less than 20 m^2 to *ca.* 150 m^2 (see Chapter 4). These houses generally have an oval shape and feature a single row of roof-bearing post-holes (Artursson et al., 2003). However, hut-like structures similar to the Late Mesolithic ones are still found, with floor areas up to 60 m^2 (Artursson et al., 2003; Sørensen, 2012). The diversity in house structures and dimensions might have been influenced by varying building traditions of different households or their intended functions (Sørensen, 2014). Radiocarbon dating indicates these structures were in use from the beginning of the Neolithic in the region, although more secure contexts start to appear from 3800 BCE, aligning with the other archaeological evidence (Sørensen, 2014). Similar house types have been found in Lower Saxony, the Netherlands and the British Isles, and have been connected to the spread of agriculture in these previously marginal areas (Müller, 2019; Sørensen, 2014).

The house typology from the Early and Middle Neolithic in the region can be divided into five groups. The earliest type of two-aisled house is the Mossby type, which dates back to the EN I – II, with a few examples from the MN I (Artursson et al., 2003). These houses are characterised by rounded gables and convex long sides. The Dagstorp I type, predominantly dating to the MN I, with some earlier examples during the EN, has straight ends and a trapezoidal shape. This type is followed, although some chronological overlap is observed, by the Dagstorp II type, dated between the MN I and III. Type II houses are similar to type I but do not have a trapezoidal shape (Artursson et al., 2003). In the MN V, the Limensgård type emerges, featuring wall ditches and straight narrow sides (Artursson et al., 2003). The last type of structures are the huts, which have already been discussed.

Settlement structures suggest a society focused on small-scale farming and animal husbandry. A typical main settlement would feature at least one large used for dwelling, along with smaller buildings serving various purposes and other activity areas, such as ritual structures, cooking areas, or waste management sites (Artursson et al., 2003; Larsson, 1984, 1992). Nevertheless, in few cases hamlets have been found, mostly dating after 3350/3300 BCE, such as Büdelsdorf and Oldenburg-Donnau (Brozio, 2016, 2019; Hage, 2016; Mennenga, 2016; Müller, 2019). The current interpretation of TRB social organisation is that it was centred around an extended nuclear family, living together in a farmstead, located close to all the necessary resources (Artursson et al., 2003; Larsson, 1984). Settlements were likely short-lived, relocating periodically to maximise resource utilisation. Alongside the typical Neolithic economy, hunting, fishing, and gathering activities are recorded as secondary activities within settlement assemblages (Artursson et al., 2003; Lübke et al., 2009). The presence of jade axes and their numerous imitations from 4000-3500 BCE indicate that the TRB population in southern Scandinavia was well integrated into the broader European network of contacts, particularly with central Europe and the Alpine region (Pétrequin et al., 2012; Sørensen, 2012).

2.1.1.3 Burial practices during the TRB

Burial practices in the region include flat-graves, long barrows and megalithic graves (Blank, 2021; Müller, 2011b; Sjögren, 2003). Megalith construction did not originate in the study region and earlier examples have been found in other parts of Europe (Müller, 2011b; Schulz Paulsson, 2019; Sjögren, 2003).

The oldest monuments found in the region are long barrows. They are earth monuments with an elongated shape, often containing several burials. They first emerged in western France around 4700-4300 BCE and are typical of the Cerny period (Rzepecki, 2011; Sørensen, 2014). They were sometimes found in groups, placed parallel to each other and could be a few hundred meters long (Rzepecki, 2011). Their construction persisted also during the Michelsberg period, albeit they were much shorter (20-70 m; Sørensen, 2014). Radiocarbon dating suggests their introduction to Britain, Poland, Denmark, and South Sweden from 4000 BCE, with most of the ^{14}C dates from the burial chambers indicating construction between 3800 and 3500 BCE (Müller et al., 2014; Müller, 2019; Sørensen, 2014). The grave goods found in the long barrows in the region point towards a similar dating to the second phase of the EN I (Sørensen, 2014: 215).

Flat-graves with inhumation burials are contemporary with the long barrows. An analysis of the burial types and the grave goods suggests that differences in ritual were not necessarily connected to class differences but rather to local traditions (Kossian, 2005; Lübke et al., 2009; Müller, 2019). However, a few of these graves pre-date long barrows and probably represent the first type of burials of the TRB communities in the region, although the majority are dated to 3800-3200 BCE (Lübke et al., 2009; Müller et al., 2014; Price et al., 2007; Sørensen, 2014). Alongside these practices, human sacrifices or executions were also practiced, as testified by the presence of human remains with signs of violence in bogs (Bennikke and Ebbesen, 1986; Price et al., 2007).

South Scandinavian causewayed enclosures often resemble those of the Michelsberg society in location, shape, and construction features, like oval structures with ditches or dykes (Andersen, 1997; Müller, 2011b). Many Danish enclosures are situated near natural crossings, and probably played a crucial role in transportation networks during the Early TRB society. These enclosures likely served multiple purposes, including the storage of crops and the performance of ritual practices (Brink, 2009a; Sørensen, 2014). They probably represented ritual *foci* within the landscape and they are always associated with megalithic burials (Müller, 2011b). The two earliest found and excavated in the study region are the enclosures of Sarup (Denmark) and Büdelsdorf (Germany) and this type of structure is dated between 3600 BCE and the end of the TRB (Dibbern, 2016; Müller, 2011b; Torfing, 2021).

Dolmens, the earliest megalithic burials in the region, date from around 3600 BCE (late EN I – early EN II) to *ca.* 3300 BCE (EN II – MN Ia transition; Müller, 2011b; Persson and Sjögren, 1995; Sjögren, 2003; Sjögren and Fischer, 2023). A dolmen is defined as a rectangular or polygonal chamber, with a maximum length of 3 m and passages, if present, less than 1.5 m long (Sjögren, 2003: 80). Although they exhibit typological differences (small, extended, and large dolmens can be observed), chronological differentiation is often not possible due to overlaps (Wunderlich, 2019). It is not uncommon that some dolmens were built inside older long barrows, as has been recorded in Borgstedt, where a dolmen dating 3700-3650 BCE was erected in a long barrow 100/200 years older (Hage, 2016; Müller et al., 2014).

Passage graves are the second and last stage of megalithic construction within the TRB societies and are assumed to date after 3350 BCE (Blank et al., 2020; Persson and Sjögren, 1995; Sjögren, 2003). They are characterised by chambers with passages longer than 1.5 m and are built on the soil surface, later covered by cairns or mounds, although regional variation is not uncommon (Sjögren, 2003: 80). Most of these structures are located in northern Germany and Denmark, with a smaller quantity located in Scania (Müller, 2019). Furthermore, it is evident that they represented important markers in the landscape as they have been repurposed or modified during later periods, even when connections to their constructors were lost (Blank, 2021; Müller, 2011b).

Radiocarbon dating suggests that megalithic graves appeared in the second half of the 5th millennium BCE in regions like north-west France, the Mediterranean, and the Atlantic coast of the Iberian Peninsula (Schulz Paulsson, 2019). The likely origin is north-west France, where a pre-megalithic monumental sequence and transitional structures are observed. The spread of the phenomenon occurred during the first half of the 4th millennium BCE via maritime connections in the Mediterranean and the Atlantic facade, reaching Scandinavia and the Funnel Beaker areas by the mid-second half of the 4th millennium (Schulz Paulsson, 2019). These developments highlight the social and economic changes of the period, such as enhanced navigation skills and technology, and the organisation necessary for maintaining long-distance networks, as evidenced by jade axes, obsidian, and amber trade throughout Europe (Pétrequin et al., 2012; Schulz Paulsson, 2019; Tykot, 1996).

2.1.2 Younger Neolithic

The Younger Neolithic period is marked by relatively little archaeological visibility in part of the study area (Larsson, 2015). However, the available archaeological data from north Germany and Denmark indicates an important change in material culture and social organisation. In the Danish and Swedish literature this period is termed as MN B, while the preceding TRB MN is referred to as MN A, encompassing the Pitted Ware cultural tradition, which is not included here because is mostly located outside the study region, except for northern Scania (Svensson, 2003). Additionally, hybrid forms between the Funnel Beaker and Pitted Ware societies have been noted both within the Funnel Beaker core areas and in north-western Scania (Svensson, 2003). As none of the case studies addressed here include Pitted Ware contexts, this archaeological group is not further discussed.

In the study region, the period is distinguished by two archaeological groups, based on material culture: the Battle Axe and Single Grave societies (Larsson, 2015; Schultrich, 2019). Both groups are associated with farming and animal husbandry, whereas it is assumed that the Pitted Ware society had more reliance on hunting and gathering (Larsson, 2015). Compared to the TRB and LN periods, evidence of YN settlements and habitation structures are more limited (Larsson, 1995; Svensson, 2003). During this period, palisade structures are known from some parts of the study region, such as the one found by the coast west of Malmö, or the palisade in Dösjebro, western Scania (Brink, 2009b). Other palisades are found in other parts of the study region, such as on Bornholm and Zealand (Brink, 2009b; Brozio et al., 2019). These structures are interpreted as central gathering places, holding some sort of social and ritual significance for larger geographical areas and groups of people (Brink, 2009b). They typically consist of one or more rows of post-holes, often with ditches (Brink, 2009b). Several activities were taking place in the palisades, such as flint burning, the production and distribution of axes and, in some cases, it has been suggested they hold a defensive function (Brink, 2009b). Their defensive function has been linked to unrest at the end of the Funnel Beaker period, influenced by the Corded Ware cultural complex. Overall, palisades were constructed in areas with a long history of habitation, evidenced by older remains in the area (Brink, 2009b).

Malmer (2002) attributed the scarcity of settlements and houses from this period to a research bias or the difficulties in identifying residential structures from this period, whereas Larsson (2006) associates the decreased visibility with a higher impact of animal husbandry and a more mobile society, sometimes defined as nomad (Andersson, 2004). However, towards the end of this period (post-2500 BCE), farmsteads appear more regularly, and large-scale excavations have uncovered longhouses, indicating a sedentary, agriculture-based society (Brink, 2009a, 2009b). This is the case for western Scania, where houses have been found in Dagstorp 11, Dagstorp 19, and Dösjebro 19 (Andersson, 2004), southern Scania at Almhov (Björhem and Magnusson Staaf, 2006; Brink, 2009a), and on Bornholm at Limensgård (Nielsen, 1999). Certainly, these are only few examples and for a more complete account of YN houses I refer to the specific literature (M Larsson, 1992, 2015). Nevertheless, the quantity of YN houses is lower than the MN and the LN periods.

Larsson and Andersson propose that the social structure of the Battle Axe society gradually evolved towards increasing complexity, while Malmer suggests that it was already fully developed since the beginning and experienced little change during the YN (Andersson, 2004; Malmer, 2002). In this latter view, Malmer assumes that the individuals buried were part of a ruling aristocracy (Malmer, 2002). The relationship between the Battle Axe culture and the Funnel Beaker society is seen as an ideological conflict between social systems. In this interpretation, the individualistic social system of the Battle Axe society ultimately prevailed over the more collective systems of the Funnel Beaker and Pitted Ware ones. The transition from the Younger to the Late Neolithic seems to have been relatively smooth (Brink, 2009a, 2009b).

The situation within the Single Grave society in Denmark is similar, with few house structures and settlements preserved (Larsson, 2015). Among the excavated structures, some of the best-known examples are the house dating to the late Single Grave period (2500-2400 BCE) from Hemmed in East Jutland, and the house from Enderupskov in southern Jutland (Boas, 1991; Ethelberg, 2000). In northern Germany, more settlements have been identified, including six that have been excavated, revealing traces of permanent habitation in Schleswig-Holstein (Schultrich, 2019: 56 ff.). The most striking aspect of the northern German and Danish YN is the predominance of burials over settlements. In Schleswig-Holstein alone, there are more than 300 burials from this period, including nearly 200 burial mounds (Schultrich, 2019: 26 ff.; Hübner, 2005). Nevertheless, the primary source of YN material culture in the region is the so-called battle axes, a widespread type of polished stone artefact, showing the existence of a rather complex society (Schultrich, 2019: 43 ff.; Hübner, 2005).

Settlement patterns changed noticeably in the YN, but occupied areas remained largely the same, with continuity into the LN period (Andersson, 2004). In some regions, settlement (in terms of territory) continuity since the MN III is observed and has long been noted , even before the first YN houses were found (L Larsson, 1992; *e.g.* Malmer, 1962). This is however not the case for Battle Axe graves, generally found in areas with little evidence of previous occupation (L Larsson, 1992). Funerary practices in this period are characterised by inhumation in flat graves in the Battle Axe society and under low rounded mounds in the Single Grave society, with occasional reuse of TRB megalithic burials and use of small stone cists (Schultrich, 2019; Sjögren, 2015). The reuse of older burials is generally widespread, though it is more common in Denmark (Schultrich, 2019: 267). Although less frequent, flat graves were also used within the Single Grave culture. The relatively low number of identified flat graves may be due to research bias, as recent excavations in Jutland suggest (Schultrich, 2019: 267). Flat-graves typically contain single individuals, though collective or multiple burial have also been found. In both cases, sexual dimorphism is exhibited in grave goods and body orientation (Sjögren, 2015). Sometimes, cremations are also recorded, likely linked to secondary burial practices (Sjögren, 2015) and might represent an influence from central German traditions (Schultrich, 2019: 267).

The pollen diagrams available for this period generally show a reduction in the anthropogenic indicators, with reforestation patterns observed in parts of Jutland, Funen and northern Germany (Feeser et al., 2012; Rasmussen, 2005). The timing is sometimes slightly different depending on the region but the trend is represented in most studies.

2.1.3 Late Neolithic

The Late Neolithic period marks the initial transition between the Neolithic and the Bronze Age, evident in significant changes in settlement patterns and house structures. During this period, house sizes increased considerably, becoming more prominent, and settlement structures grew more complex, with some forming larger agglomerations, leading scholars to describe them as hamlets or villages rather than mere farmsteads (Brink, 2009a; Larsson, 2015; Müller and Vandkilde, 2020; Vandkilde, 2005; Vandkilde and Northover, 1996). Several researchers argue that evidence of a hierarchical society in the region emerged during this time (Artursson, 2005b; Artursson, 2007a; Müller and Vandkilde, 2020), though there is no consensus on the social structure. Ebbesen (2011) challenges the idea of marked social differences, proposing a more tribal society for this period. The main argument for increased social complexity is the larger difference between the largest and smallest houses (Artursson, 2009: 51 ff.). There is still no agreement on whether this shift and the formation of the first chieftains already happened before 2000 BCE (as argued by Artursson, 2009: 204 ff.) or only after (as suggested by Kristiansen, 2006).

During this period, the same cultural tradition appears to have expanded into new regions, with northern Germany and southern Scandinavia becoming more unified again (Larsson, 2015). Flint daggers emerged as the most significant prestige artefact, replacing the earlier flint axes, and sophisticated bifacial flint-knapping techniques were developed (Vandkilde, 1996). The building tradition seems to become more standardised and the concept of a house gained greater centrality in people's lives (Artursson, 2005b; Björhem and Säfvestad, 1989; Larsson, 2015). Median house size increased as did the number of recorded settlements. These aspects have been connected to intensified agricultural activities and a growing population (Artursson et al., 2003; Kristiansen and Larsson, 2005). During this period, long distance networks became more stable and new ones were also established, with an increase in gold and copper imports (Artursson, 2009; Kristiansen and Larsson, 2005).

The pollen diagrams for this period show a clear inversion of the trend observed during the YN, with a renewed phase of landscape opening. Towards the end of the LN, the diagrams from Dallund Sø (Funen, Denmark) show that a minimum in tree cover was reached, possibly reflecting anthropogenic factors (Rasmussen, 2005). A significant regional increase in human activities is also evident from the pollen diagrams in northern Germany, particularly after 2100 BCE (Feeser et al., 2012; Feeser et al., 2019).

2.1.3.1 Late Neolithic settlement structure

During this period, house typology ranged from pit houses to longhouses, some of which had preserved sunken floors (Larsson, 2015). Similar to earlier periods, longhouses typically exhibited a two-aisled structure (Artursson et al., 2003). A common type was the Fosie type, named after the site Fosie IV in southern Malmö, where a significant number of longhouses were identified (Björhem and Säfvestad, 1989). The typical house had a rectangular shape and three roof-bearing post-holes (Björhem and Säfvestad, 1989). Excavations at Fosie IV and other regional sites suggest that a widespread settlement pattern was that of single farms, with one or more houses being replaced over time within the same area (Björhem and Magnusson Staaf, 2006). Larger houses (> 30 m), called Piledal type, have been found at several locations, such as Limensgård (on Bornholm), Almhov, or Piledal (in Scania), after which they have been named (Björhem and Magnusson Staaf, 2006). The emergence of these larger houses is interpreted as indicative of increased competition, potentially linked to the growing importance of foreign imports such as metal objects (Björhem and Magnusson Staaf, 2006).

The hypothesis of increased social complexity during this period is drawn from a well-investigated area in south-western Scania, particularly around Malmö. The landscape organisation, especially in the settlement of Almhov, suggests a higher social complexity or demographics. However, this could be related to the site's geographical location, near the Øresund (or Öresund) channel, a crucial route for maritime and terrestrial movement and long-distance contacts (Björhem and Magnusson Staaf, 2006; Brink, 2009a; Brink and Hammarstrand Dehman, 2013). In fact, Almhov has been interpreted as the dominant residential unit in the area and has been linked to socially prominent families (Artursson, 2009; Brink, 2009a). Its importance as a hub seems to be supported by the concentration of graves containing flint daggers and bronzes from the Late Neolithic and the earliest Bronze Age along the coast, interpreted as high-status cemeteries (Brink and Hammarstrand Dehman, 2013). On the other hand, the burials more closely connected to Almhov and the Hyllie area consist of simpler structures, where no status-indicating finds have been identified, possibly belonging to the local farming population (Brink and Hammarstrand Dehman, 2013). However, besides this and a few other cases, the settlements appear to have been more dispersed in the landscape (Stromberg et al., 2014).

However, interpretations of settlement structures during the Late Neolithic are varied. A notable case is Limensgård on Bornholm, where 16 longhouses dating to the Late Neolithic were excavated. These structures were situated within a roughly 100 × 100 m area, slightly larger than farmstead A in Almhov (the largest). Nielsen (1999) interprets the site as a single farmstead moving around over approximately 400 years, with each house used for an average of 25 years. In contrast, Artursson (2005b) suggests the presence of four coexisting farmsteads over three chronological phases, based on architectural features, spatial relationships, stratigraphy, and radiocarbon dating of the longhouses. Each farmstead comprised a single longhouse with an annex, with longhouses lasting between 100 and 150 years (Artursson, 2005b: 104 ff.). This scenario would be akin to that of Almhov, with multiple farmsteads existing simultaneously. This study does not aim to solve this divide in the current literature and the question will only be tackled from its demographic perspective in Chapter 4. Nonetheless, this is the first period when settlements with more than a single farmstead have been systematically identified.

2.1.3.2 Late Neolithic funerary practice

During the Late Neolithic, a diverse range of burial practices were employed, reflecting the period's complex social and cultural dynamics, similar to those observed in settlement organisation. The most notable development in this period is the emergence of gallery graves, alongside the continued use of older dolmens and passage graves, as well as the construction of individual flat graves (Blank et al., 2020; Sjögren, 2015).

Gallery graves or 'stone cists' are a type of burial found during this period, as well as during the Bronze and Iron Age (Blank et al., 2020). A gallery grave is a type of funerary monument featuring a four-sided chamber constructed with stone slabs, typically longer than 2 m. These graves often include gables and a passage or antechamber (Sjögren, 2003: 80). As usual, variation in design is common. Gallery graves can be constructed above ground and later covered, or they can be excavated into the ground (Sjögren, 2003: 80). One challenge with gallery graves is their typological resemblance to dolmens, which can sometimes lead to confusion or misinterpretation (Blank et al., 2020).

2.1.4 Bronze Age

The Nordic Bronze Age spanned the entire study area and parts of the western Baltic, with its commencement varying between 2200 BCE and 1700 BCE depending on the region (Jockenhövel, 2013). The Bronze Age is a time of change in the study region in terms of socio-political and economic change. While bronze and copper became more prevalent than in the Late Neolithic, arriving in larger quantities and not just as finished products, many Late Neolithic traditions, such as flint dagger production, persisted (Jockenhövel, 2013).

The beginning of the Bronze Age was closely linked to metal-using regions like the Únětice society, which supplied the first metal objects to the south-west Baltic, mostly before 1600 BCE when local production took off (Jockenhövel, 2013; Kristiansen, 2022a, 2022b). Increased contacts with southern societies, such as the Sögel-Wohlde, probably influenced the newly established burial traditions, with inhumations in burial mounds north of the Elbe starting from Bronze Age period II (Jockenhövel, 2013). The construction of burial mounds then became a characteristic feature of the local Bronze Age tradition (Thrane, 2013). Generally, they were built with turf but cairns are also widespread, especially in Scandinavia and depending on resource availability (Kristiansen, 2018; Thrane, 2013). Rock art is also a distinct Nordic characteristic during the Bronze Age, but it was limited to areas with rock outcrops, which within the study regions is limited to western Scania (Ling, 2008; Thrane, 2013). Bronze tradition in northern Europe is characterised by a very rich production and the presence of very local typologies (Vandkilde, 1996). The Nordic Bronze Age is noted for its rich production of bronze artefacts and local typologies, with southern Scandinavia having Europe's highest density of bronze artefacts, despite the lack of local copper deposits (Thrane, 2013).

Period I is sometimes very difficult to distinguish from the end of the LN, indicating the smooth transition between the two phases. A more noticeable difference starts to be visible from the end of period I (EBA Ib) and more markedly from period II. It is in this period that the first three-aisled longhouses are recorded; the most characteristic feature of Bronze Age settlements (Artursson and Björk, 2007). Artefact typologies and distribution allow the identification of some local groups, such as the western Holstein, the western Mecklenburg or the Segeberg (in central Holstein) groups (Jockenhövel, 2013). By period III, the Nordic Bronze Age tradition is well-established, including also previously marginal areas of the southestern part of the study region (Mecklenburg-West Pomerania) (Jockenhövel, 2013). The transition from Early to Late Bronze Age saw a shift in burial practices, with cremation becoming predominant over inhumation, a change connected to socio-economic turmoil (Jockenhövel, 2013; Kristiansen, 2018, 2022a). Cemeteries in this period are organised in the so-called urnfields, which can contain up to several hundred burials, following a southern German tradition (the Urnfield society) that spread across many parts of Europe (Jockenhövel, 2013). It is not uncommon that cemeteries in northern Germany were located around older monuments, such as megalithic tombs or barrows (Jockenhövel, 2013).

However, this change was not unidirectional. In fact, during periods IV and V, regional traits of bronze typologies typical of northern Germany and southern

Scandinavia spread across the German lowlands and the Netherlands. Generally, LBA burials do not contain many grave goods, although some cases of extremely rich burials have been found, such as the one in Albersdorf, in western Holstein or the two burials from Lusehøj, on Funen (Jockenhövel, 2013; Thrane, 1984, 2013). Another well-known example is the King's grave found in Seddin, which is, however, outside the study area considered here (in Brandenburg).

Period V saw an increase in imports from southern Germany and the Swiss Alps, indicating a shift in long-distance trade networks from the previously predominant Danube basin. The end of the Nordic Bronze Age in Period VI witnessed lower bronze circulation and the influence of Early Iron Age Hallstatt (Jockenhövel, 2013). Compared to the Early Bronze Age, the Late Bronze Age saw an increase in bronze depositions and hoards, with a consequent reduction of bronze artefacts found in tombs (Jockenhövel, 2013). Similar to the LN-EBA transition, the passage to the Iron Age was rather smooth, with a persistence of burial practices and metal depositions continuing into the later phases (Vandkilde, 1996).

The Bronze Age is characterised by a decline in forest cover, often linked to population growth. A marked reduction in tree pollen, associated with deforestation, is observed in southern Sweden, suggesting newly cleared areas were used for grazing, while arable land increased more gradually during the entire Bronze Age (Lagerås and Fredh, 2020). During the EBA, *Fagus* is established in some parts of Denmark (after 1500 BCE) and the diagrams show a rather forested landscape on Funen around Dallund Sø (Rasmussen, 2005). During the LBA, a decline in *Corylus* is observed, connected to forest clearance and animal browsing (Rasmussen, 2005). Other forest-related pollen declines, coupled with an expansion of herbaceous vegetation connected to agricultural practices. Additionally, the decline in wetland tree species and the rise of damp meadow-associated pollen suggest a transformation of wetlands into open fens and meadows, likely used for grazing and hay making (Rasmussen, 2005). This trend of increasing landscape openness and human influence occurs later compared to north-western Jutland (Hessing Huse Mose), where a significant increase in openness was already evident around periods III and IV. This level of openness in the landscape was unparalleled until much later historical periods (Bech, 2018c). After that period, a reduced human impact in the area is observed. This pattern is matched by the radiocarbon distribution available for Thy, with a peak observed in this period (Bech, 2018c).

2.1.4.1 Metal economy and social organisation

After 2000 BCE, bronze started to become the primary material for tools, weapons and ornaments in Europe, leading to significant changes in the economic system (Kristiansen, 2022a, 2022b). This shift entailed the formation of new political alliances to connect regions producing copper and tin with areas of consumption (O'Brien, 2014). Archaeological evidence indicates that this trade was overseen and protected by an emerging class of warriors equipped with more efficient bronze weapons (Kristiansen, 2022b: 89). Conflicts over trade networks and their control points, including raids on trade caravans, likely provided the means of power and livelihood for these warriors (Kristiansen, 2022a, 2022b). This may be the reason behind the construction of an increasing number of 'fortifications' from the EBA, with a peak in the LBA and following Iron Age (Kneisel et al., 2022). Different local economies are more deeply interconnected in this period and, more importantly, reliant on long distance networks and possibly on broader political structures, a phenomenon Helle Vandkilde termed '*bronzization*'; aka a pre-modern form of globalisation (Earle et al., 2015; Vandkilde, 2016).

In the study region, similar to neolithisation, the adoption of bronze smelting and artefact casting was slightly delayed, as these processes originated outside the area.

Until around 1600/1500 BCE, most copper was imported as finished products from the Únětice region, which controlled bronze flow into the area from 2000 BCE (Kristiansen, 2022b: 90). The main imports were axes and ring ingots, sourced primarily from the British Isles and the Slovak Ore Mountains, with some from the eastern Alps (Kristiansen, 2022b). Maritime trade likely underpinned the long-distance network in the south-western Baltic, with only a few hubs engaged (Kristiansen, 2022a, 2022b; Ling, 2008; Vandkilde, 2016). This seems to be connected with the explosion of rock art and the construction of burial mounds and cairns along the coast after 1700 BCE (Ling, 2008). Nonetheless, the significance of land-based trade is also underscored by the presence of copper from eastern sources and amber in southern contexts (Jockenhövel, 2013; Vandkilde, 2016).

A major change occurred after 1600 BCE, when new networks connecting the region to the Carpathian basin, notably the Mitterberg area of Slovakia and the Austrian Alps. Moreover, copper from the Italian Alps now began to emerge as the main source and became the predominant one in the following centuries (Ling et al., 2018, 2019). This situation probably fuelled the establishment of local chiefdoms, stretching between the Danish islands, Jutland and northern Germany, centered around production and distribution hubs, such as the high-quality workshops found in Jutland and Zealand (Kristiansen, 2022b; Nørgaard, 2018). In this context, it has been suggested that these chiefdoms shared structural similarities with the ones observed in central and southern Germany, covering areas of approximately 50-150 km (Kristiansen and Larsson, 2005; Kristiansen and Suchowska-Ducke, 2015).

The movement of goods and raw materials was accompanied by human mobility. In fact, the increase in diversity in strontium (Sr) isotope ratios among non-locals during the Early Bronze Age seems to coincide with the development of long-distance metal trade, linking Southern Scandinavia to regions like central and southern Europe and the British Isles, although a similar Sr signal can be found in certain regions of Norway, Sweden or Bornholm (Frei et al., 2019; Vandkilde, 2017). However, southern Europe and the British Isles are compatible with the provenience studies of copper in the area (Melheim et al., 2018). In Denmark, higher mobility was observed among individuals buried in barrows, which are assumed to be the burials of the elites, while individuals buried in flat-graves, representing the non-elite or commoners, had a local origin (Bergerbrant et al., 2017; Frei et al., 2019). Conversely, data from Scania indicates that mobility did not significantly vary with social status, and in western Sweden, mobility between 2000 and 1500 BCE was primarily short-distance, suggesting regional differences within the study region (Bergerbrant et al., 2017; Blank et al., 2018). Furthermore, gender-related variation is also observed within the study area. In southern Sweden, Sr isotopes indicate migration of both genders from different socio-economic backgrounds (Bergerbrant et al., 2017), which is very different from the findings from southern Germany and northern Italy, where female mobility was predominant (Cavazzuti et al., 2019; Knipper et al., 2017). Based on the aforementioned Sr isotope results and from an individual found in Jestrup (NW Jutland) dating to EBA III, Kristiansen (2022b) suggested that male mobility in the area could be explained in terms of these newly established networks and the movement of warriors/traders that decided to settle in Denmark after having travelled between northern Italy and Southern Scandinavia (Ling et al., 2019). Further support comes from the style of sword typologies. The presence of foreign sword types in the Early Bronze Age might reflect communities of travellers or shared cultural values, indicating immigration or conquest events (Bech and Rasmussen, 2018: 76-7; Kristiansen, 2022b: 95).

These findings seem to indicate a society organised in chiefdoms, where patterns of alliances were necessary in order to facilitate trade and movement of people (Kristiansen, 2022b: 97). Alliances were likely established and maintained through marriages and fosterage, with parallels seen in Celtic and earlier Indo-European societies (Olsen, 2019). Evidence from Sweden and Denmark suggests that fosterage was a well-established institution in the 2nd millennium BCE, with non-local children buried in western Sweden between 2200 and 1700 BCE, or the well-known case of the non-local woman and child found in Egtved (Blank et al., 2018; Frei et al., 2019).

Additionally, the concepts of guest-friendship and hospitality probably held a prominent place. This probably involved the exchange of prestigious gifts like women, cattle, and metal objects, and was essential in the construction of alliances; similar to what has been described for Archaic Greece (Morris, 1986). It has been suggested that the resources needed to feed this phenomenon came from coercion of human labour and tributes (Kristiansen, 2013). The most likely venues for these activities were the 'chiefly' halls; the extremely large longhouses found in this period, interpreted as hubs in these newly established networks (Dollar and Poulsen, 2015; Mikkelsen and Kristiansen, 2018).

Demographic growth is suggested as a driver of this expansion, with recent estimates showing rapid growth in Europe between 2000 and 1500 BCE (Müller, 2015). Radiocarbon evidence from several regions in Europe seems to support the identification of population growth (Bevan et al., 2017; *e.g.* Palmisano et al., 2021). Moreover, when high-resolution studies are carried out it is possible to confirm these growth trends, as in western Sweden (Blank et al., 2020). Improved living conditions, such as better clothing, food preservation, and housing, are posited as contributing factors to demographic increase (Brück and Fokkens, 2013; Fokkens, 2019; Kristiansen, 2022a, 2022b; Nielsen, 2019). This situation would lead to what has been defined as 'elite overproduction', with more individuals (young male warriors) competing for a fixed number of chiefly positions (Turchin, 2013). Migration, exploration expeditions and colonisation might result from this situation, as testified by multiple examples known from written sources (Kristiansen, 1998; Turchin, 2023). A well-documented archaeological case for such a pattern is the region of Thy, which experienced a period of growth between 1500 and 1100 BCE (periods II and III), possibly making it one of the central maritime hubs in the region, connecting north-western Europe to southern Norway. The presence of immigrants has already been proven and the amount of wealth found in the region dating to this period seems to indicate its centrality (Bech and Rasmussen, 2018; Kristiansen et al., 2020). Demographic pressure resulting in migration may be seen in the presence of Danish-styled burials in southern Norway (Prøsch-Danielsen et al., 2018).

A stable network for importing essential resources, especially copper and tin, was crucial. Some scholars interpreted the alignment of barrows as the remains of trails used by traders crossing the region (Holst and Rasmussen, 2013 for Denmark; Nakoinz, 2012 for Germany). This is further supported by the presence of non-local individuals and sword types from different region. Estimates based on the distribution of bronze weapons in Early Bronze Age Denmark suggest up to 12,000 swords in circulation at any time, with a minimum estimate of 4000 (Kristiansen, 2022a). Based on Bunnefeld's (2018) calculations, Kristiansen (2022b) estimates one sword-bearer for every ten households and a warrior in every household, making a total of 44,000 lances (the other weapon used for combat in that period) or 22,000 warriors. Multiplying this by household size provides an absolute demographic estimate for the region (see Chapter 2.1.4.2). Besides the demographic consequences, these findings highlight the importance and volume of the trade networks during this period.

2.1.4.2 Barrow construction and demographic estimates

The Nordic Bronze Age, and in particular during periods II and III, is characterised by the construction of large burial monuments, such as cairns and mounds, with burial mounds being the most numerous and widespread. A single mound could contain multiple depositions, usually of adults (Gröhn, 2004; Jockenhövel, 2013; Kristiansen, 2018). In some cases, such as Galgenberg in Schleswig-Holstein, it has been possible to distinguish generational differences within the depositions of a single mound, which is assumed to belong to a single household or farmstead (Jockenhövel, 2013).

The total number of burial mounds built in northern Europe during the Bronze Age is estimated to be around 100,000, many of which have been lost to ploughing (Thrane, 2013). Kristiansen (2018) estimated that around 50,000 mounds were built in Denmark alone between 1500 and 1100 BCE. Their sizes varied significantly, from less than 0.5 m high and 5 m in diameter to very large ones over 6 m high and 35 m in diameter (Thrane, 2013). A mound is typically considered large if it exceeds 25 m in diameter and small if under 10 m (Jensen, 2013). Construction techniques involved both circular and radial layouts, occasionally supported by radial wooden structures, like those found at Lusehøj in Jutland (Thrane, 1984). Bjäre, in Scania, had the highest density of mounds, at 8 mounds/km^2, while Hohøj in East Jutland was the largest; 12 m high and 72 m in diameter (Thrane, 2013). The substantial number of mounds, their material requirements and the timber demands for house construction, have been suggested as a cause for the increased openness of the landscape observed during this period, potentially leading to almost bare landscapes in the most intensively used or fragile regions like Thy (Feeser et al., 2019; Kristiansen, 2018). Around 30,000 cairns were found in the study region, mostly from Sweden, and they probably had a similar function to burial mounds (Thrane, 2013). They usually consist of a stone cist, located in the centre, which was later covered by rocks forming the cairn. Reuse and multiple phases of a single monument are not uncommon (Thrane, 2013).

Many Bronze Age barrows were built on agricultural land, often in elevated areas, and were sometimes aligned with natural features forming clusters or, as previously mentioned, following natural features in linear alignments (Kristiansen, 2018). Given the rather flat nature of the landscape in the study region, their incredible number and their dimension (2-5 m high), certainly gave them visual prominence in the landscape, more than anywhere else in Europe (Kristiansen, 2018). A burial mound is built using grass turfs, which are cut as bricks and placed on top of each other. It has been calculated that for every barrow *ca.* 3 ha of grassland were required. Kristiansen (2018) calculated that, in total, 150,000 ha of grassland were stripped in Denmark in a period as short as 300/350 years (the peak in barrow construction). This resulted in the construction of approximately 150 mounds annually. Considering the distribution, it's estimated that a new mound would have been built every 10 years in each settled unit of land (modern parishes; Kristiansen, 2018). The environmental impact was likely severe, especially in densely populated areas. It has been demonstrated that there is a correlation between the number and location of barrows and the presence of heathland, caused by the stripping of the topsoil that promoted heath growth, which was unsuitable for agriculture but usable for grazing (Andersen, 1990, 1997; Kristiansen, 2018).

Coupling Sørensen's (2010) estimate of household size as 10-15 persons/household, and Bech and Mikkelsen's (1999) calculation of settlement density at 1 household/km^2, Kristiansen (2018) assumes a population density of 10-15 people/km^2. Assuming that half of Denmark (22,000 square km^2) was populated at this density, this would equate to a total population of approximately 220,000-330,000 people during the Middle Bronze Age (Kristiansen, 2018). Every farm probably had a barrow, sometimes more, but in every barrow there were only a few burials, making it unlikely that every person, or even a large share of the population, were interred in these monuments (Kristiansen, 2018). Using an estimate of 5 individuals per barrow (which is a high-end estimate), Kristiansen (2018) assumes that over 350 years 250,000 individuals were buried. Assuming 35 years of lifetime, during the EBA II and III a total of 2.2-3.3 million people would have lived and died, meaning that only around the 10% of the population was buried (20% of adults; Kristiansen, 2018).

Similar estimates have been calculated in smaller regions, generally focusing on Thy due to the intensity of research. Here, 230 farmsteads can be assumed to have existed in today's Hassing district; a region to the south of Thy well-known for its high density of barrows and Bronze Age settlements (Kristiansen, 2018). Using the previously described estimates, this would indicate a population between 2300 and -3500, which is comparable to the population recorded in 1801 (Kristiansen, 2018). Pollen records show that landscape openness reached its maximum around 1100 BCE, with virtually no forest remaining (Andersen, 1990, 1995). Based on the reconstructed number of barrows, it is assumed that *ca.* 6000 ha of land were stripped and therefore unavailable for farming. The slight reforestation seen in the Late Bronze Age pollen diagrams is interpreted as indicative of a decline in population, possibly due to emigration. A similar pattern has been recorded in western Jutland and southern Norway, with forest depletion linked to higher population pressure, followed by a halt in the Late Bronze Age (Kristiansen, 2018).

The intensity of landscape occupation and barrow constructions opens the question of social organisation. Building a mound was labour-intensive, and soil-stripping for turf would have reduced land availability, even for grazing (Holst et al., 2013). This might have necessitated strict regulation of mound construction and land use for agropastoral activities (Kristiansen, 2018). Such constraints could have undermined household economies and fuelled conflicts over resources and metal during the subsequent Late Bronze Age in a region extending from the Netherlands to southern Norway (Kristiansen, 2018). The emergence of larger chiefdoms in eastern Denmark at the beginning of the Late Bronze Age, replacing the west in controlling trade networks, could be attributed to economic strain from competition and resource scarcity, leading to changes in ritual practices and a cessation of burial mound construction (Kristiansen, 2018). In regions where this situation was more acute, migration may have been a direct consequence, as suggested for Thy (Kristiansen, 2018).

3. Data

In this chapter I will discuss in detail all the data that have been used in this work. Broadly, the data fall into two categories:

1. Archaeological Data: this includes sites and radiocarbon dating;
2. Environmental Data: this comprises data about the region's morphology and geology.

The chapter will focus on how each type of data is categorised, their sources and the specific ways in which they have been processed and prepared for use in this study. The aim is to provide a comprehensive overview of the data sources, their characteristics and how they are used. In the first part the archaeological data are described and the case study selected for this work. Then the environmental variables are described.

3.1 Archaeological data

The archaeological data used in this study exhibit variable layers of heterogeneity, mostly due to their origin. Most of them are part of large databases or collections of sites from local or national authorities. They are typically maintained for heritage conservation and management purposes and follow local or national legislation within a specific region or country.

It is important to recognize that the primary purpose of these databases is heritage conservation and management, not necessarily research. This focus can sometimes complicate their use for research purposes. Despite the challenges they present (which I will address individually for each dataset), these databases offer the most extensive set of information available. If the goal is to conduct quantitative archaeology, these resources cannot be overlooked; they must be addressed and integrated into research. Attempting to collect 'our own' data each time is not only time-consuming but often results in duplicating work that has already been done. Furthermore, individual researchers or working groups are unlikely to match the resources and workforce that a state with its bureaus and officers can mobilize.

In addition to these datasets, this study also incorporates information derived from existing literature and data collections conducted for academic purposes by other scholars or by myself. While the primary focus of these sources is scientific, their utility may vary depending on the specific research objectives that guided each individual author.

Because of the nature of the data and differences in traditions and collection practices, several layers of uncertainty are introduced, which can be classified as follows:

- **Chronological Uncertainty**. Many sites are undated or imprecisely dated, making it challenging to determine their chronology through simple queries;
- **Spatial Uncertainty**. The original location of some sites may be inaccurately recorded due to the circumstances of their discovery;
- **Typological Uncertainty**. Differences in recording standards and confidence in the information provided can impact both chronological and spatial uncertainties.

In addition to these three layers of uncertainty, we also have to consider uncertainty of representativeness. In some areas, research intensity and post-depositional factors (soil erosion, human activities, *etc*.) create a strong bias, which is sometimes very difficult to disentangle from past agency. This in turn contributes to spatial uncertainty, although at a different scale. In this study I primarily address spatial and chronological uncertainty, paying attention to the representativeness of the data used.

In the following paragraphs, I describe the structure of the Swedish, Danish and German datasets. The aim is to quantify their uncertainties and find possible solutions. Additionally, I will discuss the data derived from literature reviews, although they occasionally intersect with national databases. As will become evident, the study area is not immune to research biases or differential losses related to site type and location. Consequently, the approach adopted was to define smaller, more homogeneous case studies, the selection of which is justified within this chapter.

3.1.1 Germany

Germany is a federal state organised in *Länder*, that have a very high degree of autonomy on several matters, including heritage management. Consequently, data acquisition necessitated individualised requests, collection and management for each federal state within the scope of the study region.

3.1.1.1 Mecklenburg-Western Pomerania

The Archaeology Department of the Federal State of Mecklenburg-Western Pomerania (*Vorpommern* in German), officially known as *Landesarchäologie*, oversees the ownership and management of archaeological data found in this state. Data are provided only upon request and under the stipulation of a contractual agreement between the State and the user, which regulates the terms of use of the data. This process is managed by the *Landesamt für Kultur und Denkmalpflege* (State Office for Culture and Heritage Preservation).

Specifically, I have been granted access to all the prehistoric sites documented in their database. The data was provided in two formats: shapefiles and Excel (.xlsx) files. Both formats contain identical information; however, the shapefiles are georeferenced, enabling spatial analysis and visualisation. They include the physical representation of each site, which can be a polygon, line, or point, depending on the nature of the site.

The geospatial data in the shapefiles are based on the ETRS 89 Zone 33 coordinate system (EPSG code 5650). The data are organised into three separate shapefiles (or Excel files), each corresponding to a distinct chronological period:

1. Prehistoric sites (undated prehistoric sites), in German *Urgeschichte*;
2. Neolithic sites (*Neolithikum*);
3. Bronze Age sites (*Bronzezeit*).

KREIS	FUNDPLATZ	TYP_KLAR	ZEITSTELLUNG
Mecklenburg-Strelitz	1	Fundstreuung	Bronzezeit
Mecklenburg-Strelitz	6	Hügelgrab	Bronzezeit
Mecklenburg-Strelitz	9	Siedlung	Bronzezeit
Mecklenburg-Strelitz	7001	Hügelgrab	Bronzezeit
Müritz	11	Fund	Nordische jüngere Bronzezeit
Bad Doberan	1	Hügelgräberfeld	Bronzezeit

Table 2. Example of data from Mecklenburg-Western Pomerania (MV). Some fields are omitted, including text description. Data from the MV Landesarchäologie.

The datasets contain the following information: spatial location (coordinates), municipality (*Kreis*), parcel or specific location within the municipality (*Gemarkung*), how the site was found expressed as a code number (*Fundplatz*), typology of find (*Typ*), relative chronology (*Zeitstellung*/*Entstheun_* in the shp version) and a brief description. Unfortunately, due to the format of the dataset all fields were truncated at 255 characters. An example of the data is shown in Table 2. Data were obtained in June 2022.

For the analysis carried out here, I am not interested in the shape of the sites but mainly in their spatial location and all polygons are treated as points, using their centroid. In general, polygons represent areas excavated by or on behalf of the *Landesamt* in the last few decades. A preliminary examination of the datasets shows that points, polygons and lines do not contain duplicates, meaning that both sets of information can be retained.

In total there are 55,933 sites dated to prehistoric times. However, some of them do not have a known spatial location (*FUNDPLATZ* number > 7000) and therefore cannot be used for spatial analysis, reducing the number of available sites to 44,867. Looking at the chronology of sites in MV we observe that sites are distributed as follows:

1. 14,130 **Neolithic** sites
   - 97 **Early Neolithic**
   - 145 Funnel Beaker
   - 8 Globular Amphora
   - 111 **Middle Neolithic**
   - 207 Single Grave
   - 693 **Late Neolithic**
   - 12,868 undated Neolithic
2. 10,236 **Bronze Age** sites
   - 527 Unspecified **Early Bronze** Age
     - 170 Period I
     - 55 Period II
     - 180 Period III
   - 1735 Unspecified **Late Bronze** Age
     - 100 Period IV
     - 123 Period V
     - 120 Period VI
   - 7224 undated Bronze Age sites

As we can see from Figure 5, sites are unevenly distributed within the region. In particular, there are several areas largely underrepresented, such as the SW part of the region (W Ludwigslust-Parchim district) and the central northern area by the Baltic Sea (approximately corresponding to the north-western part of the Vorpommern-Rügen district, between Rostock and Stralsund). On the other hand, there are some other parts with a very large concentration of sites, notably some parts of the island of Rügen, the area between Wismar and Rostock (NW Landkreis Rostock district) or central Mecklenburg, around the town of Güstrow. What is also

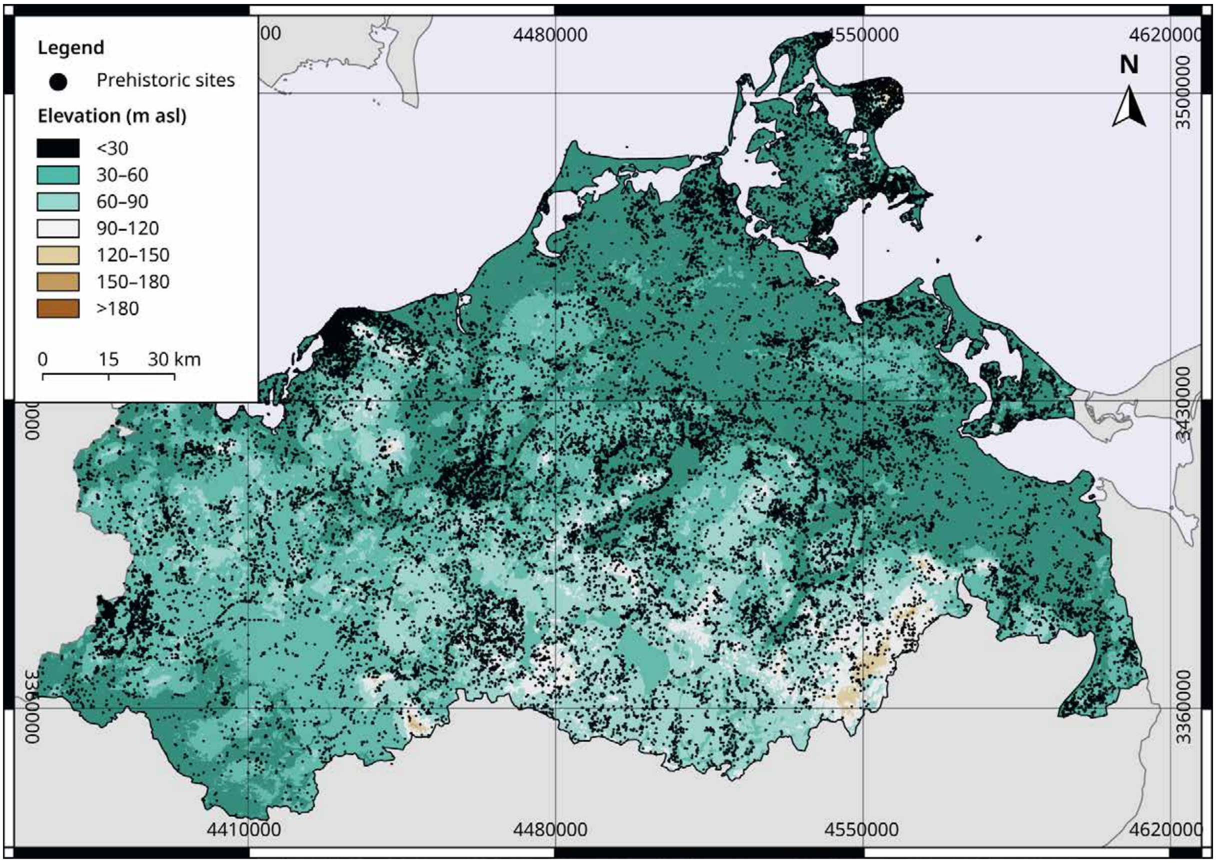


Figure 5. Prehistoric sites in MV. Data from MV Landesarchäologie. Baseline elevation map from EU-DEM v.1.1.

evident is a high concentration of sites aligned on a SW – NE axis, partly connected with modern infrastructure work and the archaeological research connected to it. Besides this, sites seem to appear with higher intensity around larger cities (Figure 6).

3.1.1.2 Schleswig-Holstein

Among all datasets, the one from Schleswig-Holstein presented the most challenges. This was primarily because, as of mid-2022, only a portion of the state's archaeological data had been digitised and made accessible. While it was feasible to access the data and archives, this could only be done on-site at the local archaeological council's office (*Archäologisches Landesamt* Schleswig-Holstein) in the town of Schleswig, with no possibility to obtain a copy of the data. Additionally, at the time of writing, most of the reports were either not digitised or only available as scanned copies, which limited their usefulness in enhancing archaeological understanding.

Such restrictions significantly complicated the process, therefore I had to rely on the available literature. Fortunately, over the last year several studies have been carried out in the region, allowing the identification of some suitable case studies for this thesis.

Due to the limited number of sites, I had to rely on specific and well-known typologies. Among these, megaliths and burials mounds are probably the best known and have already been described (Chapter 2). The most important aspect is that they are spread across the entire study area and provide a very suitable proxy for quantitative analyses. In northern Germany, there are a number of suitable regions that got the attention of several scholars over the years that deserve to be mentioned and more thoroughly investigated.

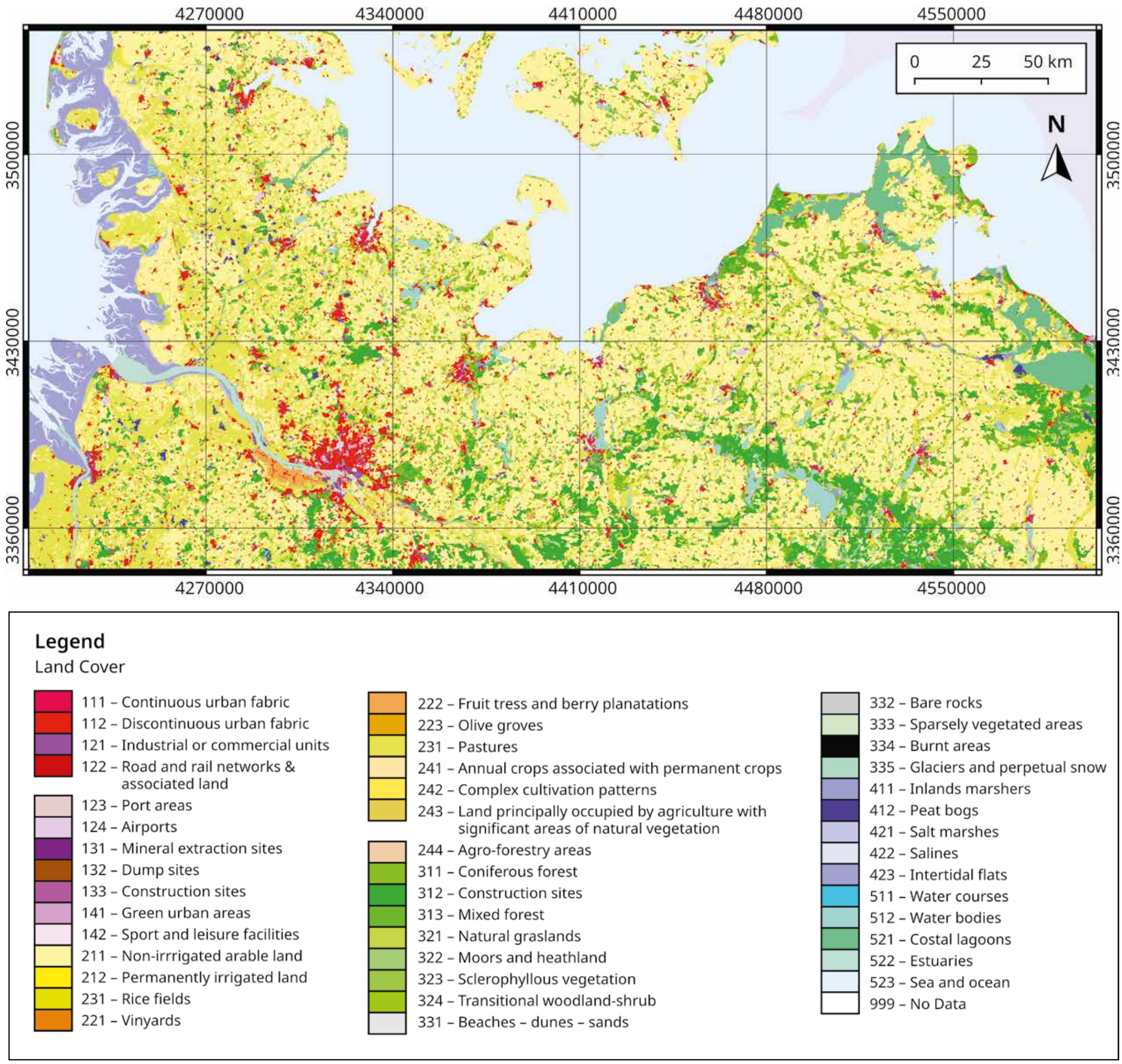


Figure 6. Land use map of northern Germany. Data from the The CORINE Land Cover (CLC) inventory, freely available at DOI: 10.2909/960998c1-1870-4e82-8051-6485205ebbac.

One of these regions is the *Dänischer Wohld*, in the modern day Rendsburg-Eckernförde district (*Kreis*). It is a peninsula located between the northern end of the Kiel Fjord and the Eckernförde Bay (Figure 7 a). However, it is larger than what today is referred to as *Dänischer Wohld Amt*, which only represents the core of the original region. The region is well-known for its Early and Late Medieval history but also for its particularly rich Funnel Beaker and Bronze Age, with numerous monuments scattered in the area. In total, there are 479 monuments, of which 227 are megalithic tombs and 252 are burial mounds (Nakoinz, 2012). Due to the nature of the source data, it is not possible to create a more precise typology of the sites and therefore I simply assume that the megaliths are from the Funnel Beaker period and the burial mounds from the (mostly Early) Bronze Age.

The second region considered here is eastern Holstein, in the *Ostholstein* district (Figure 7 b). It borders with the Lübeck Bay and the Kiel Fjord. As a case study, I will focus on the Wagria or Oldenburg peninsula (*Oldenburgische Halbinsel*), which is the extreme NE part of the region. The area has been thoroughly studied especially for the Early and Middle Neolithic periods. Numerous sites and landscape

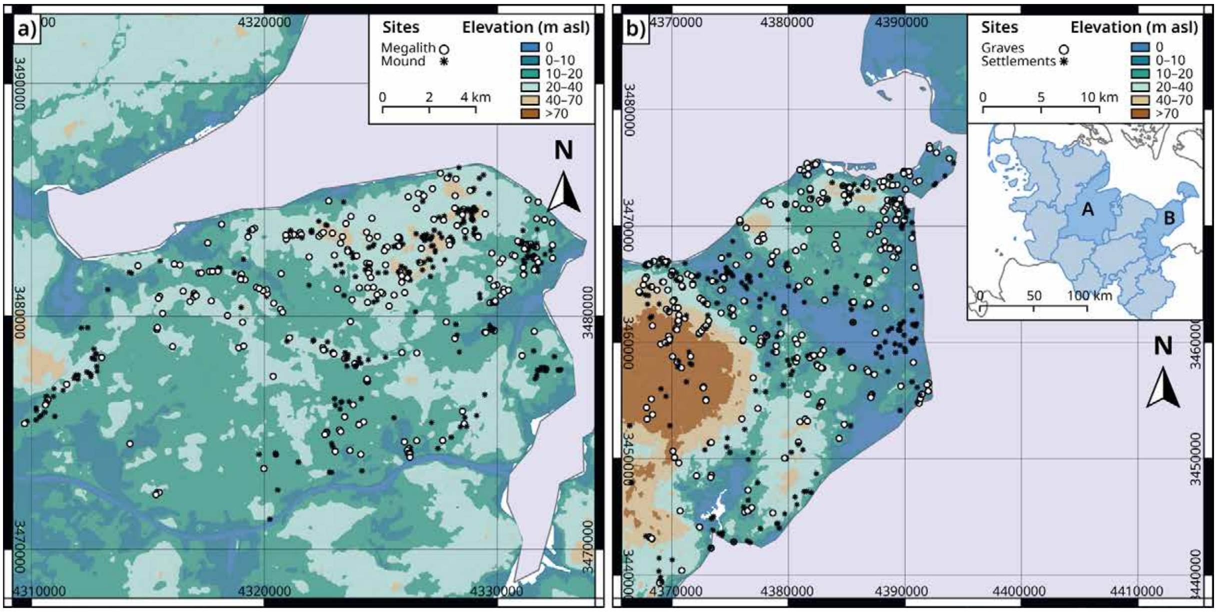


Figure 7. Case study from Schleswig-Holstein. Baseline elevation map from EU-DEM v.1.1. A. Burial mounds and megalithic tombs in the Dänischer Wohld. Data from Nakoinz (2012). B. Neolithic sites in NE Ostholstein. Data after Brozio (2016). Inset map: the districts of the study regions, highlighted within Schleswig-Holstein boundaries.

reconstructions have been made, making the area particularly suitable for demographic reconstructions (*e.g.* Brozio, 2016; Knitter et al., 2019).

The data from this area are particularly suitable for modelling due to the outstandingly deep knowledge we have about the sites and their dating. Most of the sites are dated to the second part of the Funnel Beaker Period (EN II – MN) and the relative chronology is particularly precise, especially for the MN. This allows a very precise modelling of settlement and population dynamics between 3600 and 2800 BCE, with a very high precision for the 3350-2900 BCE period. In this case, settlement and all types of grave data are also available, allowing a more in-depth modelling of the MN period. However, for the YN and LN periods the relative chronology is less precise and these periods were not included in this study.

3.1.2 Sweden

In Sweden, the National Heritage Board is responsible for the collection, management and maintenance of the archaeological site database. Unlike Germany, but similar to Denmark, access to and downloading of information on the country's archaeological record or archaeological investigation is open to all individuals, regardless of their status. Web visualisation and download is possible from the *Riksantikvarieämbetets öppna data server* (RAA). The section of interest in the present study is the *Fornlämningar och övriga kulturhistoriska lämningar* (Ancient monuments and other cultural-historical remains).

The primary challenge with the Swedish database is the absence of easily queried chronological information. There is no field indicating a dating or a reference to a relative chronology, and any information pertaining to the dating of sites must be derived indirectly, either by examining the descriptive text associated with each entry or, in certain cases, by analysing the typology of the sites. Consequently, in most cases it is necessary to read the site description and the attached report(s). In some instances, these reports may be unpublished and stored in hard-copy at Ministerial archives. Besides this, there are thousands of possible Prehistoric sites, making a manual scraping unfeasible.

For this reason, it is necessary to work using well-known site typologies and using regular expressions (*regex* in informatics jargon) on the description fields in order to extract information in a simple and effective way. The sites recorded in the database are stored in various formats, notably lines, polygons and points, depending on their nature and the context of their documentation. Polygons typically delimit surveyed and excavated areas, along with accompanying information about the outcomes of these activities. Occasionally, within a polygon, additional features may be recorded, such as other polygons (*e.g.* excavation trenches) or point features, representing previously known sites or find spots. This causes the existence of many potential duplicates in the database that require careful scrutiny during the querying phase. In the GitLab repository the scripts used to obtain the specific sites are provided and will only be briefly described here.

Three different geopackages can be downloaded from the *Riksantikvarieämbetets* data server:

1. *arkeologiska_uppdrag_grävda_ytor_län_skåne*. This file includes the excavated areas between 2009 and 11.2021. Data are stored as polygons;
2. *arkeologiska_uppdrag_undersökningsområden_län_skåne*. This file includes the investigated areas (surveys), with data stored as points and polygons. In general, the database of the excavated areas (1) is a subset of this dataset. A closer look at the database shows that the first recorded date is 2001 with 22.02.2022 being the latest. However, several empty date fields are also recorded;
3. *lämningar_län_skåne*. This file includes all the areas under protection and the existing monuments. It is important to note that in this dataset also investigations dating before the 2000s are recorded, although only if the area is under protection (*i.e.* if something had been found or recorded).

All three datasets utilise coordinates within the Swedish national system, SWEREF99 TM (EPSG: 3006). Only the *lämningar_län_skåne* dataset contains direct information about archaeological remains, while the others lean toward administrative and managerial purposes. The database contains the following information: site identification, coordinates, site typology, site description and contextual information regarding the monument status, administrative information such as province, municipality, date of entry into the database, *etc*. Additionally, a link to the web viewer is provided, which offers access to supplementary materials, such as the written report of each site (when available). It is noteworthy that descriptions within the database vary due to differences in recording methods and timelines. Sites surveyed or investigated post-2004 tend to have digitised and readily accessible reports, whereas older records may only exist in hard copy within the RAA archives.

The database encompasses sites documented through diverse means, including field surveys, archaeological excavations and archival research. This aspect further complicates homogenisation and requires careful queries in order to extract the data used for this work. The queries are primarily conducted on fields related to typology, geography and site descriptions, and are all available in the online repository. Collectively, over 60,000 sites spanning various prehistoric and historical epochs are recorded in the database (Figure 8 a). It is evident that data distribution across the region lacks uniformity. This unevenness seems to be mostly driven by modern factors such as infrastructure projects, urban expansion and human activities. These areas are predominantly concentrated in the southern and western coastal regions, as well as the north-eastern area. These regions, characterised by lower elevations, witness more intensive agricultural practices, resulting in a more pronounced human imprint. In contrast, central Scania remains densely forested and less densely populated, as illustrated in Figure 8 b.

Besides the national database, I rely on some of the very well-known research projects carried out in the area (Artursson, 2007b; Hadevik and Steineke, 2009;

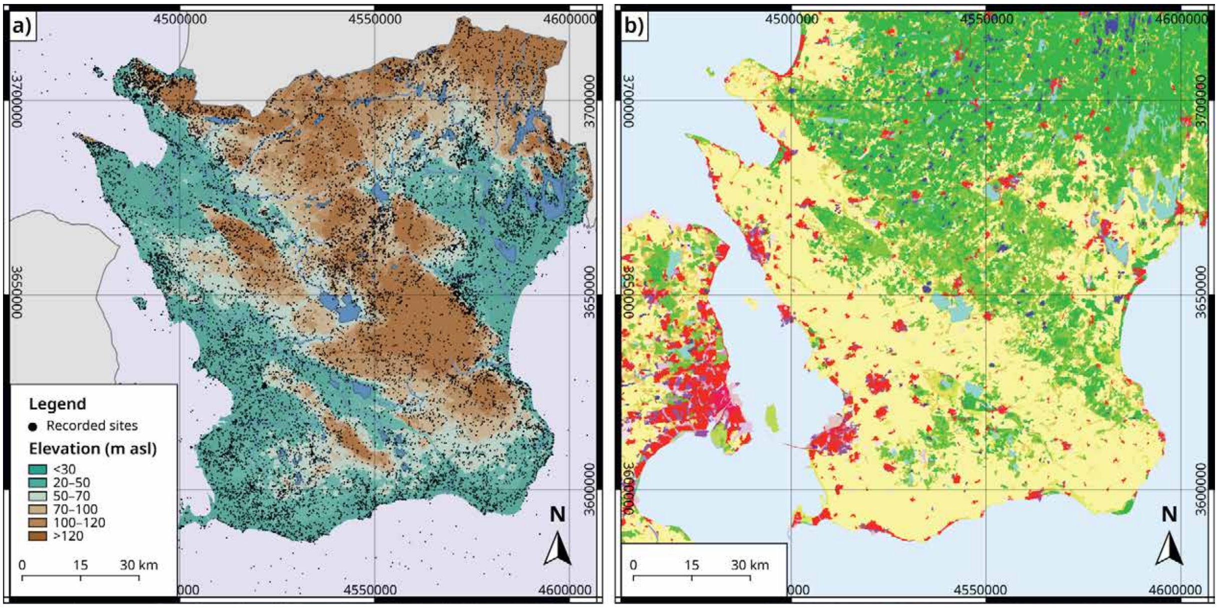


Figure 8. a) Ancient sites and monuments in Scania (Fornlämningar och övriga kulturhistoriska lämningar). Data from the RAA. Baseline elevation map from EU-DEM v.1.1; b) Land use map of Scania. Data from the CORINE Land Cover (CLC) inventory. For the legend and the reference of the dataset see Figure 6.

Sjögren, 2006; Tesch, 1993). These studies provide a very good basis to improve the possibilities offered by the database alone, as often these publications are written by expert archaeologists who are well-acquainted with the area and its archaeological record. The main downside of this aspect is that it adds complexity to the data structure, reducing the possibilities of reproducibility and reusability.

3.1.2.1 Site typologies

The Swedish sites included in this study are stray finds of specific typologies, megalithic tombs, burial mounds, cairns and stone settings. Monuments are the simplest typology to query. In the database, these monuments are recorded with their primary or secondary types (*lamningtyp* or *ing_lamn* and *egenskap* fields), which, depending on the class of sites, have a more or less defined chronology. Among them, the TRB Megaliths are possibly the easiest to date and analyse. In the database, they are generally labelled as *stenkammargrav* in the *lamningtyp* field and as *gånggrift* or *dös* (passage grave or dolmen) in the *egenskap* field. As previously discussed in Chapter 2, these monuments are distributed throughout the entire study region and are generally dated to the EN II – MN II period (3500-3000 BCE), although later reuse is not uncommon up until the Late Neolithic period (Bilotti, 2023; Persson and Sjögren, 1995; Sjögren, 2003). In Scania there are 193 megaliths, 136 classified as Dolmen, 56 as Passage Grave and 1 with an uncertain typology (Figure 9). However, it is worth noting that only 162 sites are defined as *Stenkammargrav* in the site typology field. In the other cases, it was necessary to query the secondary typology field (*ing_lamn*) or analyse the description, which made the process rather time-consuming but necessary, as these sites constitute up to 16.1% of the total. Excluding uncertain sites defined as 'possible ancient remains' (*Möjlig fornlämning*), 'other cultural historical remains' (*Övrig kulturhistorisk lämning*), or without an 'antiquarian assessment' (*Ingen antikvarisk bedömning*) in the *antikv_bed* field reduces this number to 5.7% (6 out of 106). In general, TRB megalithic graves are not densely distributed in the Scanian landscape (except for the western and southern coast) compared to other parts of Southern Scandinavia, such as Falbygden or Zealand, or monuments from other periods like burial mounds (see Fritsch et al., 2010 for megalithic tombs distribution in central and northern Europe).

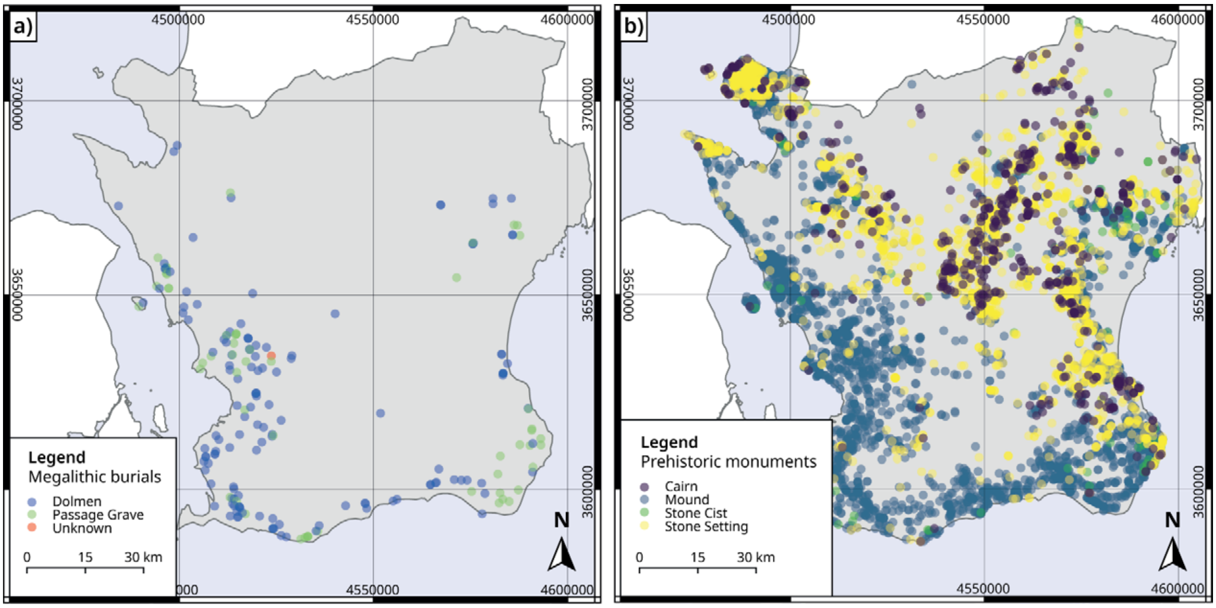


Figure 9. Distribution of monuments in Scania. a) Funnel Beaker megalithic graves. b) Late Neolithic (stone cists) and Bronze Age monuments. Data from the RAA.

There are 4021 burial mounds (*hög*) in Scania, making them the most prevalent type of monument in the county. While they can be found almost everywhere, they are most densely concentrated along the coastline, particularly the western region (around Landskrona and between Malmö and Landskrona), the Bjäre peninsula in the north-west, the south-eastern coast (near Simrishamn and between Simrishamn and Ystad) and the central-eastern area (Figure 9). There are 582 cairns (*röse*) in the area, with the largest concentration found in the Bjäre peninsula, the central part and central-northern part of the county, mirroring the distribution of burial mounds (Figure 9). This dichotomy is significant and has been previously noted (Bilotti, 2023) although it requires further investigation and discussion. Attempting to identify possible outliers or sites that were not correctly attributed to this class of monuments yielded limited results, as it required a substantial amount of effort and offered only marginal benefits (possibly contributing to about 0.4% of the total mound attributions). A similar effort was made for cairns, resulting in a gain of approximately 0.5% of the total amount of sites. In this latter case the low number of possible additional cairns (only 3) allowed a direct examination. The results revealed that 2 of them dated to the Middle Ages (Knarrström, 2004) and the other was only surveyed (Olsson, 2003). This makes the effort not worth the gain and therefore it was not carried for other site typologies.

The other types of prehistoric monuments found in the area are stone cists (*hällkista*) and stone settings (*stensättning*). In the case of stone cists, the main site typology is the same as that of the megaliths (*stenkammargrav*) but their appearance and chronology is closer to stone settings, mounds and cairns, although generally dating to the Late Neolithic (Blank et al., 2018). In the database they can be queried like the megaliths through the *egenskap* field. There are only 113, primarily concentrated in the south-eastern and north-eastern coasts, although some are found in western Scania. The low number of sites is likely due to their modest appearance in comparison to other monuments, making them more challenging to identify without excavations and easier to destroy or overlook. Stone settings, on the other hand, are more visible and have been found and recorded in larger numbers. In Scania there are 2635 stone settings (*stensättning*), with a distribution pattern similar to that of cairns, primarily located in the northern, central and eastern parts of Scania. The densest concentration is on the Bjäre peninsula, followed by eastern and central Scania (Figure 9).

Table 3. Flint artefacts from Scania and their relative chronology (after Mennenga, 2016).

Name	Name (SE)	Query	Relative Chronology	No.
Point-butted axes	Spetsnackig yxor	spetsnackig	EN I	363
Thin-butted axes	Tunnackig yxor	tunnackig	ENI – MN II	986
Thick-butted axes	Tjocknackig yxor	tjocknackig	MN III-V	1016
Battle axes	Båtyxor / Stridsyxor	båtyxa | båtyxor | stridsyxa | stridsyxor	YN/MN B	122
Daggers	Dolk	dolk	LN (+ BA)	720

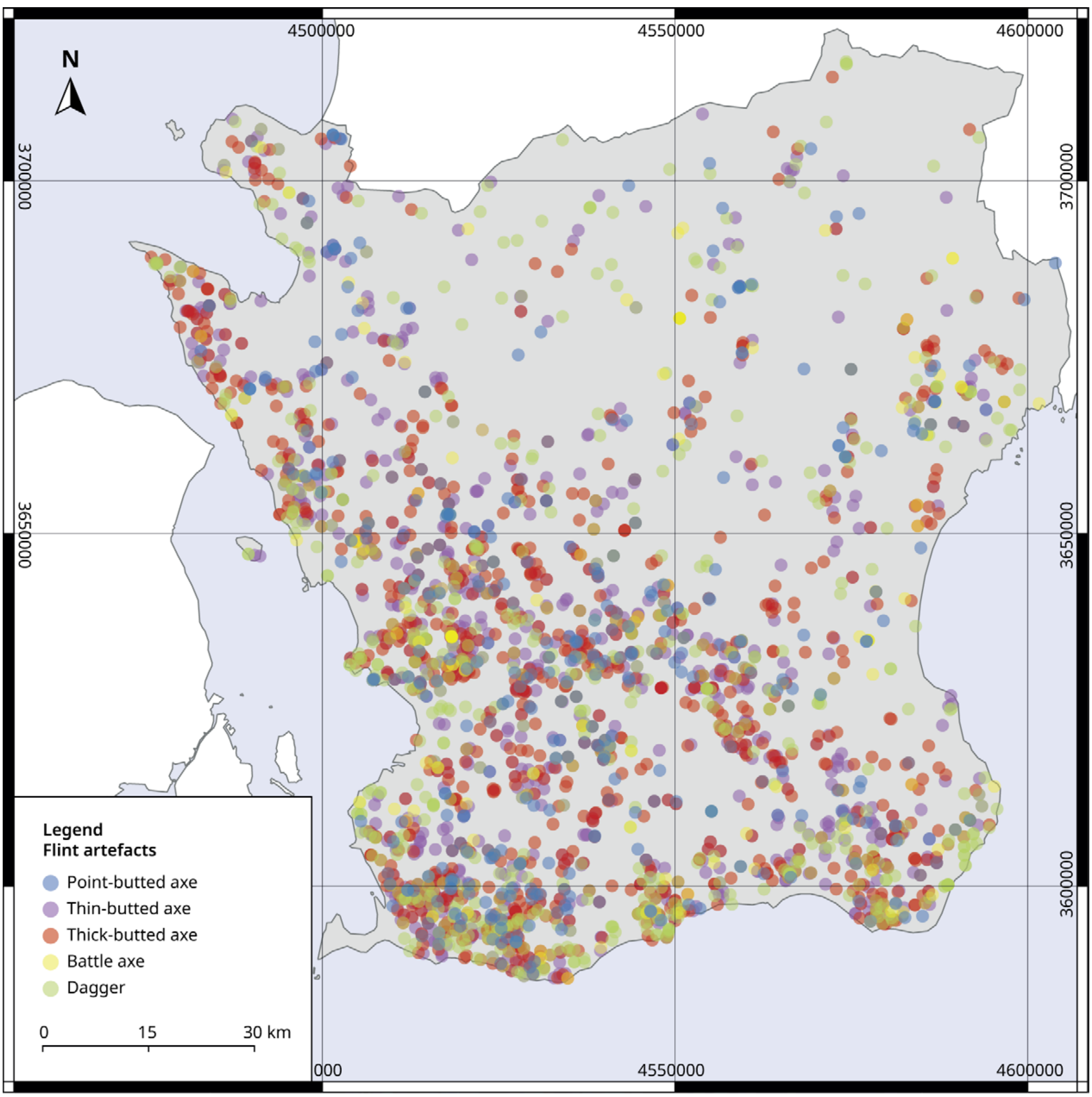


Figure 10. Distribution of flint artefacts from Scania divided by typology. Data from the RAA and query after Table 3.

Lastly, the typology of well-known Neolithic artefacts can also be queried from the database with relatively little effort. Querying Bronze artefacts from the National database was not straightforward and for the distribution of bronze artefacts a separate database collected by C. Horn and S. Schultrich has been used. This database is still unpublished and has been cleaned by myself and S. Schultrich. In particular, flint polished axes and daggers were included. Unfortunately, sub-typologies are not easy to identify and therefore higher relative chronology precision could not be achieved. The number of artefacts per category, their name in Swedish, the query used to retrieve them and their relative dating are summarised in Table 3 and their distribution is shown in Figure 10. The typology adopted in this study follows Mennenga (2016). As in the other cases, the query was carried out in R, using the *grepl* pattern matching function (regex expression) as follows:

```
sc_sites[grepl(query_string, sc_sites$beskrivn, ignore.case = TRUE),]
```

The sites described here are all derived from the Swedish National Database and the queries used to obtain them are documented in R scripts accessible in GitLab. Flint artefacts can be obtained with the *01_swedish_axes.R* script, whereas the megaliths and monuments can be obtained by running the *00_scania.R* script. This approach guarantees the reproducibility of the analyses performed for the Swedish case studies. It also provides a convenient method for researchers interested in similar site types within the region or other parts of Sweden to easily extract this data without having to redo the process on their own or manually. In addition, if sites are missing or discovered in the future, they can be effortlessly incorporated by updating the input data or adjusting the query.

A last site category worth mentioning is the Stone Age settlements (*stenålders-boplats*). This category includes sites dating from the Mesolithic to the Neolithic but obtaining a precise chronology for these sites is often unattainable due to their typical composition, which often consists of stone scatters documented during survey expeditions containing mixed, un-datable or fragmented material. Nevertheless, whenever they contained a datable flint artefact they have been included.

3.1.3 Denmark

The archaeological data of Denmark are provided by the Danish Ministry of Culture (*Kulturministeriet*) and managed by the Agency for Culture and Palaces (*Slots- og Kulturstyrelsen*) and can be downloaded freely from the *Fund og Fortidsminder* section of the Agency's website. It is also possible to use a webgis to visualise the data, as for the Swedish database. Data is stored and can be downloaded as points or polygons. In this case, points were selected over polygons because while every polygon was also represented as a point, the reverse was not true. Data can be downloaded in formats such as MapInfo Tab, ESRI Shapefile, or CSV, with shapefile preferred for this study. Data can be downloaded in two different coordinate systems, the World Geographic System 1984 (WGS84, EPSG: 4326) or the local zone of the Universal Transverse Mercator projection (UTM) based on the European Terrestrial Reference System 1989 (ETRS89/UTM zone 32 N, EPSG: 25832). The projected coordinates were preferred and then transferred into the CRS adopted throughout the project (see Chapter 1.1.1). Besides the usual information concerning the location (coordinates) and administrative information (municipality), in this case, chronological information is provided, in a format that is particularly suitable for queries and quantitative analysis. There is a relative chronology field (*datering*), which contains information about the broader period, in our case stone age or bronze age (*stenalder* and *bronzealder*). In addition, two absolute chronology fields are available, indicating the starting and ending date in years BCE/CE (*fra_aar* and *til_aar*). A link to the online source is provided where additional information and, if available, excavation reports

systemnr	stednavn	stednavnsb	datering	fra_aar	til_aar	geom
31638	Verdens Ende	Uspecificeret	Stenalder	−2350	−1701	POINT (4259619 3748050)
115366	Dolmer	Uspecificeret	Bronzealder	−1700	−501	POINT (4374083 3703086)
140668	Poulsgård	Ejendom, gård, hus	Bronzealder	−1700	−1101	POINT (4305759 3547259)
127074	Vallensbæk golfbane	Offentlige byg-ninger og pladser	Stenalder	−2350	−1701	POINT (4471487 3616345)
138082	Ørsted Syd	Beretningsnavn	Bronzealder	−1100	−501	POINT (4341219 3710086)
136216	Vognserup	Bebyggelse, havne og industrianlæg	Bronzealder	−1100	−501	POINT (4419465 3623641)

Table 4. Example of data from the Danish database (Agency for Culture and Palaces). Only a subset of fields is shown.

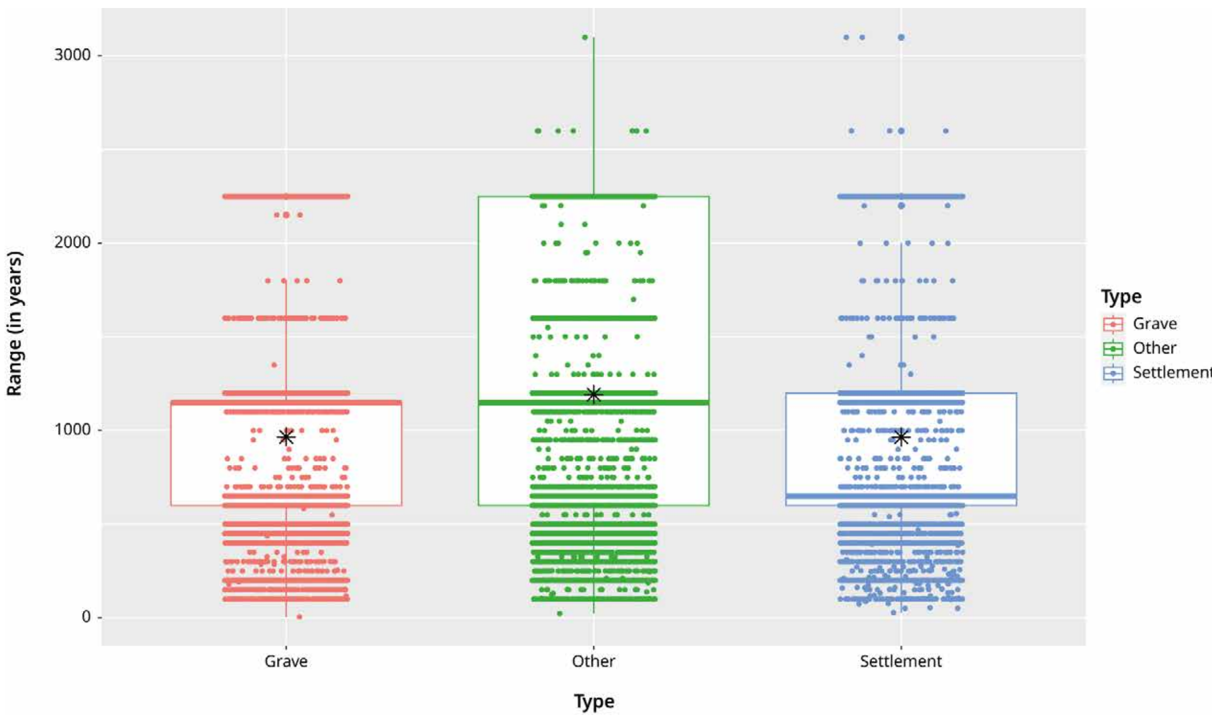


Figure 11. Boxplot of the chronological precision of the sites recorded in the Danish national database (Stone and Bronze Age) divided by typology. The black star represents the mean value. Data from the Danish Agency for Culture and Palaces.

can be retrieved. The dataset is relatively easy to navigate and to query. An example of what the data look like is provided in Table 4.

The database comprises 73,495 sites dating from the Late Mesolithic to the Early Iron Age (7000-2000 BP). The main issue is that the chronological accuracy varies considerably, as shown in Figure 11. On average, the chronological range for a site is approximately 1000 years, indicating that its actual date could fall anywhere within this time window. Certainly, many sites are better dated. For example, there are 6308 sites that have an uncertainty within 200 years, comparable to the estimated duration of a Nordic Bronze Age period or certain Neolithic phases. Nonetheless, the majority of these more precisely dated sites are graves (4093) and only 648 are settlements. The remaining 1567 are categorised as stray find or undefined. Moreover, it has to be noted that most of these well-dated sites date to the Bronze Age, with only a limited number of precisely dated Neolithic sites (Figure 12).

In order to use the database for this study, data selection and cleaning were performed. Additionally, several fields were appended to facilitate queries and analyses and enhance readability. These additional fields include typological categories in English, a precision field calculated by subtracting the start year from the end year, and a new chronology (with start and end year values) in years BP.

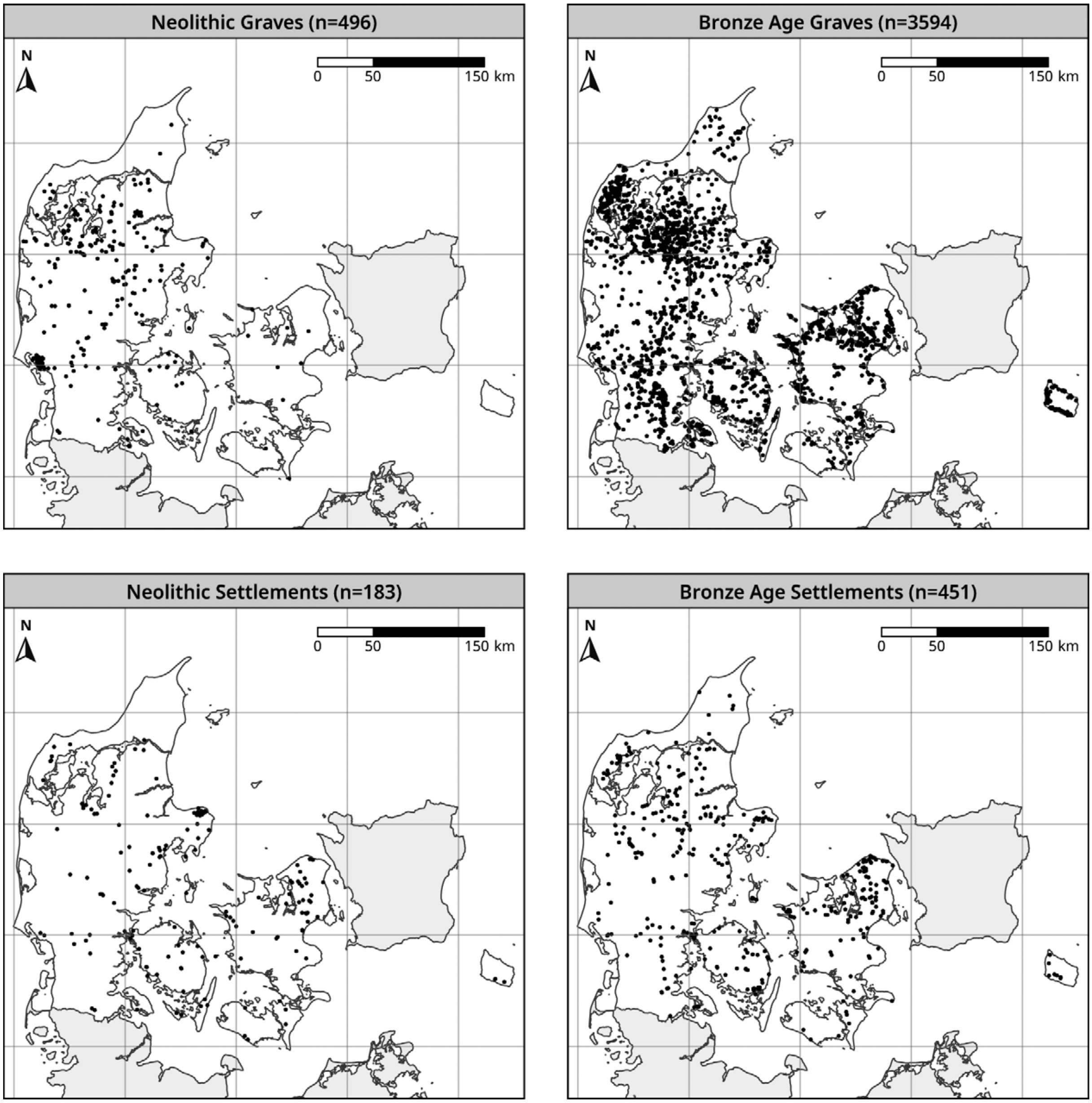


Figure 12. Neolithic and Bronze Age sites with a chronological precision within 200 years. Data from the Danish Agency for Culture and Palaces.

Initially, each field received a direct translation from its Danish equivalent. This was followed by an aggregation process where similar typologies were grouped together; for instance, different forms of funerary depositions were collectively categorised as graves, while different types of settlement remains were labelled as settlements. The final layer of this structuring involved a substantial simplification, aiming to distinctly highlight the primary function of each site. This simplification led to three broad categories: settlements, graves, and 'other'. The latter category includes all sites that cannot fit in the other two, including, among others, stray finds, depositions or roads.

The structure and organisation of the Danish database makes it particularly usable for queries and quantitative analyses, facilitating the process of modelling and allowing a more efficient and better handling of the data compared to the other datasets.

3.1.4 Case study selection

One of the primary challenges associated with the archaeological data described earlier is the generally limited chronological precision. In many cases, sites either lack specific dating information, as in the case of Sweden or, when dates are available, the resolution is low, as illustrated for the Danish sites (Figure 12). As previously mentioned, typological characteristics can offer indirect dating clues, aiding in reducing chronological uncertainties. This is particularly true for some of the better preserved and useful proxies utilised in this study, notably, monumental graves such as megaliths, burial mounds and cairns.

Megalithic construction can be narrowed to a period of approximately 600 years, spanning from 3600 BCE to 3000 BCE and with frequent patterns of later reuse (see Chapter 2). Similarly, burial mounds and cairns are generally dated to the Bronze Age, with most of the monuments erected during periods II and III, although some were built also during the LBA (see Chapter 2). A possible issue derives from the fact that some mounds might conceal megaliths and when not investigated, typological certainty cannot be reached. Moreover, burial mounds were built also during the Iron Age, though they are generally easier to identify typologically. Nevertheless, both groups of monuments have a relatively precise dating, are numerous and provide valuable information about the use and occupation patterns of the landscape. In summary, the broad chronological spectrum, regional disparities in monument construction, ambiguities in typological categorisation, patterns of reuse, the predominant lack of excavation at most sites and variances across different datasets all pose challenges for high-resolution analysis in large archaeological datasets. These complexities necessitate a cautious approach when interpreting the data. Nevertheless, a key achievement of this study is addressing and effectively managing these uncertainties. Integrating radiocarbon dating from large databases with archaeological site data, where possible, offers a more robust framework for addressing these challenges, increasing the reliability of our hypotheses.

Despite the extensive number of archaeological sites in the region, it is crucial to acknowledge the existence of gaps and variations in archaeological knowledge. Consequently, focusing on individual case studies proves more fruitful than attempting to encompass the entire study region. This approach facilitates the selection of apt case studies, enabling more coherent comparative analyses across different areas. Although not performed here, the models produced in this study can be used to predict site distributions and patterns in other regions.

The criteria for choosing case studies in Schleswig-Holstein, as previously detailed, are primarily informed by data availability and structure and therefore not considered here. In order to gain a better understanding of site intensity variation across the remaining regions, a density map has been generated using all available archaeological sites. The underlying assumption adopted here is that regions exhibiting the highest site densities likely indicate more intense research activities and, as a consequence, a better knowledge of the archaeological record. Each selected region was then analysed in conjuncture with the available literature in order to refine and select the most suitable case studies.

The results of the density analyses were carried out at different scales and show that several regions could possibly be suitable case studies (Figure 13). Among these, some potential case study candidates could be north-western Jutland, north-central Jutland, north-western Zealand, some of the Danish islands such as Bornholm, Als, or Ærø, most of the coastal areas in Scania, the island of Rügen and the area west of Rostock in Germany. Depending on the bandwidth used in the density estimation, some other areas may appear as more or less relevant (Figure 13). Based on these results and an assessment of the available literature, the following case studies were selected: the Thisted area in the North Denmark Region (*Nordjylland*), Viborg and

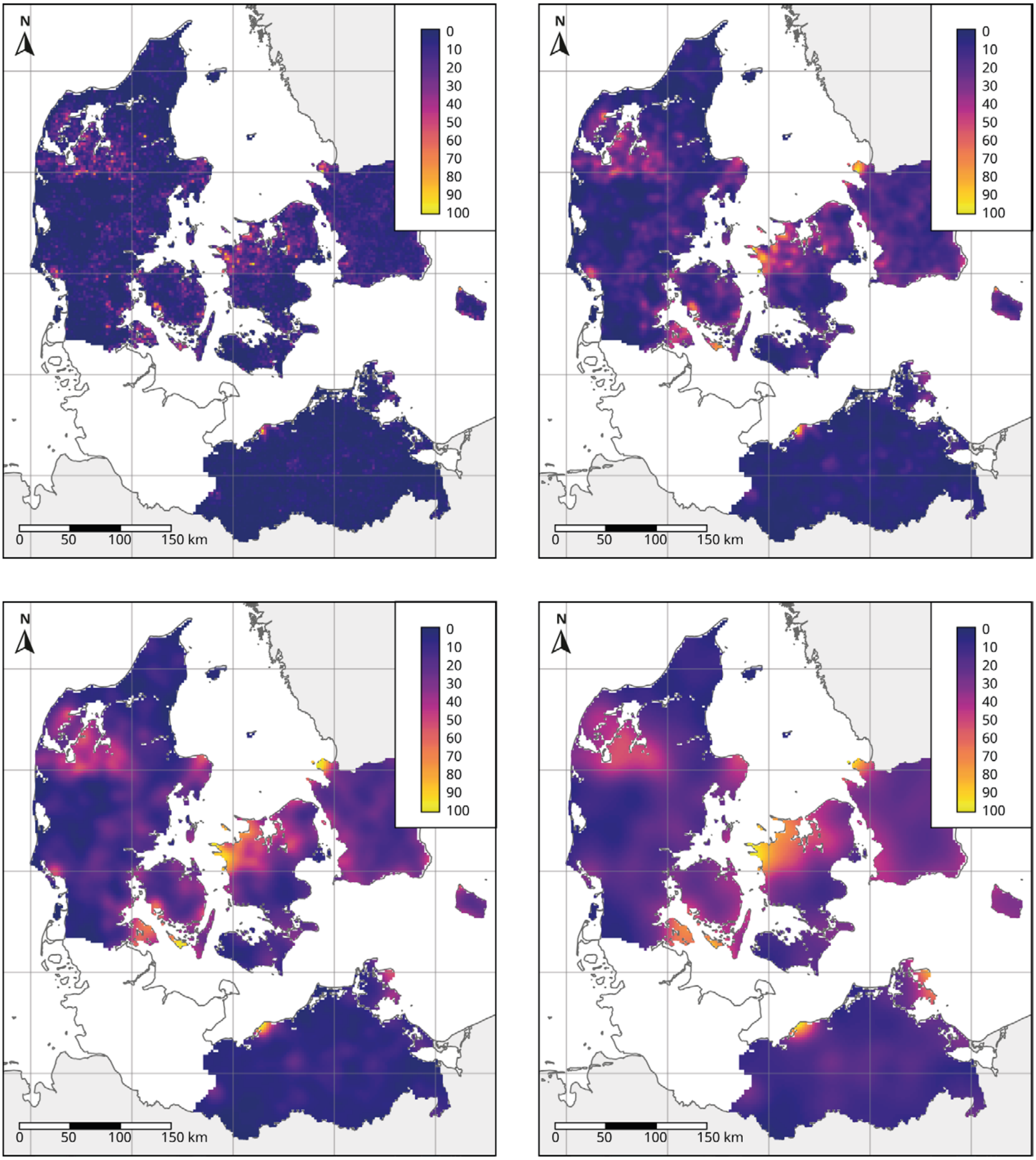


Figure 13. KDE of prehistoric sites in Denmark, Scania and Mecklenburg-Vorpommern using different bandwidths. See Chapter 5.1.3 for a description of KDE. From top-left to bottom-right: 1000, 2500, 5000 and 10000 m sigma.

Skive municipalities in the Central Denmark Region (*Midtjylland*), north-western Zealand in the Zealand and Capital Regions (*Sjælland* and *Hovedstaden*), the Bjäre peninsula, western Scania, south-western Scania, north-eastern Scania in Sweden, and Rügen in Germany.

The areas in Sweden are particularly well-known for their research activity. Specifically, the Bjäre peninsula in Båstad municipality is Europe's most dense region for Bronze Age burial mounds (Thrane, 2013), attracting significant research interest (Nord, 2009). Western Scania, particularly north of the E22, south of Helsingborg and south-west of Svalöv and Eslöv, has undergone extensive investigations, thanks to major infrastructure projects like the West Coast Railway (*Västkustbanan*; Andersson, 2004). South-western Scania, including the Malmö,

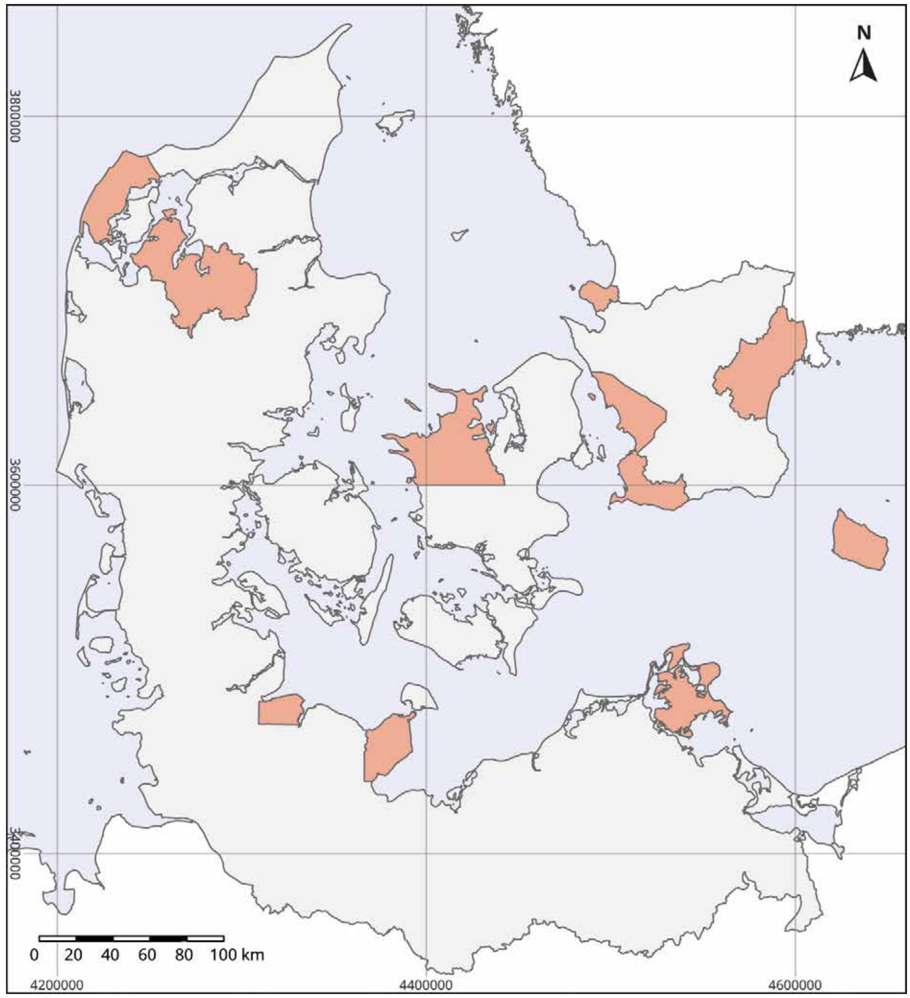


Figure 14. Case studies considered for this work. The following regions were selected (from west to east): Thisted (DK), Central Jutland (DK), south-eastern Schleswig (DE), eastern Holstein (DE), north-western Zealand (DK), the Bjäre peninsula (SE), western Scania (SE), south-western Scania (SE), Rügen (DE), north-eastern Scania (SE), Bornholm (DK).

Trelleborg and Vellinge municipalities, has seen intensive excavations driven by urban development and projects like the Öresund Link and the City Tunnel (Artursson, 2005a; Björhem and Magnusson Staaf, 2006; Björhem and Säfvestad, 1989, 1993; Hadevik and Steineke, 2009). North-eastern Scania, encompassing Kristianstad and Bromölla municipalities, also experienced widespread archaeological investigations and overarching compendia of the archaeology of the region (Artursson, 2007b).

Similarly, Denmark has seen a comparable level of research intensity. In Thy, Thisted municipality, several projects were carried out, including the Aas and Thy Archaeological Projects (Bech, 2018a, 2018b; Mikkelsen, 1996). Central Jutland, particularly in Skive and Viborg municipalities, has a rich prehistoric heritage thanks to several years of excavations primarily conducted by the Viborg Museum (Mikkelsen et al., 2012). North-western Zealand, despite limited urban and infrastructure development, was extensively investigated in the mid-1950s, yielding an incredible amount of archaeological finds (Kristiansen, 1981; Mathiassen, 1959). The original boundaries of these mid-50s projects have been adopted in this study. Lastly, Bornholm has also been the focus of several projects, yielding a considerable amount of archaeological data (Nielsen, 1999; Nielsen and Nielsen, 2020). All the case studies included in this work are shown in Figure 14.

3.2 Radiocarbon data

The methodology of this study integrates radiocarbon dating as a pivotal element for some of the case studies. The significance of radiocarbon dates in archaeological research is undeniable, as they are among the most reliable dating methods. In the present work, radiocarbon dates are used to complement the modelling process, allowing for the simulation of the chronologies of relatively dated sites that in many cases may lack precision.

Recent years have seen various teams dedicated to the collection and refinement of radiocarbon dates. In most cases, the primary goal was to use this data for demographic estimations, making it also accessible to a broader audience, as seen in the EUROEVOL and XRONOS initiatives (Hinz and Roe, 2023; Manning et al., 2016).

A key issue with these databases is their tendency to constantly lag behind current research, given the continuous production of new radiocarbon dates, particularly in commercial archaeology. While a systematic review of the grey literature from Denmark, Germany and Sweden is impractical due to the sheer volume and ongoing nature of datings, some regions benefit from local archaeologists who have compiled and published extensive datasets in specialised journals. This is the case for southern Sweden, where Friman and Lagerås (2023) recently published an extensive collection of radiocarbon dates, alongside their study on regional population dynamics. Their work presents 6637 dates ranging from 9000 BCE to the present, significantly surpassing the data in older databases. As of late 2023, the EUROEVOL database contained only 775 dates for Sweden and XRONOS had 2375 (excluding duplicates), predominantly from central and southern Sweden. In Denmark, the available data consisted of 2311 entries from the XRONOS database, with more recent publications not yet available.

3.3 Environmental data

The modelling of site distribution in this study primarily uses environmental variables, which are categorised into three main types: elevation model-related, distance-based, soil data. To facilitate the analytical process, all the variables were used in raster format. When required, vector data were converted to raster.

3.3.1 Elevation and distance-based variables

Elevation represents the vertical height from a point to mean sea level. It significantly influences the ecosystem, as variation in elevation has an effect on parameters like temperature, precipitation, and air pressure (Gebhardt et al., 2020). Consequently, its significance for settlement patterns has been well-established in various studies (Bilotti et al., 2024a; Carrero-Pazos et al., 2019; Costanzo et al., 2021; Metta and Bilotti, 2023). It is generally used in its digital version, known as Digital Elevation Model (DEM).

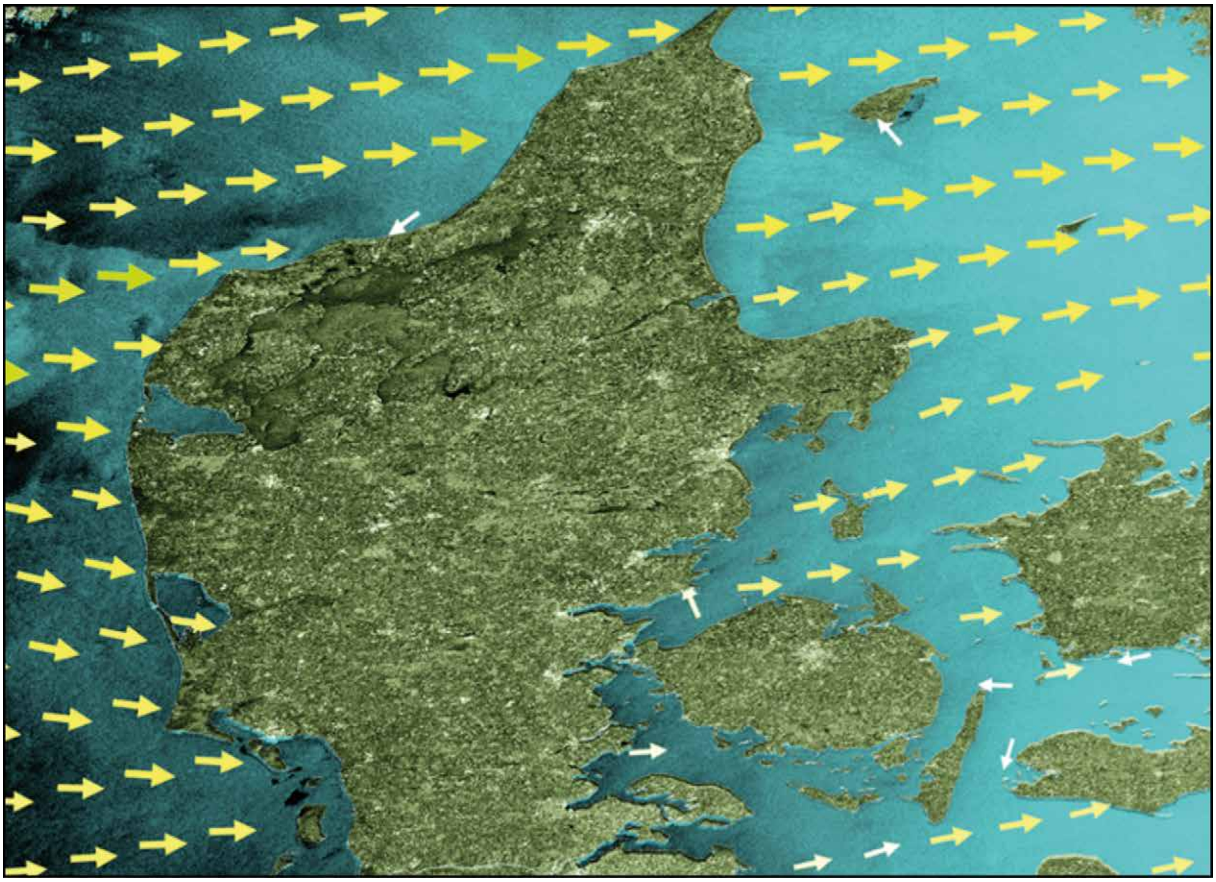
When selecting elevation models for spatial analysis, one must consider the aims, scale and area of the study. Models range from high-resolution, like the approximately 1-metre resolution LiDAR-derived models, to the coarser SRTM-90 m resolution DEM, available at CGIAR-CSI. LiDAR data, while detailed, may pose challenges such as difficulty in filtering modern features and increased computational demands, particularly in medium- to large-scale studies. Conversely, using a DEM that is too coarse can obscure important landscape features (Bilotti et al., 2024b; Herzog, 2014). Given these considerations, the European Digital Elevation Model (EU-DEM) version 1.1 was chosen for this study. This model was produced by the European Environment Agency (EEA) under the Copernicus programme and offers a good balance with its nominal resolution of 25 m. The elevation data for the EU-DEM v1.1 can be accessed from the Copernicus Land Monitoring Service (last accessed on 4th May 2022).

Slope is a topographic feature indicating the steepness or inclination of a surface and it is typically measured in degrees or as a percentage. It is a widely used topographic measurement, significantly impacting various aspects such as water flow, sedimentation, and energy expenditure (Zevenbergen and Thorne, 1987). In archaeology, slope is frequently considered to influence site location preferences, which it has therefore been extensively used to study (Bilotti et al., 2024a; Carrero-Pazos et al., 2019; Costanzo et al., 2021; Metta and Bilotti, 2023). In this study, slope is computed in degrees using the *terrain* function from the *terra* package in R (Hijmans, 2023), with the DEM as input. The function calculates the rate of change in elevation, considering variation between 8 or 4 neighbours depending on the parameters. In this case, 8 neighbours were used, following the Horn algorithm (Horn, 1981). Southern Scandinavia, known for being relatively flat and low in elevation, experiences minimal variation across the region in both these parameters. However, even slight differences in values can influence settlement choices, as slope affects water runoff and, depending on soil type, water retention and wetness.

Soil moisture, another crucial landscape component, influences plant species growth and impacts hydrology, ecology and human activities such as agriculture (Raduła et al., 2018). Therefore, understanding the variation in soil moisture is essential in various scientific disciplines (Raduła et al., 2018). The so-called Topographic Wetness Index (TWI) has been developed for this purpose and it assesses soil moisture based on land topography (Beven and Kirkby, 1979; Raduła et al., 2018). The index is calculated using the formula TWI = ln (a/tan β), where *a* represents the specific catchment area and *β* is the slope (Beven and Kirkby, 1979). Differences in indices are due to differences in the calculation of the catchment area and flow direction (Raduła et al., 2018). In this study, the 'SAGA Wetness Index' was employed instead of the standard TWI. This variant offers a more realistic assessment of the catchment area, particularly in valley floors close to channels (Boehner et al., 2002; Boehner and Selige, 2006). The SAGA GIS functions, including this one, can be accessed within an R environment using the *Rsagacmd* package (Conrad et al., 2015; Pawley, 2023).

The south-western Baltic is deeply connected with water, particularly with the sea, which played a central role in human history. The region is well-known for its relationship with sea-faring and water movement, which have been object of various research (*e.g.* Austvoll, 2020; Broodbank, 2016; Kristiansen et al., 2020; Ling et al., 2018; Vandkilde, 2016). However, modelling mobility and water-based movement in prehistory presents significant challenges and requires a specialised focus, which is not possible at this stage (see Bilotti et al., 2024b for a discussion). Nonetheless, it is possible to employ a number of indirect proxies to determine the impact and importance of the sea and water in the study area. The simplest one is distance from water, be it the sea or internal waters. Both have been used as a covariate.

Hydrologic streamflow data derives from the Copernicus European Union's Space programme (last accessed 20th of May 2023). Rivers come in spatial lines format, which were extracted and filtered according to their stream flow hierarchy (Strahler order number). All river sectors with a Strahler order number equal to or greater than 3 were selected from the catchments of the rivers (in alphabetical order) Elbe, Göta and Skjern. The area contains more river basins, but they are aggregated to these three principal rivers in the study region by the issuing institution. Additionally, lakes with a size above 50 ha were selected and included in the distance raster. The coastline derives from the Nomenclature of Territorial Units for Statistics (NUTS) 2021 issued by the Geoportal of the European Commission



(EUROSTAT), which contains the administrative boundaries of the European countries (last accessed 25th February 2022). The script used to compute the distance rasters is the *01_distance_rasters.R*. After defining the study area, the script reads, transforms, and filters river and lake data, combining them in a single spatial layer. Utilising the *distance* function from the *terra* package (Hijmans, 2023), it calculates the distance from the study area to the nearest coastline and river features, storing the results as TIFF files.

Figure 15. Denmark and the wind fields over the North Sea. Image acquired by Envisat's Advanced Synthetic Aperture Radar (ASAR) instrument on 30 September 2009. Size and colour of the arrows depend on wind speed (from 0 to 20 m/s). ESA, CC BY-SA 3.0 IGO. https://www.esa.int/ESA_Multimedia/Images/2009/12/Wind_field_observations_in_Denmark (last accessed 20th August 2024).

In addition to other factors, wind patterns are considered to have significantly influenced site location and travel in the study region. Historical variations in storminess and wind strength have been noted, with certain periods experiencing more intense winds, potentially impacting these factors (Goslin et al., 2018). The relevance of wind strength is particularly evident today along the North Sea coast, a region known for its high wind energy yield in Denmark (Troen and Lundtang Petersen, 1989). Consequently, wind exposure has been incorporated as a covariate in the analyses.

Two specific wind-related indices were calculated: 'Wind Effect' and 'Wind Exposition'. The Wind Effect Index identifies areas exposed to winds from a particular direction, with values above 1 indicating exposure and values below 1 suggesting shelter. Meanwhile, the Wind Exposition Index represents the average wind effect across all directions, calculated at set angular intervals. The interpretation of values follows the same principle as the Wind Effect Index (Böhner and Antonić, 2009; Gerlitz et al., 2015). These indices are computed using SAGA GIS functions, accessible in R via the *Rsagacmd* package. For this study, the Wind Exposition Index focused on winds from the west and south-west, believed to be the dominant wind directions in the area (Figure 15).

3.3.2 Soil and geological data

Soils certainly had a very important role in site location patterns and preservation, as they have different properties and characteristics. Therefore, before describing the soil data that has been used, it is instructive to briefly discuss the various soil types present and their characteristics. This overview is not exhaustive in terms of formation processes and geomorphology but aims to provide context for understanding the study area and determining the significance of different soil types. The information in this paragraph derives from the ISRIC – World Soil Information, to which I refer for further information.

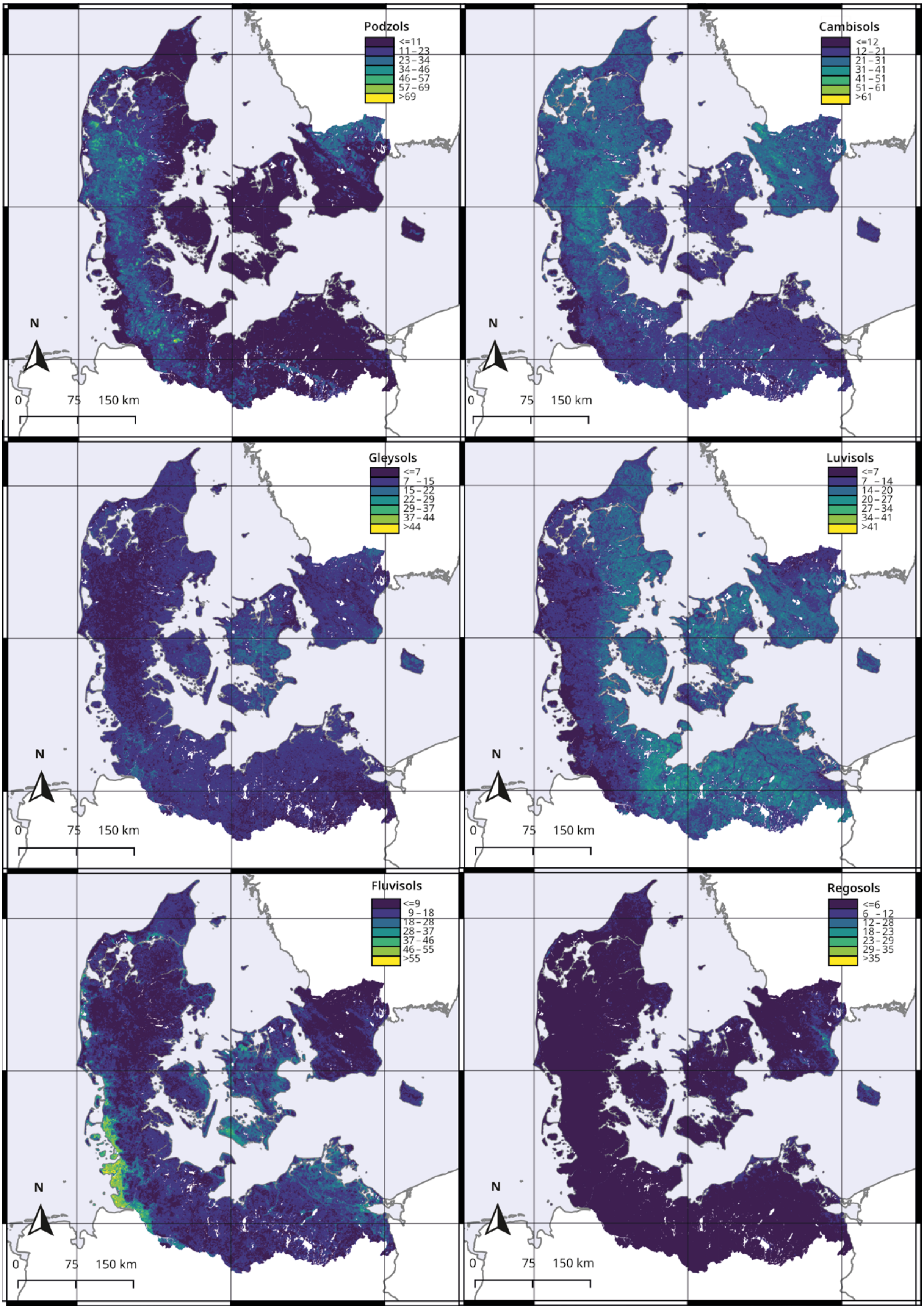
- Acrisol: Characterised by a subsurface horizon (argic) with more clay than the overlying layer. They exhibit a cation exchange capacity under 24 cmolc per kg and a base saturation of less than 50 percent within 25 to 100 cm from the soil surface;
- Arenosol: These are sandy soils, either loamy sand or sand in texture. They may contain finer layers less than 15 cm thick. Coarser fragments, if present, do not exceed 40% of the total volume. These soils are typically found in coastal areas of the study region;
- Cambisol: Identified either by slow formation (due to factors like low temperatures) or young parent material. They must exhibit specific characteristics, such as a cambic horizon;
- Fluvisol: Generally young and developed on alluvial deposits, they are over 25 cm thick and begin less than 25 cm from the mineral soil surface;
- Gleysol: Occurring where the water table is near or at the surface, causing prolonged wetness. Gleysols have specific definition criteria involving gleyic properties and reducing conditions in sublayers which are not discussed here;
- Histosols: Characterised by organic horizons, which can be either dry or wet. Specific requirements regarding the thickness and volume of organic matter;
- Luvisol: Notable for an argic horizon with more clay than the upper layer, starting within 100 cm from the mineral soil surface and with a cation exchange capacity of 24 cmolc per kg clay or more;
- Podzols: Found mainly in cool, temperate and moist regions, characterised by a dark spodic horizon beneath a thin albic, histic, umbric, or ochric horizon;
- Regosols: A diverse group comprising soils that do not fit into other categories, usually very poorly developed.

In most cases, besides this main categorisation a soil could have many different qualifiers, such as vitric, andic, calcaric, *etc*. horizons or combined characteristics (*e.g.* cambic arenosols). This is especially true for the high resolution (1:200,000) soil maps, which however have not been used here and are therefore not further discussed.

While there are numerous soil and geological datasets available for the study area, their diverse nature and the inclusion of discrete rather than continuous variables present challenges for the analysis carried here. These challenges necessitate extensive data cleaning, standardisation and adaptation, which, while crucial, is a time-consuming process that was not feasible for this study. Consequently, instead of relying on the available national soil databases, I decided to use the ISRIC SoilGrid database. This database offers continuous data that can be more straightforwardly integrated as a standard covariate in the analyses.

The ISRIC SoilGrid database is an open-access global resource detailing key soil types and grain size composition. It has been created using machine learning techniques to create predictive models based on the WoSIS Soil Profile Database,

(Opposite page) Figure 16. SRIC SoilGrids soil types. Only the 6 most represented soils in the regions are shown. Top L–R: Podzols, Cambisols; centre L–R: Gleysols, Luvisols; bottom L–R: Fluvisols, Regosols. Data obtained using the geodata package in R (Hijmans et al., 2023).


Podzols
<=11
11 – 23
23 – 34
34 – 46
46 – 57
57 – 69
>69
N
0
75
150 km
Cambisols
<=12
12 – 21
21 – 31
31 – 41
41 – 51
51 – 61
>61
N
0
75
150 km
Gleysols
<=7
7 – 15
15 – 22
22 – 29
29 – 37
37 – 44
>44
N
0
75
150 km
Luvisols
<=7
7 – 14
14 – 20
20 – 27
27 – 34
34 – 41
>41
N
0
75
150 km
Fluvisols
<=9
9 – 18
18 – 28
28 – 37
37 – 46
46 – 55
>55
N
0
75
150 km
Regosols
<=6
6 – 12
12 – 28
18 – 23
23 – 29
29 – 35
>35
N
0
75
150 km

which includes over 230,000 soil profiles from around the world. Moreover, the model combines these profiles with more than 400 environmental covariates, including climate, land cover and morphological data. The accuracy of the database's outputs is directly related to the volume of input data. For the countries in this study, the database utilised 5020 soil profiles, predominantly from Germany (4360 profiles), with Denmark and Sweden contributing 72 and 590 profiles respectively. The final product is a raster map with a nominal resolution of 250 metres, providing a comprehensive and uniform data source suitable for the study's requirements.

The latest available data from the SoilGrid database were generated in 2020 and can be directly accessed in R using the *soil_world_vsi* function from the *geodata* package (Hijmans et al., 2023). The workflow to download, crop, reproject and save the relevant soils is provided in the *01_isric_soil.R* script. A further advantage of this dataset is that it quantifies for each location the percentage of different soil classes rather than indicating the prevalent one, as in most soil maps. The available soil classes are: Acrisols, **Albeluvisols**, Alisols, Andosols, **Arenosols**, **Cambisols**, Chernozems, Cryosols, Durisols, **Fluvisols**, **Gleysols**, Gypsisols, **Histosols**, Kastanozems, Leptosols, Lixisols, **Luvisols**, Nitisols, **Phaeozems**, Planosols, Plinthosols, **Podzols**, **Regosols**, Solonchaks, Solonetz, Stagnosols, Umbrisols, Vertisols.

However, not all of these soil types are present in the study area, and some are found only in low concentrations or sporadically. Therefore, the dataset was filtered to include only the most representative soil classes, using a minimum threshold of 15% for maximum concentration. The most prevalent soil types in the study area are highlighted in **bold** in the list above. It is important to note that even with this threshold, some soil classes are relatively scarce in the study region and are only discussed in part (only 6 soil classes exceed 20% maximum concentration). Some of the most represented soils are shown in Figure 16.

4. Demography

This chapter aims to briefly introduce the concepts of palaeodemography, particularly focusing on their application to the case studies. The different methods and the available demographic estimates are described and some considerations are made about the local and micro-regional reconstructions. During the second part of the chapter, I will focus on several case studies, reconstructing the number of inhabitants of a settlement and settlement densities from well-studied region across different periods. The results serve to connect the medium- to large-scale model presented in the Chapter 5 and Chapter 6.

Demography is a science that studies human populations, primarily focusing on population size, composition and distribution (Chamberlain, 2006; Daugherty and Kammeyer, 1995). In contexts where direct measures are feasible, it often employs proxies like censuses, written records, or headcounts. However, in archaeology, where direct methods are not possible, researchers rely on indirect proxies. These include a variety of evidence such as skeletal remains, settlement size and density, site counts, carrying capacity assessments and comparisons with historical or ethnographic data (Chamberlain, 2006; Hassan, 1981; Wilkinson, 1999). Considering the challenges in reconstructing prehistoric population dynamics and the limitations of a PhD thesis, this study will focus specifically on population size and density and their change through time.

4.1 State of the art in Palaeodemography

In the last few decades, the study of prehistoric demography has become almost synonymous with radiocarbon curves. For this reason, the next paragraph briefly describes this method and its implications. Nevertheless, other methods have been applied and other types of reconstructions are also discussed.

4.1.1 Radiocarbon dating

Radiocarbon dates have become the preferred demographic proxy for various reasons, the main certainly being their availability, ease of use and chronological precision (Contreras and Meadows, 2014). The relative simplicity in extracting and interpreting radiocarbon data, as opposed to complex or qualitative variables like the number of structures, artefact quantities and settlement patterns, further contributed to its widespread use (Contreras and Meadows, 2014). Additionally, radiocarbon dates are perceived as culturally neutral and therefore less prone to cultural biases, although it may not always be the case (for a discussion see Contreras and Meadows, 2014 and their cited references). However, its application is not without challenges. For instance, a significant volume of data is needed, which is currently only viable for medium to large regions, possibly concealing local patterns. An increase in the available amount of data would likely overcome this issue, as shown by Friman and Lagerås (2023). Certain regions are currently underrepresented and therefore a direct comparison may simply represent differences in research intensity and accessibility rather than demographic patterns (Crombé and Robinson, 2014).

The theoretical background for using radiocarbon dates as a demographic proxy stems from the '*date as data*' concept proposed by Rick (1987). In his initial formulation, Rick suggested treating dates as artefacts indicative of human activity, implying that a greater number of artefacts from a specific period suggests increased human activity (Rick, 1987). The most important implication is that compared to other proxies, radiocarbon dates are directly comparable in terms of chronology and across different regions. However, Rick highlighted the presence of inherent biases in this method, namely preservation and recovery bias (Rick, 1987: 56). For instance, changes in burial practices, such as the shift from inhumation to cremation, can result in a skewed representation in favour of cremations in regions where collagen preservation is poor, rather than a demographic change (Contreras and Meadows, 2014). Soil conditions can also play a crucial role in the preservation of archaeological sites, as post-depositional factors, including natural and cultural events, can lead to differential site loss. This often results in older sites being less represented compared to more recent ones, due to their longer exposure to these factors (Rick, 1987: 57). Rick's conclusion was that, due to these biases, only relative reconstructions are possible.

Despite the aforementioned issues, several studies have attempted to use radiocarbon data as a demographic proxy and after the first wave of studies new issues have been identified and possible solutions adopted (starting with Gamble et al., 2005; Shennan and Edinborough, 2007). In particular, it has been argued that the correlation between material production leading to ^{14}C samples and demography, and the statistical representation of these samples in the overall dataset may not be direct nor representative (Contreras and Meadows, 2014; McLaughlin, 2019). The representativity issue could be lessened with the increasing number of ^{14}C samples available, though full agreement on the correlation aspect seems unlikely. From a methodological perspective, the connection between the sum curve's peak and population size may not be straightforward but influenced by various factors like sample production, survival, sampling, research biases, as already noted by Rick (1987), as well as calibration and computational issues (Contreras and Meadows, 2014). Furthermore, rapid population changes might be masked by statistical noise and therefore important historical events, such as the Black Death, may not be noticed in the radiocarbon curves (Contreras and Meadows, 2014). Some later studies addressed this criticism and it seems that it can be partially overcome by preferring Kernel Density Estimation (KDE) to the more widespread Summed Probability Distribution (SPD; see Chapter 5.1 for their technical explanation; McLaughlin, 2019). Nonetheless, in cases where the chronological precision of the events is around 100-200 years even the SPDs seem appropriate (Edinborough et al., 2017). In this study, 200 years is the aimed chronological resolution and therefore this aspect may not represent an issue.

Despite these considerations, radiocarbon curves are generally regarded as the 'best imperfect proxies' (a term used by Contreras and Meadows, 2014). Probably, the most promising approach in the study of prehistoric demography is the combination of multiple proxies, as suggested by Hinz et al. (2022). Unfortunately, at the time of writing this method is still under development and available only as a preprint. While other multi-proxy methods exist, they often rely on visual correlation of different curves without integrating them into demographic estimates with confidence intervals. In this study, I try to overcome these issues by combining site counts and distribution with radiocarbon dates, a process discussed more in detail in the following chapters.

4.1.2 Demographic fluctuations in northern Germany and southern Scandinavia

During the last decades, new advances in prehistoric demography overturned the notion of 'long-standing' demographic equilibria, revealing that demographic change and oscillation were commonplace (Shennan, 2013). Demographic discontinuities included events such as the loss of local populations and cultural lineages, immigration and cultural change (Shennan, 2013). Understanding these demographic patterns is vital for grasping historical, social, cultural, and economic transformations. In fact, it has been suggested, and to some extent proven, that variations in group size can lead to both adaptive cultural evolution or the detrimental erosion of culturally learned abilities (Henrich, 2004). Specifically, the greater our reliance on extensive bodies of culturally transmitted knowledge, the more we depend on large social groups (Derex et al., 2013). In cases where survival without specific cultural knowledge is challenging, group size reduction can expose a population at risk of extinction or a loss in fitness (Boyd et al., 2011; Derex et al., 2013; Diamond, 1978). Notably, such a decrease in group size and the consequent loss of skills might result in societal downfall, especially when coupled with demanding environmental conditions (Derex et al., 2013). Therefore, addressing the problem of absolute demographic reconstruction – rather than relative changes – is essential as it may help identifying cases where this possibly happened in prehistoric times or if the specific population was resilient enough to overcome these challenges.

A primary difficulty in palaeodemographic studies is that they often focus on relative rather than absolute changes, as exemplified by the SPD curves. This limitation can hinder a full understanding of socio-cultural evolution patterns. However, there are some studies providing absolute demographic reconstructions for Europe (Müller, 2013a, 2015, 2019; Müller and Diachenko, 2019). These studies offer essential insights, representing a significant step towards understanding demographic patterns. To gain a deeper understanding, it is crucial to examine the relationship between local scales (settlement level) and the micro- and meso-regional levels which could reflect social structures like polities or chiefdoms or simply site catchment.

The current understanding of demographic patterns in European prehistory follows a 'boom and bust' model (Bevan et al., 2017; Müller, 2019; Shennan, 2013; Shennan et al., 2013). The spread of agriculture in Europe, from the south-east around 8500 years ago to the rest of the continent, caused regional population increases followed by busts. The timing and strength of these events varied across the continent, depending on when farming was introduced in each region (Shennan et al., 2013). In particular, for southern Scandinavia this pattern can be observed starting from 4000 BCE, although it seems that some internal variation can be seen in the region, with the earliest and strongest peaks observed in the Danish Isles, rather than Jutland or northern Germany (Shennan et al., 2013). Northern Germany did experience an early increase, but its intensity was not comparable to the Danish Isles. On the other hand, Jutland and Scania witnessed a peak a few centuries delayed (mid-4th millennium) compared to the introduction of the Neolithic (Shennan et al., 2013). The curves of Denmark and Scania show that towards the end of the millennium there was a decline in population, although it is observed later, at the beginning of the 3rd millennium BCE, on the Danish Isles. This decline continues on the Danish Isles, while both Scania and Jutland experience a renewed period of growth a few centuries after the beginning of the millennium (Shennan et al., 2013). A significant decline is observed on the Danish Isles, which has been attributed to edge effects factors in the radiocarbon curve.

One key issue with this method is the relatively small number of radiocarbon dates used for individual sub-regions, except for Germany. Specifically, there were only 409 dates for Jutland, 329 for the Danish Isles and 281 for Scania (Shennan et al., 2013). While the quantity of dates is not necessarily problematic for statistical confidence, the availability of a much larger pool of recent dating data from labs or excavation reports could alter the overall interpretation. In fact, in Scania, a recent study using over 6000 radiocarbon dates, as opposed to the 281 used by Shennan et al. (2013), suggests that the previously assumed time lag may not exist and the adoption of farming around 4000 BCE corresponded to an immediate population increase (Friman and Lagerås, 2023). Nevertheless, the booms observed by Shennan et al. (2013) in the mid-6th millennium BCE closely correspond to the period of more extensive megalithic construction, which is assumed to have started or begun peaking around 3500 BCE (Persson and Sjögren, 1995; Sjögren, 2003).

More recently, a study from Feeser et al. (2019) attempted a multi-proxy approach, combining archaeological ^{14}C dates and palaeoenvironmental data from northern Germany and south-western Denmark in order to understand the demographic patterns in that region between the Neolithic and the Bronze Age. Their study identifies five distinct phases of population growth or 'booms' around 4000-3500, 3000-2900, 2200-2100, 1450-1300 and 1000-750 BCE, and four 'bust' phases around 3400-3100, 2400-2300, 1650-1500 and 1250-1100 BCE. Despite some divergences attributed to biases in data, due to changes in settlement and burial practices or regional differences, the overall correlation between the archaeological, palynological and soil erosion was considered strong by the authors (Feeser et al., 2019). The main issue of this study is assuming independence of the three proxies, which might not be the case, possibly undermining parts of their results. The initial population increase aligns with the introduction of the Neolithic, consistent with other studies, although usually it is recorded later (*e.g.* Hinz et al., 2012; Shennan et al., 2013). The first bust is ill-represented in the SPD curve and it has been explained by the authors as due to regional variation within the study area. Nevertheless, the proxies seem to align more closely around 3100 BCE. The transition between the Funnel Beaker and the Single Grave culture is marked by the increase of human impact in the palynological proxy, possibly linked to a lifestyle shift towards grazing rather than a real demographic change, as in this period soil erosion continues to diminish (Feeser et al., 2019: 1602). Moreover, the second bust (2400-2300 BCE) is not equally observed in all proxies, with soil erosion increasing during this period and decreasing in the following century, before rising again around 2200/2100 BCE, when the authors report a new boom phase (Feeser et al., 2019: 1602). This bust and the following boom correspond to the end of the Younger Neolithic and the beginning of the Late Neolithic in the study region, traditionally considered as a period of increased human imprint in the landscape. The following bust phase was identified during the Early Bronze Age (1650-1500 BCE), with a sharp decline in the palynological proxy and their SPD (Feeser et al., 2019: 1603). This pattern could also be explained by a shift from extensive to intensive agriculture during this period. A new sharp increase is observed during the Middle Bronze Age (1450-1300 BCE), which seems to agree with the results obtained for other regions using different proxies (Kristiansen, 2018, 2022b). This period is followed by a new bust phase (1250-1100 BCE), reflected in the palynological and SPD curves, but with a peak in soil erosion, which has been linked to an increase in high-intensity precipitation during this period (Dreibrodt and Wiethold, 2015). Despite a decline in the SPD, attributed to a well-known research bias, the other proxies show an increase in human activity from the late 9th century BCE (Feeser et al., 2019: 1603).

In their recent account, Müller and Diachenko (2019) proposed a reconstruction of European demography between 6500-1000 BCE with a temporal resolution of 500 years. The study identified and analysed four major regions, acknowledging that the temporal and spatial limitations meant only the most significant technological, social, or climatic changes could be correlated with demographic shifts. Here, only the results for central and northern Europe are considered. In particular, three different phases of population growth are identified: 5000-4000 BCE, 3500-2000 BCE and 1000-500 BCE (Müller and Diachenko, 2019). They argue that in the first time-window the population increased from less than 1.5 to 1.9 p/km^2, then to 2.4-2.6 p/km^2 and finally to 3.6 p/km^2 (Müller and Diachenko, 2019: 6). In between these periods two busts in the curve are observed, around 3500 and 1500 BCE. They connect the initial increase to the introduction of agriculture and the introduction of new technologies such as the plough, the wheel, and the wagon as the driver of the increase in population around 3500 BCE. On the other hand, population declines are linked more to internal social developments than to climatic events (Müller, 2017b).

Another absolute reconstruction is available for the Early Bronze Age in Denmark. Between 1500 and 1100 BCE, Kristiansen (2018) estimated a population of 220,000-330,000 people, based on some density estimates from Bech and Mikkelsen (1999) and household size reconstructions based on Sørensen (2010), as discussed in Chapter 2.1.4.2. In particular, the reconstructed population density for settled areas in their study is 10-15 p/km^2. However, Kristiansen only considers half or at most two thirds of Denmark as 'settled', reducing the global density to 5-7.5 or 6.7-10 p/km^2. In both cases, his results are significantly higher than the estimates from Müller and Diachenko (2019). However, it's important to note that their figures for southern Scandinavia and central Europe include regions like central Sweden, southern Norway, and the Alps, which likely had lower population densities than the south-west Baltic.

4.2 Household size

Reconstructing household size and composition over extensive areas and long timeframes is certainly a challenging task. It can be influenced by numerous factors, and there is no consensus in academic literature on standardising household size, plus prehistoric settlement studies often equate households with extended families without concrete data or analysis to support this (Sørensen, 2010). However, there are exceptions where settlements have been examined to understand household dynamics in north European prehistoric societies (see Sørensen, 2010 for a comprehensive overview).

Household size estimations in European prehistory are infrequent in academic literature. Based on house size, Fokkens (2003) suggested that a LBA longhouse in the Netherlands was occupied by an extended family of approximately twenty individuals. 10-30 people are thought to live in a single household in Iron Age southern England, though there could be significant differences compared to southern Scandinavia and northern Germany (Evans and Hodder, 2006; Sørensen, 2010). M Larsson (1992) assumes that during the Neolithic a nuclear family was sharing a single house, with estimates ranging between 5 and 10 individuals. One of the most recent and complete accounts, although focusing only on the Bronze Age, has been made by Sørensen (2010). She estimated that a Bronze Age household in southern Scandinavia was composed of *ca.* 10-15 individuals. This estimate is based on a combination of previous research, historical analogies, and house size. For the latter, a range between 5-10 m^2 per person as minimum requirements was used (Sørensen, 2010).

The complexity of determining household size depends on several factors, including the demographic composition of the population and varying social and economic practices across different periods. Moreover, the size of a house can be influenced by a multitude of aspects, ranging from socio-cultural norms and individual preferences to economic circumstances and environmental conditions. Given these complexities, thoroughly investigating the social and economic practices across different time periods is not feasible at this stage. Thus, it is necessary to find a suitable and flexible proxy for the models presented here. I decided to rely on floor area as a proxy for household size because it is easily measurable and has been proven to have a linear relationship with household size (Casselberry, 1974).

The concept of using floor area as a proxy was initially proposed by Naroll (1962), who suggested a requirement of 10 m^2 per individual based on 30 ethnographic case studies. However, subsequent research proved that this attempt was empirically unreliable and some amendments were made on the case studies selection. In particular, Casselberry used a more discriminating approach, excluding temporary structures from the computation of average house floor (Casselberry, 1974). Using an approach similar to Naroll's, Casselberry estimated a requirement of 6 m^2 per individual (Casselberry, 1974). The main drawback is the reduction in the number of case studies, which in this case was only 9. Nevertheless, this figure was later corroborated by Brown (1987) and Porčić (2012), with the latter extending the ethnographic sample size and differentiating between mobile and sedentary societies (11 and 35 case studies respectively). Although Porčić's account shows the flaws of previous models for mobile societies, it largely confirms the observed trend for the sedentary ones, identifying a mean requirement of 6.97 m^2/person and a median of 6, aligning with Brown (1987) and Casselberry (1974). Thus, in the present study I adopt the 6 m^2/person for calculating household size.

4.2.1 House size variation in the study area

This section examines variations in house size over time within the study area, with the results briefly discussed here before being integrated into the final model. The analysis includes 1106 houses, all with complete or reconstructable floor plans. The majority are located in Denmark (873), followed by Sweden (180) and Germany (53). Although this dataset is not exhaustive, as ongoing excavations continually uncover new structures, the assessment of published house *corpora* and existing reports indicates that the sample is robust enough for quantitative analysis and is unlikely to be significantly impacted by future discoveries.

Another characteristic of the house data is the predominance of Bronze Age over Neolithic dwellings. This is partly due to the data collection process. In fact, part of the dataset used here originated from an existing *corpus* focusing on Bronze Age archaeology in Denmark and Germany kindly provided by J. Kneisel. The remaining data from those regions and Sweden form part of a compilation assembled by the author from published materials and excavation reports. For the Swedish sites, the availability of radiocarbon dates facilitated a refinement of their relative chronology (as discussed in Bilotti 2024). This improved the precision of the chronological resolution, allowing for the selection of random calendar dates directly from the radiocarbon dates linked to each house during the dataset's chronological modelling. This approach provides a more detailed and specific temporal framework than relying on a general radiocarbon curve. However, this degree of detail was not achievable for the Danish data.

To analyse house size temporal variation, I employed the same methodology used in the modelling of site distribution (see Chapter 5), categorising houses into 200-year intervals to align with the chronological periods of predictive modelling, starting from 6050 BP (4100 BCE). Each house was assigned a random calendar date within its chronological range, iterating this process 100 times. For houses with radiocarbon dates, calendar dates were sampled from their specific dating (only for Sweden). The methodology and its application are documented in the *00_houses.R* script. The house size variation in the study region is shown in Figure 17 and Figure 18. The last three time-windows, corresponding to the Pre-Roman Iron Age (500-1 BCE), are included for completeness, as they mostly represent houses with uncertain dating between the Late Bronze Age and the Early Iron Age. However, these were not used in the final models.

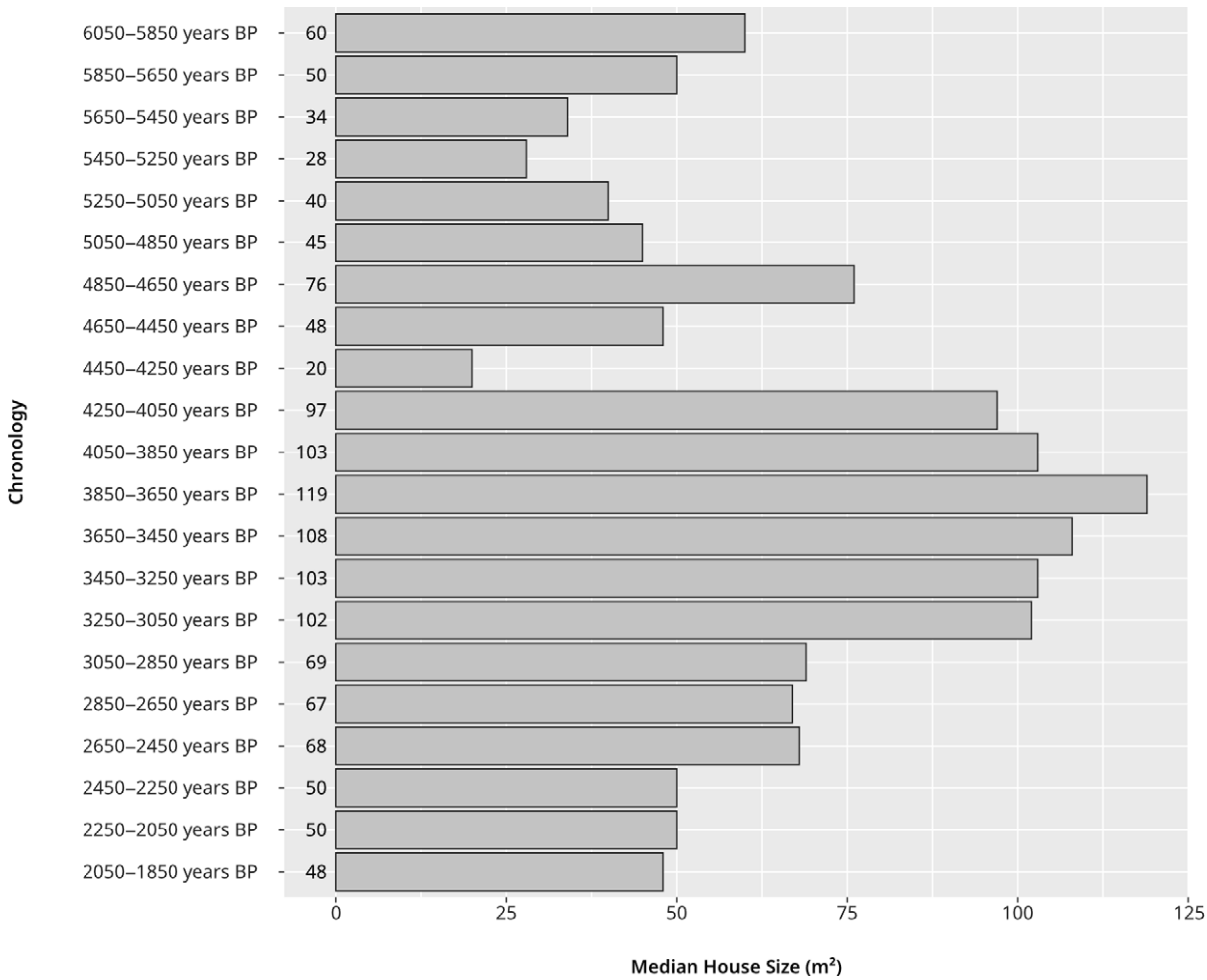


Figure 17. Median house size variation over time. Estimates are based on data from the author and provided by J. Kneisel.

Analysing the results, it is possible to observe that over time, the sizes of dwellings have considerably fluctuated, suggesting non-static dynamics. Around 6050 to 5850 years BP, houses had a median size of 60 m², which is a value sensibly higher compared to the following EN and MN periods. Between 5850 and 5650 years BP, median house size decreases to 50 m², although this does not correspond to a reduction in the largest houses recorded for this period, which is likely a reflection of the simulation process. This trend continues between 5650 and 5450 years BP, when median house size diminished to 34.08 m² and 5450-5250 years BP, with median house sizes reaching 27.6 m², reinforcing the trend towards smaller living spaces. In general, there seems to be a substantial difference between Denmark and Sweden, however, for this period this is mostly due to the fact that most of the Neolithic houses used in this study come from that region.

The patterns start an inversion between 5250 and 5050 years BP, which corresponds to the end of the EN and the beginning of the MN I. During this period, median house size increases to 40 m². Between 5050 and 4850 BP the median increases to 45 m² and reaches a relative peak of 76 m² around 4850-4650 BP, which corresponds to the passage between the MN and the YN (2800 BCE). However, during the rest of the YN the median house size decreases again to values of 48 and 19.6 m², between 4650-4450 and 4450-4250 years BP respectively. This value is the lowest observed in this study.

During the LN period, the median house size grows again to 97 m², until reaching the peak at 118.6 m² towards the end of the period (3850 to 3650 years BP). This period represents the one with the highest median, although the largest houses found in

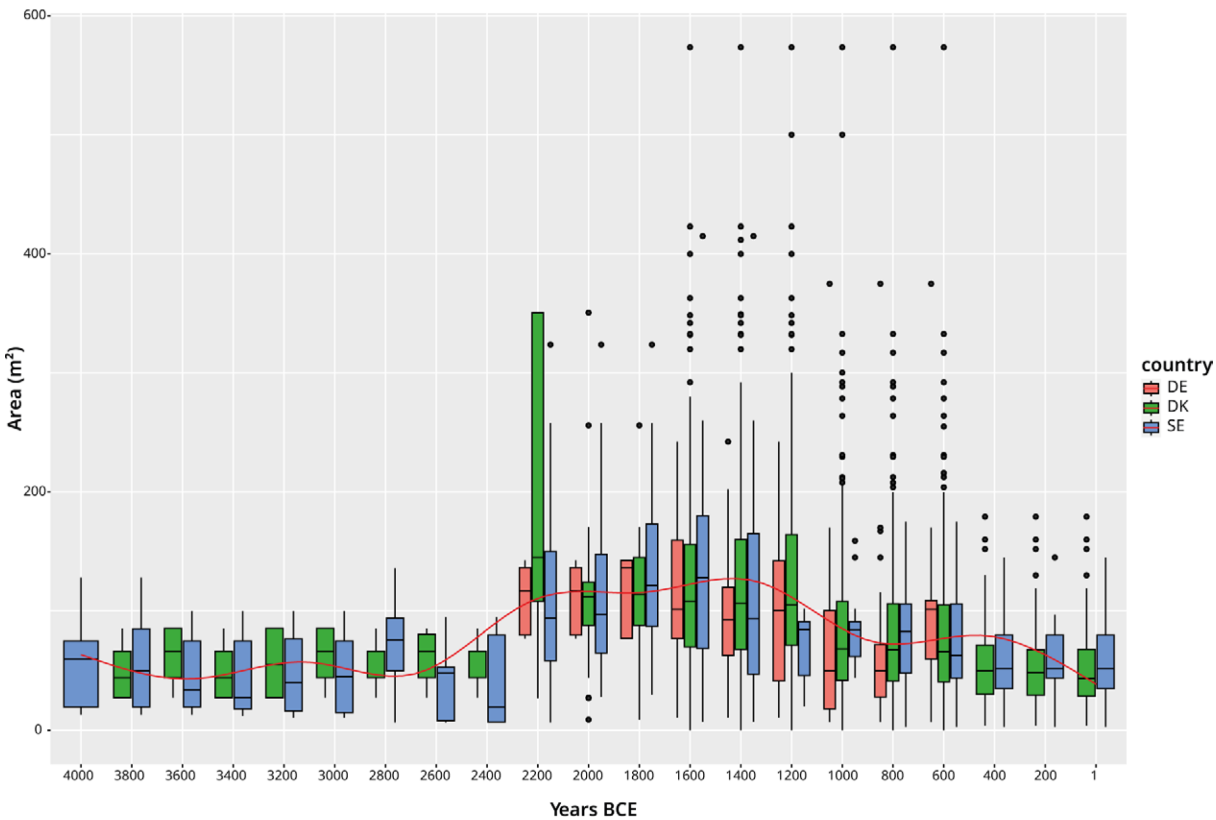


Figure 18. Boxplot of house size variation over time. The red line represents the median values for the entire study region. The boxplot represents the houses found in each modern country of the study region. Estimates are based on data from the author and provided by J. Kneisel.

the study region date to the Bronze Age. During the Bronze Age period, the median remains fairly constant and above 100 m² until period III, with values of 108.5, 102.9 and 102 m². The pattern of house sizes begins to exhibit a downward trend from 3050-2850 years BP (period IV), with a decline to 68.9 m². During the rest of the Late Bronze Age this trend stabilises at values around 67 m². During the following Early Iron Age, the median house size drops to values of around 50 m². This variation has been previously noticed and discussed, and may represent the fact that towards the end of the Bronze Age and during the Early Iron Age sparse settlements tend to coalesce together and form villages, with more, but smaller, houses. Moreover, this also corresponds to the suggestion that during the Late Neolithic and Early Bronze Age the study area experienced a boom in wealth (see Chapter 1).

The presence of outliers, especially in Denmark during the Bronze Age, indicates that there were houses which were significantly larger than the median values. The spread of the data, as seen in the box plot lengths, also suggests variability within each period, with some periods exhibiting a wide range of house sizes, potentially reflecting socio-economic disparities or variability in dwelling typology (see Chapter 2 and Chapter 7).

4.2.2 House duration

In demographic reconstructions, estimating the occupancy duration of a single dwelling is crucial, as it greatly impacts the demographic estimates of a settlement. For example, if a house is assumed to have functioned for 50 years within a settlement continuously occupied for 200 years, and there are four houses, it implies that only one house was used at any given time. However, if a house was occupied for 100 years, two houses might have been in use concurrently, significantly impacting the population estimates for the settlement. Unfortunately, determining the exact lifespan of a house is not possible, and here I simply try to define the most likely upper and lower ranges.

Scholars have suggested various estimates for house duration in prehistoric Europe, with some focused specifically on southern Scandinavian dwellings. According to Welinder (1998), a plausible estimate for the longevity of a house may be around 50-100 years. Artursson (2005b) proposed a duration of 100-150 years for the dwellings at Limensgård, Bornholm, implying a potential seamless use of a structure over five or six generations. Factors like soil conditions and the type of wood used can influence a house's longevity. Experimental reconstructions have also shown the critical role of timber rotting (Zimmermann, 1992). These findings suggest lifespans as short as 25-35 years. This is in line with Gerritsen's estimate of a lifespan between 25 and 40 years (Gerritsen, 1999; Müller, 2013b). Regional variations certainly existed; for example, houses in north-western Denmark built with willow (as in Bjerre Enge) may have had shorter lifespans, while those in the Netherlands or Norway, built using alder or conifers, could have lasted longer. Dendrochronological data from Zijderveld points to a duration above 50 years (Arnoldussen, 2008: 92), while in Forsand (Rogaland, Norway) radiocarbon dating evidence supports a duration of a century or more (Løken et al., 1996: 69). Further complicating the issue, variability has been documented even within the same region. In Legård (Thy), houses were built with sturdier boles and could have therefore have lasted longer than the houses in Bjerre Enge (Bech, 2018b). Consequently, house lifespan estimates have to be adapted to each case study. For Almhov (LN Scania), an estimate of 50-100 years seems reasonable, whereas for Bjerre (EBA Thy), a range of 30-50 years is more fitting. This approach aims to enhance the precision of individual case studies, thereby improving the overall model results.

4.3 Case studies

In order to determine settlement density in the region during different periods, I selected some case studies from well-investigated areas. The results are then used as a baseline for the calculation of the final demographic reconstructions. To ensure reliable results, only settlements that have been thoroughly excavated and have a well-defined chronology are considered. This necessity limits the selection to a handful of case studies, though the extensive excavations conducted over recent decades provide a reasonably clear insight into intra-site dynamics. A key challenge arises from the fact that the predominant lifestyle involved small, relatively isolated farmsteads. This lifestyle has two significant implications: first, modern excavations, often conducted alongside infrastructure projects like road or pipeline construction, typically result in narrow trenches that may not fully represent the entire settlement. Secondly, the space between houses and farms, which likely played an important role in landscape occupation, are often overlooked. Despite these limitations, there are some well-investigated case studies that offer a representative overview of certain periods.

Here, I briefly outline the selected case studies, exploring the dynamics of each settlement and their regional context. For each settlement, I provide an estimated range of inhabitants, calculated based on house size and the number of contemporary houses. As most sites in the study are farmsteads with similar structures, it is not necessary to describe all the excavated sites in the region. However, many of these sites have been analysed in order to build the house database and were not selected because their region may not have been as well-investigated as the ones selected here. In fact, the key objective of this section is to identify well-studied regions where settlement density can be determined with a high degree of confidence.

While the primary focus is on the patterns of houses and their chronological phases, it is important to recognise the variety of findings in these areas, including graves, pits and stratified cultural layers, which all contribute to the region's archaeological narrative. These elements, indicative of various activities, are integral to understanding the area but are not directly linked to population numbers. Therefore, they are not extensively discussed in this context.

4.3.1 Saxån-Välabäcken valley, western Scania

The Saxån, approximately 43 km in length, is a river situated in western Scania. It originates near Trollerholm (Svalöv) and runs to the Baltic Sea, south of Landskrona. The region considered here encompasses only the river valley from where it meets the Välabäcken, extending along the Välabäcken valley up until the town of Kävlinge, covering approximately 20-30 km². The Välabäcken is a rather small stream, *ca.* 1-2 m wide and flowing across its alluvial valley, as wide as 200-300 meters (Andersson, 2004: 26). The two rivers meet near the town of Dösjebro, forming the homonymous valley, which was an extensive area of wetlands. It is important to note that since the early 19th century, the landscape of Scania changed greatly due to the drainage of wetlands and their conversion into a tilled landscape. It is likely that wetlands were also common during the Neolithic period, when the sea level was also higher than today (+ 2/3 m in the Early Neolithic and up to + 5 m in the Middle Neolithic, Andersson, 2004: 26-7).

This study area forms part of the larger region explored during the West Coast Railway project (*Västkustbanan*), spanning approximately 230 km² from the Öresund strait to the inland ridge area 20 km away from the coast (Figure 19; Andersson, 2004: 25). The initial phase of the project focused on assessing the condition of archaeological remains and conducting preliminary inquiries, revealing an area rich in well-preserved Neolithic artefacts and a second phase, aimed at carrying archaeological excavations in the areas affected by the railway construction (Andersson, 2004: 13).

The area was already known before as one rich in Neolithic remains, with a composite landscape made of megalithic graves, settlement remains and depositions (Andersson, 2004; Hårdh, 1982, 1990; Karsten, 1994). In this paragraph, I focus on the remains dating to the Early and Middle Neolithic (Funnel Beaker culture), as their preservation is in a very good state and allows for demographic reconstructions over a relatively large area. Other regions with a comparable knowledge of Neolithic dynamics are located on Bornholm, Zealand, East Holstein, Ystad and south-western Scania. However, this region is probably the most thoroughly investigated and has been selected for this period.

Within the timeframe under consideration, two principal types of settlement areas have been identified: primary habitation areas, where everyday life and routine activities took place and 'separate' sites that functioned as temporary camps or specialised activity areas, possibly used for shorter or seasonal periods (Andersson, 2004). This differentiation is crucial for demographic analysis, as settlements that were short-lived or intermittently occupied could skew population estimates.

In total, over 70 sites dating back to the Early or Middle Neolithic have been excavated in the region. These include not only those uncovered during the West Coast Railway project but also sites from regular rescue archaeology operations and research excavations. Additionally, many other sites have been identified through surveys, although these are harder to interpret (for a critical discussion of this aspect see Andersson, 2004: 50). Taking into account only those sites that have undergone re-examination, have been accurately dated and precisely located, there are approximately 250 sites dating to the Early and Middle Neolithic period. The number and chronology of settlements found in the area is summarised in Table 5.

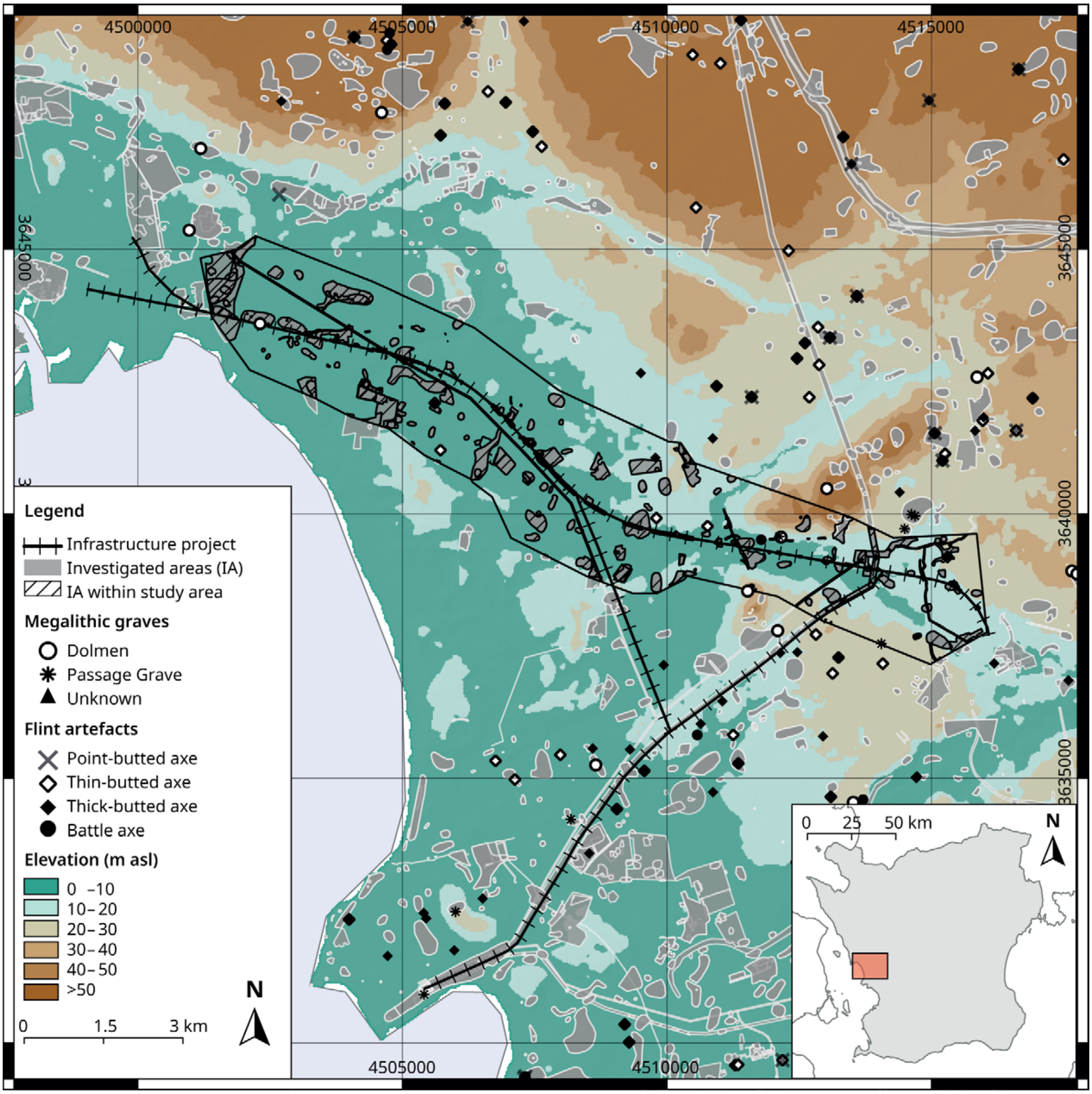


Figure 19. Subset of archaeological finds and monuments from the Early and Middle Neolithic periods within the Saxån-Välabäcken valley. The railway line built for the Västkustbanan and the excavated areas are highlighted. The total area measures 27.303 km² and the investigated area 5.589 km². Data from RAA, Baseline elevation map from EU-DEM v.1.1.

Periods	Main Settlement	Dwelling/Activity Site
EN I	6	18
EN II – MNA II	12	76
MNA III – V	6	45
MNB	7	42

Table 5. Early and Middle Neolithic settlements in the context of the West Coast Railway project. Data from Andersson (2004).

4.3.1.1 The Early Neolithic

In the study area, the number of well-documented Early Neolithic sites is limited. Yet, when these sites are excavated, they often reveal extensive activity layers and, in some instances, house remains. One of the main sites is Saxtorp 23, where traces of EN I activities are found from an area of about 25,000 m^2, identified through surveys and excavations. A single house has been found on the site, but wells, tool production, and other activities have been documented (Andersson, 2004). Three radiocarbon dates from this site suggest an occupation period between 3800 and 3500 BCE, although there is the possibility of a slightly older occupation (Figures 20-21).

Given that it's improbable for a single house to have been continuously used for 300 years, if we operate under the assumption that Saxtorp 23 was consistently occupied throughout the EN I period, it is likely that additional houses existed beyond the confines of the currently studied area. Consequently, this would suggest that the settlement was home to a single farmstead for the entire duration of the EN I.

Another well-investigated site in the area is Dagstorp 19, a settlement dated to the Early and Middle Neolithic periods with some later occupations. The excavations at this site revealed about fifteen houses from the Early and Middle Neolithic, which is among the highest number of such houses found at a single location in Sweden (Andersson, 2004: 63 ff.). The settlement extends across gentle slopes and flat areas, with the majority of findings clustered along a 500-meter stretch of fine sand beside the Välabäcken. A particularly well-preserved layer of occupation, untouched by later activities, was discovered in one section of the site. This layer contained a dense assortment of artefacts including pottery and flint tools typical of the Funnel Beaker culture. One house in the western part of the site has been radiocarbon dated to the Early Neolithic. Two pits rich in materials contemporary to the house were also found in the vicinities. To the east, two additional houses have been identified, both radiocarbon-dated to the Early Neolithic. However, one of these appears typologically closer to MN houses (Andersson, 2004: 63 ff.; Artursson et al., 2003; Lagergren-Olsson and Linderot, 2000).

The available radiocarbon dating from the site shows that the settlement could have been continuously occupied throughout the EN I (Figures 20-21), with a peak of probability before 3700 BCE. Looking at the single dates we can observe that the earliest occupation probably consisted of a single hut at the beginning of the EN, followed by the other house(s) and the two pits, one of which has a slightly later date. Assuming a maximum lifespan of 100 years for each house (see Chapter 4.2.2), it is possible that the site was continuously occupied, with only one house in use during each phase. In general, we can assume that this was the pattern for a standard EN village in southern Scandinavia.

Other sites with EN occupation in the area are:

- Saxtorp 3. A Late Mesolithic site with some finds indicating EN occupation;
- Tofta 17. A Palaeolithic and Late Mesolithic burial area. In the area, EN activities have been documented (Cademan Nilsson and Ericson Lagerås, 2000). Part of a house, probably belonging to the Mossby type, was discovered here, and was later covered and partially destroyed by a barrow. The dating to the EN I period is based on house typology, artefacts and stratigraphic analysis (Andersson, 2004; Cademan Nilsson and Ericson Lagerås, 2000). It is possible that one of the flat-graves also dated to the EN I;
- Saxtorp 12. The site is located very close to Tofta 17, on the opposite side of the river. It is dated to the Late Mesolithic – Early Neolithic and a large quantity of artefacts have been found. The nature of the assemblage points toward the presence of a stable settlement, possibly connected to Tofta (Andersson, 2004: 61-62).

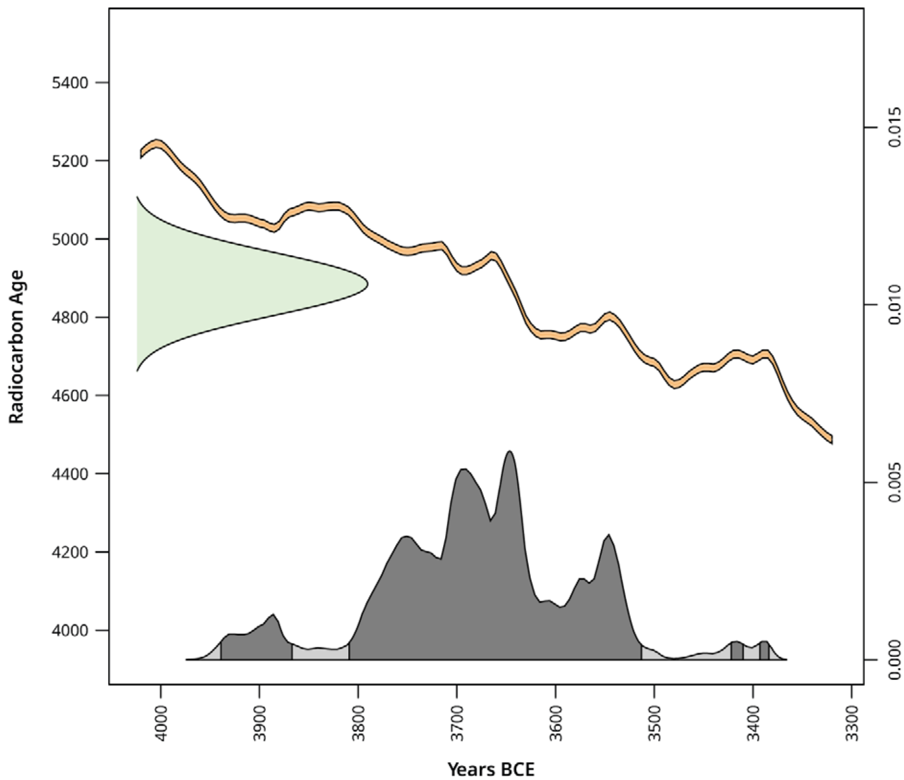


Figure 20. Summed propbability of the three radiocarbon dates from Saxtorp 23, recalibrated by the author from the uncalibrated dates provided by Andersson (2004), using the IntCal20 curve using the rcarbon package (Crema and Bevan, 2021; Reimer et al., 2020). The 95% interval is highlighted.

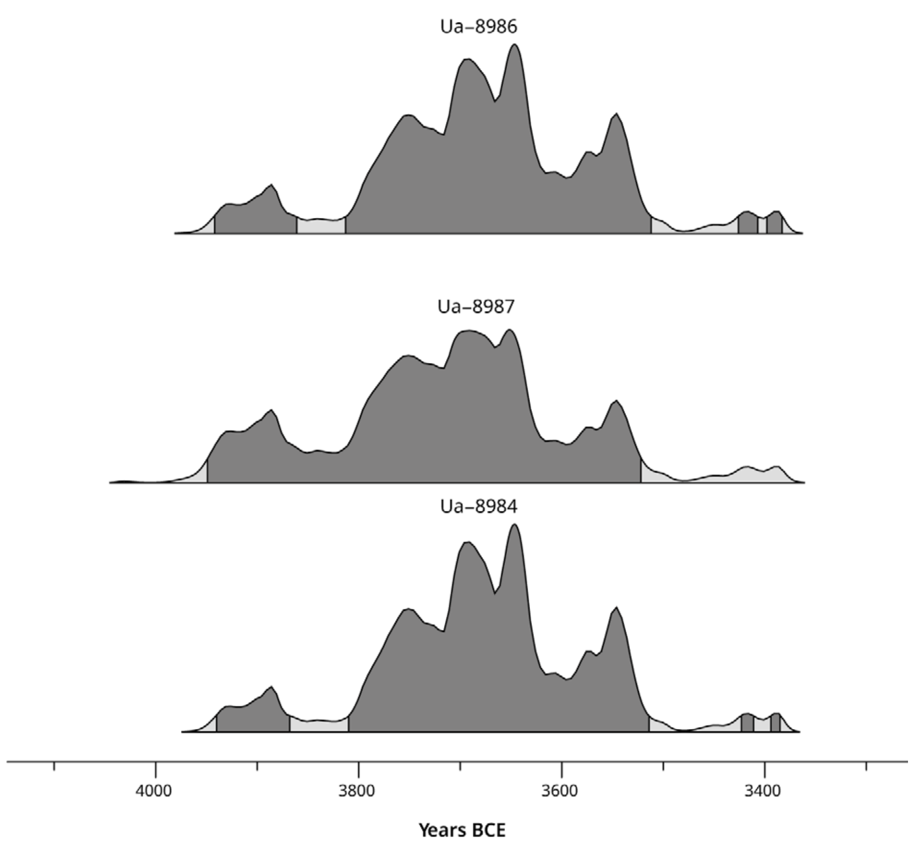


Figure 21. Radiocarbon dates from Saxtorp 23, recalibrated by the author from the uncalibrated dates provided by Andersson (2004) using the IntCal20 curve using the rcarbon package (Crema and Bevan, 2021; Reimer et al., 2020). The 95% interval is highlighted. Ua-8984 comes from charcoal in a well; Ua-8987 is a sample from a sooty layer of the house; Ua-8986 is from a charcoal sample from a flat-earth grave found in the settlement area.

4.3.1.2 Early Neolithic II – Middle Neolithic II

During this period, a notable shift in settlement patterns is observed across southern Scandinavia. In particular, there seems to be an expansion in settled areas, as testified in different parts of Scania and as described in Chapter 2. Within the area examined by the West Coast Line project, 88 settlements have been dated to this period, 33 of which have been excavated. Of these, 12 are considered to be 'main' settlements and 5 are located within the area considered here (Andersson, 2004: 71 Fig.22).

The main site for this phase is Dagstorp 19, already active during the EN I. Undoubtedly, the main phase of this site was the MN I, with four houses and a hut dated to this period, alongside several pits, layers, and finds (Lagergren-Olsson and Linderot, 2000). These four houses are situated relatively close to each other and appear to be spatially related. However, only one of the houses was radiocarbon dated. The layout and organisation led the excavators and most scholars to believe that these structures were simultaneously occupied, constituting a single hamlet or farmstead (Andersson, 2004: 73 ff.). As the excavated area is not so extensive, it is likely that more houses from the period or successive phases are located outside of the area. The median size of houses from this period is estimated to be between 40 and 45 m^2. Using Casselberry's formula, this would suggest a population of approximately 25-30 (26.67-30) individuals living in the farmstead during the MN I.

The other contemporary settlements in the area are:

- Saxtorp 26 'West', a settlement situated near an early Neolithic wetland. The excavation covered an area of *ca.* 6000 m^2. Several huts and long-houses have been found, but only one can be dated to the EN II – MN I based on architecture and three radiocarbon dates, with the other structures dating to the Iron Age (Artursson, 1999);
- Västra Karaby 7, located about 5 km south-east of Saxtorp 26, was discovered in the 1970s beneath a Bronze Age barrow. Unlike Saxtorp 26, this site did not yield any houses, but an extensive 150 m^2 occupation layer rich in materials dating to the EN II – MN I (Andersson, 2004: 72-3);
- Stora Herrie 38, located 4 km east of Dagstorp, was already known before the Railway Project (Andersson, 2004: 76-7). The excavation uncovered a 300 m^2 occupation layer, several hearths, pits, and other features. Notably, a trench containing daub with wattle impressions was discovered, potentially indicating the remnants of a collapsed house wall. The artefacts from the site predominantly date to the early MN and, to a smaller extent, the late EN (Andersson, 2004: 76-7);
- Stora Herrie 35 is the last settlement dating to the considered period. The Neolithic remains consist in some pits and features. The dating derives from the abundant material culture found in the site (Andersson, 2004: 79).

4.3.1.3 Middle Neolithic III – V

This period represents a contraction in the occupation of the landscape in the area, with only two 'main' settlements within the considered region and 6 in total (Andersson, 2004: 99). However, considering that this period is only 200 years long (3000-2800 BCE), the reduction in settlements is slightly less marked. During this phase, Dagstorp 19 remains the most important excavated settlement in the area (Andersson, 2004: 100 ff.). A layer rich in materials, two long-houses, and a sunken floor were dated to this period. In general, the material culture found at the site has a MN III character and therefore it is possible to restrict the main occupation of the settlement to this phase. Only one radiocarbon date is available for this phase (Ua-25062, 4360±70 BP) and its two sigma calibration (3330-3214 BCE, 12.94%; 3186-3150 BCE, 3.21%; 3130-2878 BCE, 79.3%) shows that it is most likely dated to the MN II – III or (lower probability) the MNIa. As there is only one date available, it is hard to determine a chronological evolution of the settlement, although we can restrict the occupation to (mostly) the MN III. Calibration was carried in R using the *oxcAAR* package (Hinz et al., 2021).

The second settlement dating to this period is Saxtorp 23, which also had remains from earlier periods. Four circular huts and several finds have been dated to this phase. However, it is not possible to determine the contemporaneity of these huts nor their exact chronology within the period, as the four radiocarbon samples taken from each of them yielded very different results, spanning from the Early Mesolithic to the MN V – YN transition (Andersson, 2004: 107). The material culture from this site clearly indicates a MN occupation, stretching as late as the MN – YN transition (Andersson, 2004: 107). Another important area is Västra Karaby 101, which had a Battle Axe culture palisade. However, the excavation shows that the site had a certain relevance also towards the end of the MN (MN A) and could be considered as an activity area or a possible main settlement for that period too (Andersson, 2004: 111 ff.).

4.3.1.4 Demographic estimates

Within the surveyed region, five sites are identified as main or permanent settlements during the EN I. Among these, three sites have yielded remnants of a total of five houses. It is reasonable to infer the presence of at least one house at each of the remaining sites, suggesting a total of seven houses. The excavated area in the region is approximately 5589 km^2. Considering that the study region encompasses 27,303 km^2, which is 4.89 times larger, we might assume the existence of *ca.* 34.2 houses. Considering a span of 400 years for the EN I, given that the earliest ^{14}C dating starts around 3900 BCE (Andersson, 2004), and assuming an average house lifespan of 50-100 years, we would expect between 4.27 and 8.55 contemporary farmsteads within the region.

Applying the same method used for the EN I, we can assume 9 houses dating to the MN I (5 from Dagstorp, one for each other settlement). Based on the ratio between the total area and the excavated area we would expect 44.0 houses. Depending on their lifespan, this would result in 11-22 contemporary houses over the 200-year duration of MN I. Compared to the previous period, this certainly represents an increase in population density.

For the later MN III – V period, three houses have been found in Dagstorp and we could assume that Saxtorp or Västra Karaby could have been permanently settled in this period, totalling 4 structures. Although it is not possible to separate the different phases, the entire period lasts only 200 years; the MN I and half the EN I. For this period, we would then expect 19.54 houses. The resulting demographic estimates for the EN I and MN are summarised in Table 6.

4.3.2 Hyllie area

The Late Neolithic archaeological findings in the Malmö region are particularly comprehensive, a result of numerous excavations and some large-scale projects such as the Öresund Link and the City Tunnel projects. This area is arguably the most indicative for studying this period, supported not only by commercial archaeology

Table 6. Demographic estimates for the Saxån-Välabäcken valley.

Period	Houses	Min. Houses	Max. Houses	Min. Inhabitants	Max Inhabitants	Min. Dens. (p/km²)	Max. Dens. (p/km²)
EN I (3900-3500 BCE)	7	4.27	8.55	29.95	59.90	5.36	10.72
MN I (3300-3100 BCE)	9	10.99	21.98	73.28	146.56	13.11	26.23
MN III – V (3000-2800 BCE)	4	4.89	9.77	36.64	73.28	6.56	13.11

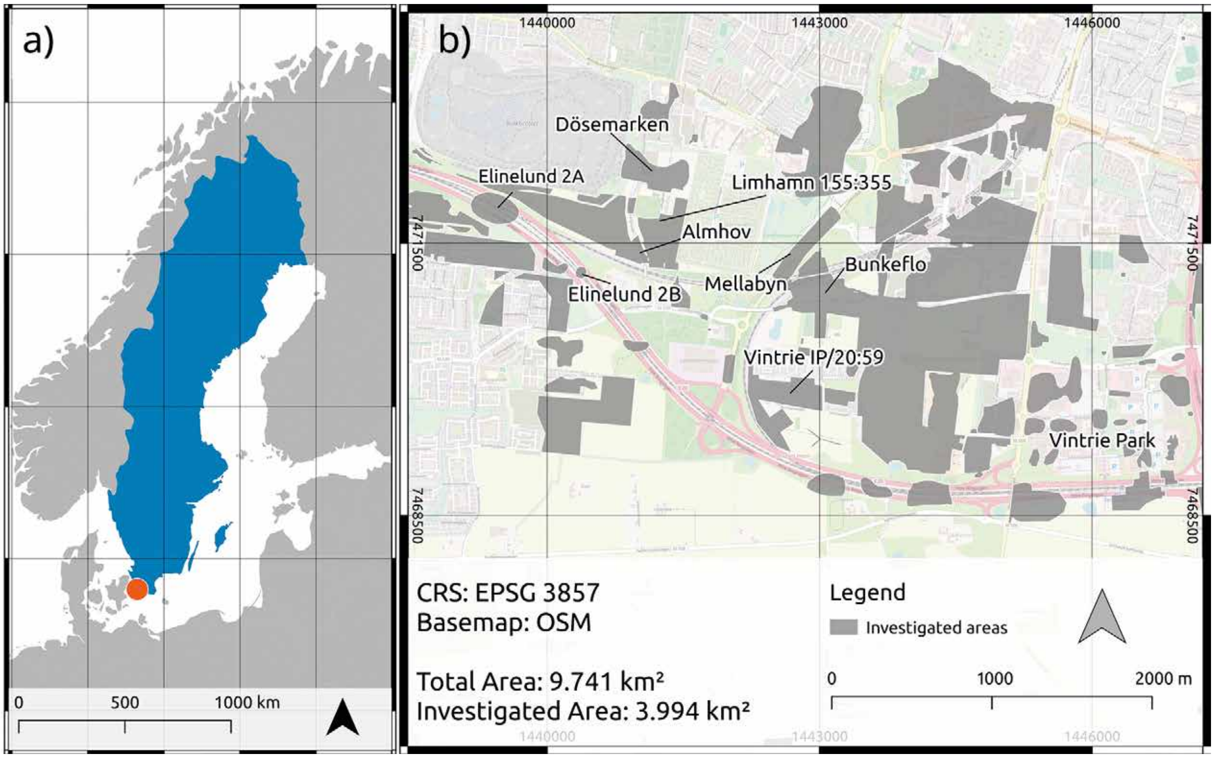


Figure 22. a) Location of the study area in Sweden marked with an orange dot. Made with Natural Earth. Free vector and raster map data (naturalearthdata.com); b) Hyllie Mosse with the investigated areas. Figure a) after Bilotti (2024).

excavations but also by a variety of research projects (Artursson, 2005a, 2009; Björhem and Magnusson Staaf, 2006; Björhem and Säfvestad, 1989; Brink, 2009b; Hadevik and Steineke, 2009). In particular, the *Hyllie mosse* (bog/marsh), yielded a large number of prehistoric sites (Figure 22). The focus here is primarily on the late Younger Neolithic, the Late Neolithic and the initial phase of the Bronze Age, with a particular emphasis on Almhov, one of the most significant settlements from this period (Bilotti, 2024).

Besides Almhov, the most important sites considered here are: Elinelund 2A and 2B, Bunkeflo, Vintrie IP, Vintrie 20:1 and 20:59 (Bilotti, 2024; Gidlöf et al., 2006; Hammarstrand Dehman et al., 2007; Lövgren et al., 2007; Sarnäs and Nord Paulsson, 2001). Another region with significant archaeological potential, capable of reshaping current understandings, is Dösemarken, situated north of Almhov. Recent excavations there have revealed at least one farmstead complex with multiple dwellings, akin to those at Almhov, dating from the Younger Neolithic to the Early Bronze Age (Berggren and Brink, 2012). Moreover, some nearby areas have been surveyed and yielded more possible sites, such as in Mellanbyn (Brink, 2009a; Friman, 2006).

4.3.2.1 Almhov

In the Hyllie area, the farmsteads at Almhov are particularly prominent. These farms originated during the transition from the Younger Neolithic to Late Neolithic and subsequently experienced gradual expansion throughout the Late Neolithic period (Bilotti, 2024). However, they began to diminish in size at the onset of the Early Bronze Age. The site underwent extensive excavation as part of the City Tunnel Project (*Citytunnelprojektet*; Hadevik and Steineke, 2009). It stands out in Southern Scandinavia as the site boasting the highest number of Late Neolithic and Early Bronze Age domestic structures (Brink, 2009a). Due to its unique characteristics, it is challenging to ascertain whether Almhov is comparable to other contemporaneous settlements in the area.

Figure 23. Settlement plan of Almhov with the LN-EBA houses. The individual farmsteads (A to H) are shown as grey circles. Dots represent dolmens, and triangles represent long barrows dating from the Funnel Beaker period. From Brink 2009a, reproduced with permission of the author.

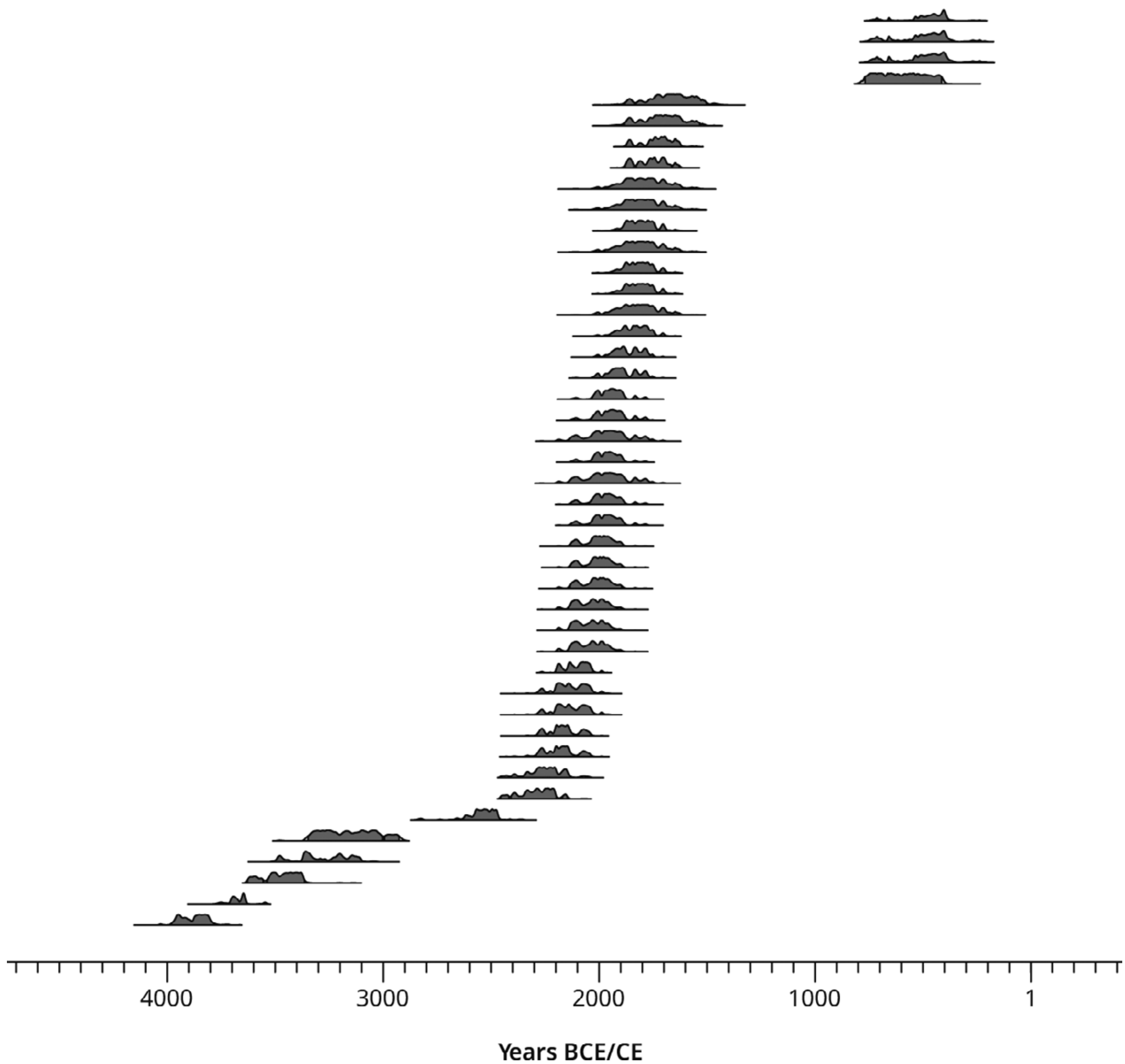


Figure 24. Calibrated dates from Almhov houses. Samples have been recalibrated using the IntCal20 curve using the rcarbon package (Crema and Bevan, 2021; Reimer et al., 2020). Original data from Brink 2009a.

Nonetheless, Almhov only represents a fraction of a larger archaeological landscape, without clear-cut boundaries between intra-site and near-site. A total of 38 houses have been found on the site (Figure 23), clustered in 8 smaller groups (named A to H). There are 44 radiocarbon dates linked to these houses, indicating that the settlement was likely continuously inhabited from approximately 2300 to 1500 BCE, with possibly an earlier and a later phase of occupation (Figure 24). While the radiocarbon dates are invaluable, their quantity and nature do not provide a definitive understanding of the connections between the houses or their precise duration. Therefore, the interpretations by archaeologists play a significant role and could considerably influence or vary the overall perception of the site.

The substantial number of houses and the contemporaneity of some of these led to the use of the term 'village' (*bebyggelsen* in Swedish) to describe Almhov. However, this term is problematic and likely does not accurately reflect reality. Instead, the term 'farms in collaboration' (*gårdar i samverkan*) has been adopted as more appropriate (Brink, 2009a: 2). Nonetheless, this may simply be a matter of terminology, as Welinder loosely defines a Neolithic and Bronze Age village as a site with closely located farms that cooperate and share common management (Welinder, 1998:

128). The primary objective of this study is to determine the contemporaneity and potential interactivity between two or more farms; therefore, we can avoid focusing on nomenclature issues. Following the literature (Brink, 2009a) and an analysis of individual house dating and typology, it is possible to define the number of houses belonging to each phase and farmstead. Farmstead A is the largest cluster of houses, with 13 densely clustered buildings. Farmstead B had three houses and is situated only 25 m away from farmstead C, which has five houses clustered together, thus blurring the distinction between these two areas. There are six houses in farmstead D, four in E, two in F, three in G, and only one in H. According to radiocarbon dating, only farmsteads A and C may have been continuously occupied throughout their respective timeframes (Brink, 2009a: 14 ff.).

Four phases have been identified on the site. Phase Ia (2470-2200 BCE) featured a single farmstead, indicative of the Battle Axe culture. This was not significantly different from the subsequent Ib phase (2310-2030 BCE), where one, or at most two, farmsteads were occupied simultaneously, with the second represented by a single house in area D. In Phase II (2140-1910 BCE), farmstead A had at most two contemporary houses, later replaced by another two. In farmstead F, two houses were possibly occupied concurrently. Area D might have remained active during this phase. Brink's (2009a) calculations suggest a minimum of two and a maximum of four houses occupied concurrently in a single sub-phase. However, in order to get a more homogeneous estimate it is necessary to use the average lifespan of a house, as previously defined for the area (50-100 years), and the total number of houses. In this scenario, the estimate ranges between a single farmstead (seven houses occupied for 50 years make 1.4) and three farmsteads.

During Phase IIIa (2130-1770 BCE), farmsteads were located in areas A, E, F, B, C, and D. Initially, two buildings in farmstead A were active, increasing to three by the phase's end. Three houses are also located in area D, but it is unlikely that they were occupied simultaneously. The other areas could only have had a single house at any given time of this phase, but probably at most one was active at the time. As all the occupied areas except from farmstead A are located in the NW of the settlement, it is possible that they represent different phases of the same farmstead. The minimum number of houses in this phase would be two (14 houses occupied for 50 years over *ca.* 350 years) and a maximum estimate of four houses (multiplying by 100 instead of 50). During phase IIIb (1920-1640 BCE) farmstead H is activated around the middle of the period, with the areas previously occupied still active. As no further farmsteads are established, it is possible that this phase represents the cusp in terms of demographic expansion of the settlement. This phase lasted 280 years and had 10 houses. Consequently, the min./max. estimates remain roughly the same compared to the previous phase: 1.79-3.57 (*ca.* 2-4).

Phase IV (1880-1520 BCE) marks the final phase of the site, between the LN II and EBA Ib. Six farmsteads had longhouses dated to this phase and for the first time sector G was occupied. Compared to Phase III, there was a slight reduction in the number of simultaneously active houses: 1.53-3.01 (*ca.* 2-3). Nevertheless, this estimate is still above the LN I value. After this phase, the site is abandoned and reoccupied only 1000 years later (Brink, 2009a: 29).

Overall, the estimates presented here (Table 7) are lower than those suggested by Brink (2009a). While it is possible that the site had five or six coexisting houses during its peak, the chronological span of the phases implies considerable variability, with calculations tending to smooth out short-term events (see Bilotti, 2024 for a discussion).

4.3.2.2 The other settlements

In total, over ten excavated areas were active during the aforementioned five phases. Numerous burials discovered in the region suggest a well-structured landscape. It is

Phase	Min. Farms	Max. Farms	Min. Inhabitants	Max. Inhabitants
Ia (2470-2200 BCE)	1.0	1.0	9.7	9.7
Ib (2310-2030 BCE)	1.0	2.0	16.2	32.3
II (2140-1910 BCE)	1.4	3.0	23.3	50.0
IIIa (2130-1770 BCE)	2.0	4.0	36.9	73.9
IIIb (1920-1640 BCE)	1.8	3.6	34.1	68.1
IV (1880-1520 BCE)	1.5	3.0	28.4	56.8

Table 7. Minimum and maximum number of farmsteads per phase in Almhov.

improbable that all houses that once existed in the area have been unearthed, but the extensive excavations over the years have likely yielded a representative sample. Typically, the settlements in the area are smaller than Almhov, consisting of just one or two farmsteads and occupied only during certain phases.

Elinelund 2A (Figure 22) was active during phase I, with four houses in total, two for each sub-phase, with the houses occupied sequentially. However, there may have been a hiatus between the two phases. Considering four houses in 470 years in total, the minimum estimate would be 0.43 houses and the maximum 0.86. The settlement is then reoccupied in phase V, which is not considered here (8 houses between 1680-1100 BCE). The nearby settlement of Elinelund 2B had three houses dated to phase Ib, translating to an occupation density of 0.53-1.07 houses. Seamless occupation between phase I and IIIa is doubtful, but it is possible that some houses were not identified during the excavation phase due to the intricate pattern of post-holes, or that because they lay outside the excavated area (Brink, 2009a: 32-33). Only one house is dated to phase IIIa, making continuous occupation unlikely (min. = 0.14, max. = 0.28).

Vintrie IP, and Vintrie 20:1 and 20:59, (Figure 22) were articulated into five distinct phases – Ia, Ib, II, IIIa and IV – segmented into three separate farmstead sites, each exhibiting its own temporal development (Brink, 2009a: 33-35; Hammarstrand Dehman et al., 2007). During phase Ia, 3 houses are found, meaning a range of possible active farmsteads of 0.56-1.11. A single structure is dated to phase Ib, but it is possible that one of the houses from phase Ia continued at the beginning of Ib. The range of possible houses in this period would then be 0.36-0.71, or lower. Four houses dated to phase II and an additional one to the transition between phase II and IIIa, with a possible number of coexisting farms of 1.09-2.17. One house is dated to phase IIIa, possibly two considering one dating to the transition phase (0.28-0.56). However, it is possible that there was a break in the occupation of the site during this period (Brink, 2009a: 33-35). A house was possibly built 200 years later, during phase IV, although its dating is uncertain as could also be from the end of the Battle Axe period.

The settlements of Bunkeflo and Mellanbyn (Figure 22) are relatively close to each other and can be considered as a single farmstead. Their structures can be dated to phases Ib, II, IIIa, and IIIb (Brink, 2009a; Lövgren et al., 2007). A single farm is dated to period Ib (0.19-0.37). Two farms dated to period II (0.22-0.43), four to period IIIa (0.56-1.11) and one to period IIIb (0.18-0.36).

The Vintrie area is occupied by a single farmstead active between the YN – LN transition and the EBA. House remains suggest a relatively fixed location across generations, especially at Vintrie Park area C3 and possibly Svågertorp industrial areas L and J (Brink and Hammarstrand Dehman, 2013: 166 ff.). Based on radiocarbon dating sequences, the area seems to have had at most a few contemporary farms, from phase Ib to phase IIIa, *i.e.*, from LN I to at least early LN II. In particular, the area was organised as follows: a single farmstead in Svågertorps industriområde L during phase Ia/Ib (min. = 0.13, max. = 0.25), two (areas J and N) during phase Ib (0.54-1.07), two in Svågertorps industriområde L and Vitrie Park C3 during phase II (0.43-0.87), three farms in Svågertorp 8A, Svågertorps industriområde P, and Vintrie Park C3 in phase IIIa (0.42-0.83), a single farmstead in Svågertops industriområde X

Phase	Min. Houses	Max. Houses	Min. Inhabitants	Max. Inhabitants
Ia	1.49	2.96	14.5	28.8
Ib	2.23	4.44	36.1	71.8
II	2.17	4.34	36.2	72.3
IIIa	1.82	3.61	33.6	66.7
IIIb	1.57	3.15	29.7	59.6
IV	0.14	0.28	2.6	5.3

Table 8. Number of houses and inhabitants in the Hyllie mosse by phase. Minimum and maximum number of farmsteads per phase (without Almhov).

during phase IIIb (0.18-0.36), and a single one in industriområde J during phase V (Brink and Hammarstrand Dehman, 2013: 166 ff.).

Dösemarken is a settlement area located a few hundred metres north of Almhov. The area between the two sites has not been investigated and it may have additional farm remains, which would imply that the two sites are actually parts of a single, more or less contiguous settlement unit (Berggren and Brink, 2012). The remains from the younger Middle Neolithic to the earliest Bronze Age were primarily concentrated on a slight elevation in the westernmost part of Area I. Further house remains were located in the eastern part of Area I/additional area and two more emerged within Area II. Two houses dated to phase Ia, alongside the palisade enclosure (0.37-0.74 houses). These houses are the oldest dated to this phase in the area (Berggren and Brink, 2012). Moreover, the buildings here have a close chronological and spatial connection to the palisade which, however, seems to cease around 2500 BCE (Brink, 2009b: 257). The occupation of Dösemarken, on the other hand, continues for several more centuries. Only one house and an enclosure are dated to the following phase Ib (0.18-0.36). The farmstead on the west seems to have been abandoned at the end of phase Ib or at the beginning of phase II. During phase II, the settlement is located further east within Dösemarken and there were two houses, dating to slightly different moments (0.43-0.87). During phase IIIa two houses were built, although only one has been radiocarbon dated. One of the two buildings has been interpreted as a possible annex and not necessarily as a dwelling (Berggren and Brink, 2012). During the phase, these houses were abandoned and two more were built on the previously abandoned western area. The range of possible coexisting houses in this period is 0.56-1.11. Four houses were built during phase IIIb. The ^{14}C sequence suggests that they were built consecutively, with a possible number of contemporary houses between 0.71-1.43. After this phase, the remains of the settlement became scarce, and possibly only one house is dated to this period (0.14-0.28).

Six Late Neolithic houses have been found in Limhamn 155:355 (Berggren, 2015). This site is very close to the northern edge of Almhov and might represent a part of it. The spatial organisation and dating of the houses suggest that they were not contemporary. Only one house has been dated to the LN II/EBA I (phase IIIb). Considering the entire span of the LN period, there could have been up to 1 farmstead throughout the period (2200-1600 BCE). A minimum estimate would be 0.5.

Looking at site distribution in the area, it is very likely that the estimates provided here are rather conservative. Unfortunately, this cannot be otherwise, as some remains have been lost forever and some areas have not been excavated. In addition, in some other cases, remains of occupations have indeed been found but their nature does not allow a clear interpretation. For example, in Limhamn 155:355 m.fl. only a single longhouse has been found while it was not possible to assess the nature of the other features excavated (Berggren, 2013).

The area considered here is about 9.741 km², of which 3.994 km² has been investigated (Figure 22). Combining the information from the settlements and interpolating the same figures for the unexcavated areas, it is possible to determine the local population density in the considered period (YN III – EBA I). The results of the

Phase	Min. Houses	Max. Houses	Min. Inhabitants	Max. Inhabitants	Min. Density (p/km²)	Max. Density (p/km²)
Ia (2470-2200 BCE)	2.49	3.96	24.2	38.5	6.06	9.64
Ib (2310-2030 BCE)	3.23	6.44	52.3	104.1	13.09	26.06
II (2140-1910 BCE)	3.57	7.34	59.5	122.3	14.90	30.62
IIIa (2130-1770 BCE)	3.82	7.61	70.5	140.6	17.65	35.20
IIIb (1920-1640 BCE)	3.37	6.75	63.8	127.7	15.97	31.97
IV (1880-1520 BCE)	1.64	3.28	31.0	62.1	7.76	15.55

Table 9. Number of houses and inhabitants in the Hyllie mosse by phase. Minimum and Maximum Number of Farmsteads per Phase (combined) and demographic estimates.

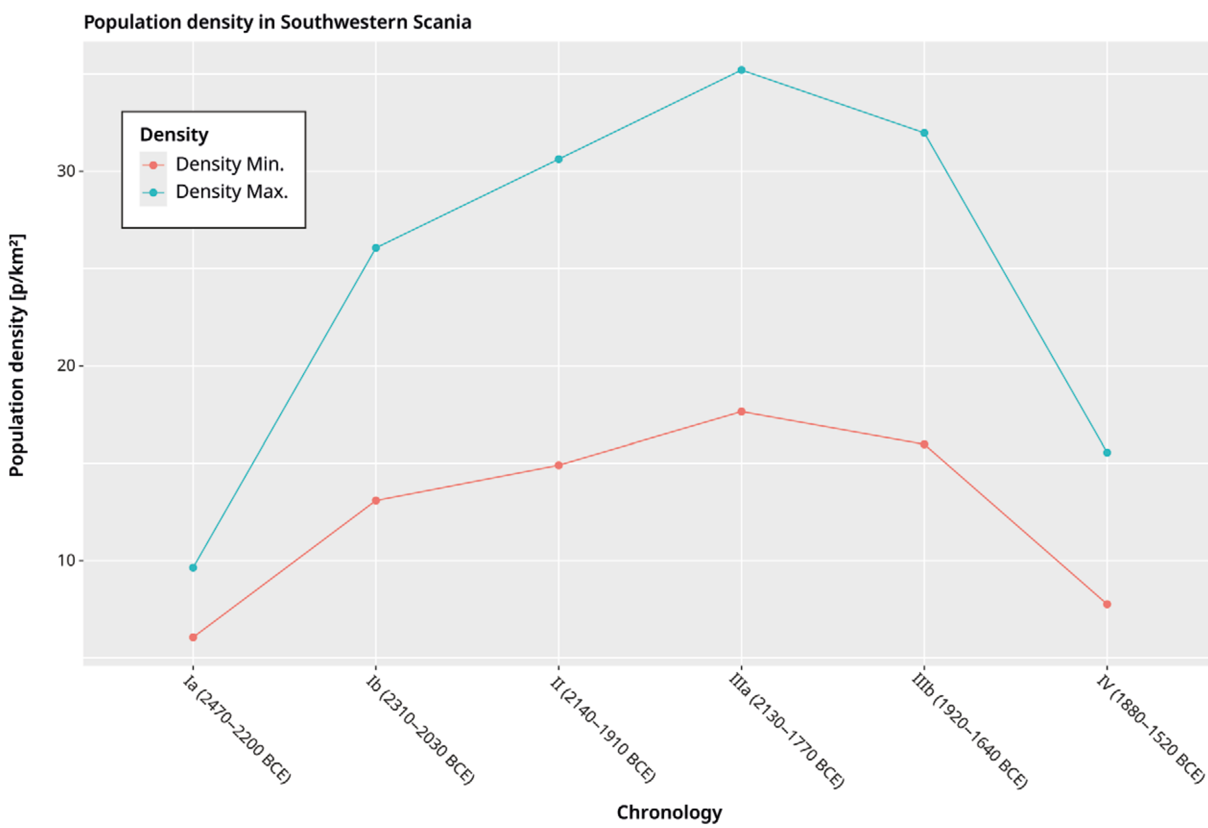


Figure 25. Population density around Hyllie mosse between late YN and EBA I.

settlements described in this paragraph are summarised in Table 8. The evolution pattern is similar to the one observed in Almhov, with the difference that the peak in Almhov occurred during phase IIIa, while in the rest of the area it was during phase II. It is possible that once Almhov gained a more stable centrality in the landscape, it partially drained or limited the development of the other settlements in the region. The overall density variation is shown in Table 9 and can be visualised in Figure 25.

4.3.3 Thy

The area of Thy is particularly well-studied and it shows a very intense landscape occupation during the Bronze Age, and especially during the EBA. One of the best-known sites is Bjerre Enge, which is used here for the intra-settlement reconstructions.

4.3.3.1 Bjerre Enge

The settlement of Bjerre Enge is located near a beach ridge system formed during the Bronze Age, now covered by sand drift but once prominent (Sogaard et al., 2018). To the north-west there is Bjerre So, a lake that existed during the Bronze Age but has since been drained (Sogaard et al., 2018). Natural borders encompass the site to the west, north and partially to the east, while to the south the landscape is uniform for about 4 km, where the contemporary site of Ballerum is located (Bech, 2018b). Excavations revealed that sand had already covered the beach ridge layers before the establishment of the settlement, potentially making it more attractive due to better agricultural properties than the ridge itself (Bech, 2018b).

The earliest recorded human activity in the area is a stone axe dated to the LN II. However, permanent occupation of the area only started around 1500 BCE, the date to which the earliest houses have been dated in Bjerre Enge. The site can be divided in two main phases: an early one during BA periods II and III, and a later one during periods IV and V. Based on the radiocarbon dating and the material culture, it seems that the site was not occupied during the LBA VI and early Pre-Roman Iron Age (Bech, 2018b: 17). Bjerre's structure and organisation share similarities with other Bronze Age settlements in southern Scandinavia, Belgium and the Netherlands, making it a valuable case study for the region and period (Bech, 2018b: 24).

In general, the typical Bronze Age settlement constituted a single farmstead, sometimes two, occupying an area of about 1 km^2 which can be considered as the near-site, where most of the subsistence activities were taking place (Bech, 2018b; Bech and Mikkelsen, 1999). Farmsteads would move within this space over generations, repeatedly dismantling and rebuilding houses. Archaeological remains have been found in at least 19 areas around Bjerre Enge (Bech, 1997). During the excavations, trenches were opened following a regular plan, aligned NNE – SSW, matching the local field boundaries. However, this also unintentionally increased the likelihood of intersecting Bronze Age houses, generally oriented perpendicular to the excavation trenches (Mikkelsen, 1996). Each trench was 1.7 m wide and the cumulative length was 2.678 km. When a house was intercepted, the trench was extended (Bech, 2018b: 25). In total, an area of 40 ha – plus a test area of 4 ha – was investigated, with *ca.* 1% of the total available surface excavated. The trenches, dug regardless of local morphological variations, can be considered as a random sample of the entire site (Bech, 2018b: 27). Archaeological finds were not evenly distributed but tended to cluster or align with local morphology. The analysis of the post-hole alignments, their organisation, and comparison with other well-known settlements in the area (notably Fårtoft) allowed the identification of between 6 and 10 longhouses, although some may have been missed (Bech, 2018b: 27). Generally, each excavated area appeared to have a single active structure, with one exception where two houses might have coexisted (Mikkelsen, 2018). Based on the trenches' distance and the characteristics (size and orientation) of Bronze Age houses in the area, Bech (2018b) proposes two scenarios:

1. The first scenario considers the possibility that interruptions in the longitudinal axis of the trenches, particularly in areas without archaeological finds and often at lower elevations (such as wetlands), may have led to an underestimation of the number of discovered longhouses;
2. The second scenario considers that the breaks in the trenches were located in areas where sites are less likely to be found, thus these areas are included in the 'investigated' category. Under this assumption, the total area effectively investigated would account for 2% of the overall settlement. This is double the size of the area that was actually excavated.

Determining which of the two scenarios is more accurate would necessitate excavating the additional parts, which is currently not feasible. Nevertheless, based on the width and orientation of the trenches, the excavators were able to make an educated guess about the degree of coverage for different setups. Specifically, if 10% of the area was excavated with trenches spaced 18 m apart, then, 93% of the houses would have been uncovered (Bech, 2018b: 47). This high rate of discovery depends on the fact that trenches are nearly perpendicular to the typical BA house. To achieve a 10% degree of coverage, given the actual trench width, a total length of 25.8 km × 1.7 m would need to be excavated. In the excavated area, a house was found, on average, every 446 m (2678 m / 6 houses) or 268 m (considering 10 houses), or every 882-529 m in the second scenario. Consequently, the number of expected houses over a hypothetical 25.882 km length of trial trenches can be estimated. This figure would represent 93% of the houses, which can then be converted to 100%.

Before defining the number of contemporary houses, it is important to establish whether the occupation was continuous and to determine the lifespan of a house. With this information, demographic estimates can be provided. Radiocarbon dating shows that there was settlement continuity in the area for 700-800 years (between 1500 and 800/700 BCE) (Bech, 2018b: 27). As discussed in Chapter 4.2.2, a lifespan of 30-50 years is suggested for Bjerre Enge and the results of Bech's (2018b) calculations for the number of possible coexisting farmsteads are summarised in Table 10.

The results suggested by Bech (2018b) indicate a rather uniform level of activity during the entire period, with a certain degree of variation during some phases. Notably, after the site's initial occupation around 1500 BCE, there was a significant increase in activity during period III (1300-1100 BCE). Unfortunately, radiocarbon dating does not allow for a clear understanding of the patterns of contemporaneity. Similarly, dendrochronology cannot provide a definite solution: as the wood used for house construction was relatively young, it does not allow for clear identification of overlaps.

Despite these challenges, it is possible to distinguish at least between Early and Late Bronze Age. In this case, looking at the available data it is possible to identify 5 (up to 7) EBA houses while only 1 (up to 4) can be dated to the LBA. This represents a notable improvement over previous assessments, offering the potential for more refined demographic estimates for Bjerre Enge. The results of the dating of each house are summarised in Figure 26. In most instances, the houses unearthed at Bjerre Enge cannot be precisely dated to a specific phase of the Bronze Age. An exception might be represented by House IB in Bjerre 6 (period II). However, as its interpretation would require a correct disentanglement and periodisation with House IA, which is not possible, it has to be considered like the others.

Using the same framework adopted by Bech (2018b), for the EBA II and III we could expect between 26/37 and 52/73 houses. Given the same estimated house

Table 10. Results of the calculations carried by Bech (2018b) for the number of houses to be expected in Bjerre Enge based on different scenarios.

House Lifespan	Settlement Duration	Houses	Min. Expected Houses	Max. Expected Houses	Min. Contemporary Houses	Max. Contemporary Houses
30	700	6	32	62	1.4	2.7
30	700	10	53	104	2.3	4.5
30	800	6	32	62	1.2	2.3
30	800	10	53	104	2.0	3.9
50	700	6	32	62	2.3	4.4
50	700	10	53	104	3.8	7.4
50	800	6	32	62	2.0	3.9
50	800	10	53	104	3.3	6.5

lifespan we would get the scenarios shown in Table 11 a) for the EBA II – III. For the LBA (period IV and possibly the beginning of period V), the number of estimated houses would be 5/10-15/29 and the results of the demographic reconstructions are shown in Table 11 b). Based on the dating of House I in Bjerre 7, 800 BCE was taken as the end date for the settlement.

Defining the precise boundaries of the habitation area at Bjerre Enge is challenging, as it could extend beyond the 0.75 km^2 surrounding the excavation area, especially towards the south (Bech, 2018b: 36). One approach could involve using the burial mounds in the area, as they are believed to have been constructed within settlements' catchments. However, identifying the specific farmsteads associated with these mounds is not straightforward and cannot be carried out here. Therefore, in

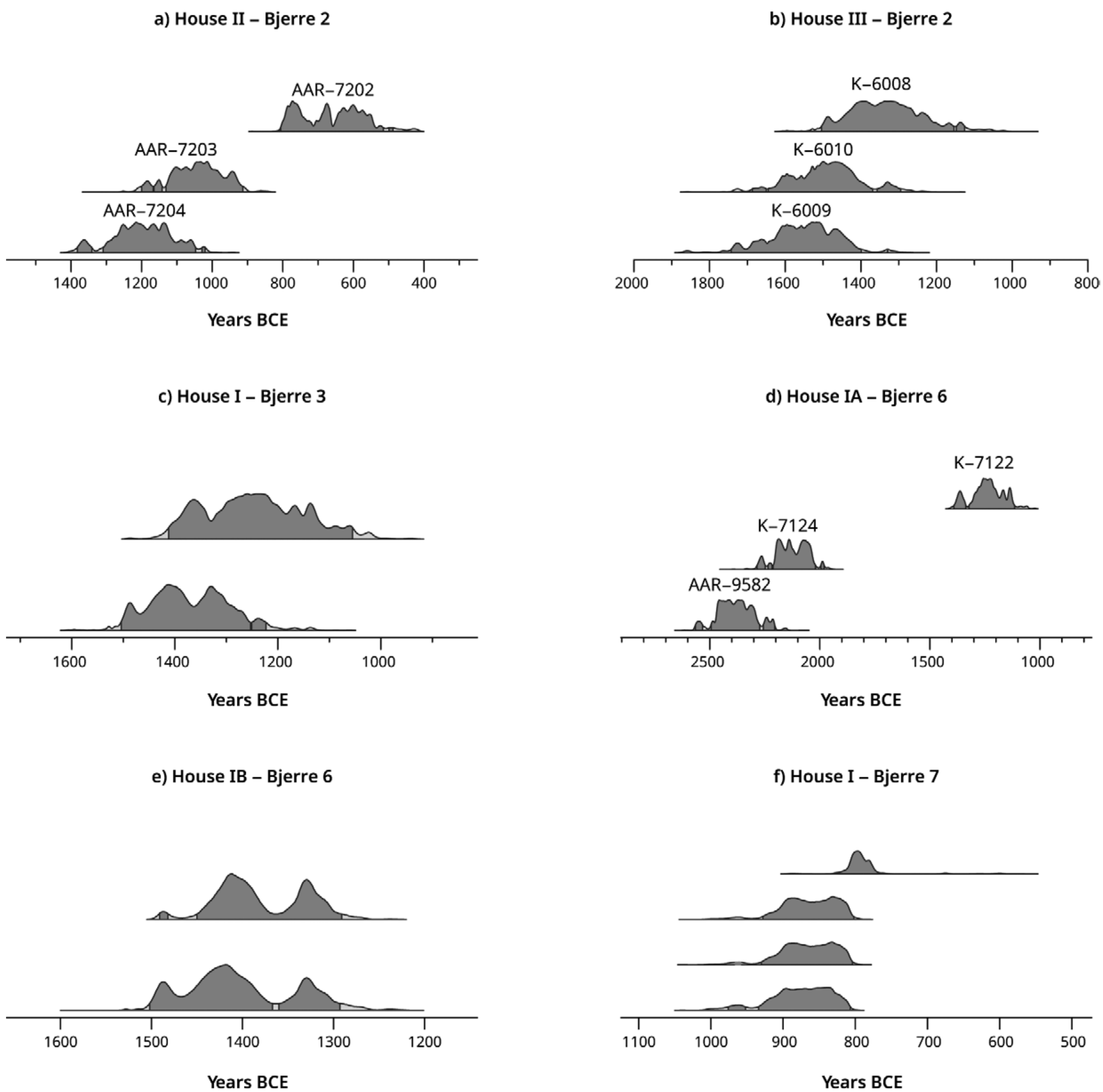


Figure 26. Radiocarbon dating of the houses found in Bjerre Enge. In some cases, the attribution of the sample to the house is uncertain: a) AAR-7202 probably comes from a later layer; b) K-6010 is from a different phase; d) The LN dates are from 2 oak tree samples, probably from fossil-oak from peat and therefore older than the house itself. Data and interpretation from Haack Olsen (2018), Haack Olsen and Earle (2018a), and Haack Olsen and Earle (2018b). Samples have been recalibrated using the IntCal20 curve and the rcarbon package (Crema and Bevan, 2021; Reimer et al., 2020).

a)

Scenario	House Lifespan	Houses	Contemporary Houses	Inhabitants
1	30	48.32	3.62	62.13
1	50	67.65	8.46	143.76
2	30	24.47	1.84	31.46
2	50	34.25	4.28	72.79

b)

Scenario	House Lifespan	Houses	Contemporary Houses	Inhabitants
1	30	9.66	0.97	11.10
1	50	28.99	4.83	54.12
2	30	4.89	0.49	5.62
2	50	14.68	2.45	27.40

Table 11. Number of possible contemporary houses in Bjerre Enge during the a) EBA II – III and b) LBA IV – V.

order to calculate the settlement density of the region, it is necessary to rely on other nearby settlements.

A nearby site that returned a high number of houses dating to the Bronze Age is Fårtoft. Here, 38 houses have been found, 18 of which have been radiocarbon dated between period II (one house) and the second half of period III and first half of period IV (Bech, 2018b: 45). At Fårtoft, the discovery of houses located up to 200 metres apart suggests that the spatial distribution observed in Bjerre Enge was a common pattern during the Bronze Age (Bech, 2012; Bech and Haack Olsen, 2013; Bech and Hornstrup, 2013).

4.3.3.2 Aas

A suitable region for the type of estimates provided here is Aas, located approximately 20 km south of Bjerre along the Limfjord coastline (Figure 27). This area is known for several Bronze Age sites and it is geographically well-defined, situated on a ridge between the Limfjord to the east and a bog area to the west. Aas is a morenic formation about 3 km long and 800 m wide, covering an area of about 4 km^2 (Mikkelsen, 2018: 477). In total, 30 longhouses have been excavated in the area and most of them are dated to the Bronze Age, with more sites dating to the LBA (Bech, 2018b; Bech and Mikkelsen, 1999; Mikkelsen, 1996, 2018). Extensive excavations and surveys were conducted over more than a decade as part of the Aas project and the Thy Archaeological Project (Bech, 2018d; Mikkelsen, 1996).

The earliest occupation of the area dates to the Bronze Age period II and III. During this period, three settlements are known: Dalgaard, Vilhøj and Ejsdal. At the end of period III and during the LBA, an additional habitation area was established at Brydevig (Mikkelsen, 2018). Vilhøj is the site with the highest number of houses (20) and it may contain more undiscovered houses, with estimates suggesting 25-55 houses (Mikkelsen, 2018: 488). The dating indicates one house from period II, 2-5 from period III, 11-13 from the LBA and 3-4 from the Early Iron Age (Mikkelsen, 2018: 483). Considering the prevailing model of a single farmstead composed of one or two longhouses and a lifespan of 30-50 years, we can assume a continuous occupation of the settlements considered here during the period under consideration (Mikkelsen, 2012). However, as we have seen for Almhov, the presence of several coexisting farmsteads organised in hamlets or small villages should not be excluded and has been supported by other authors (*e.g.* Artursson, 2005b). Considering an occupation between 1400 and 500 BCE (end of BA II – VI) and assuming 25-55 total houses we would obtain a minimum of 0.83 contemporary houses (considering 30 years per

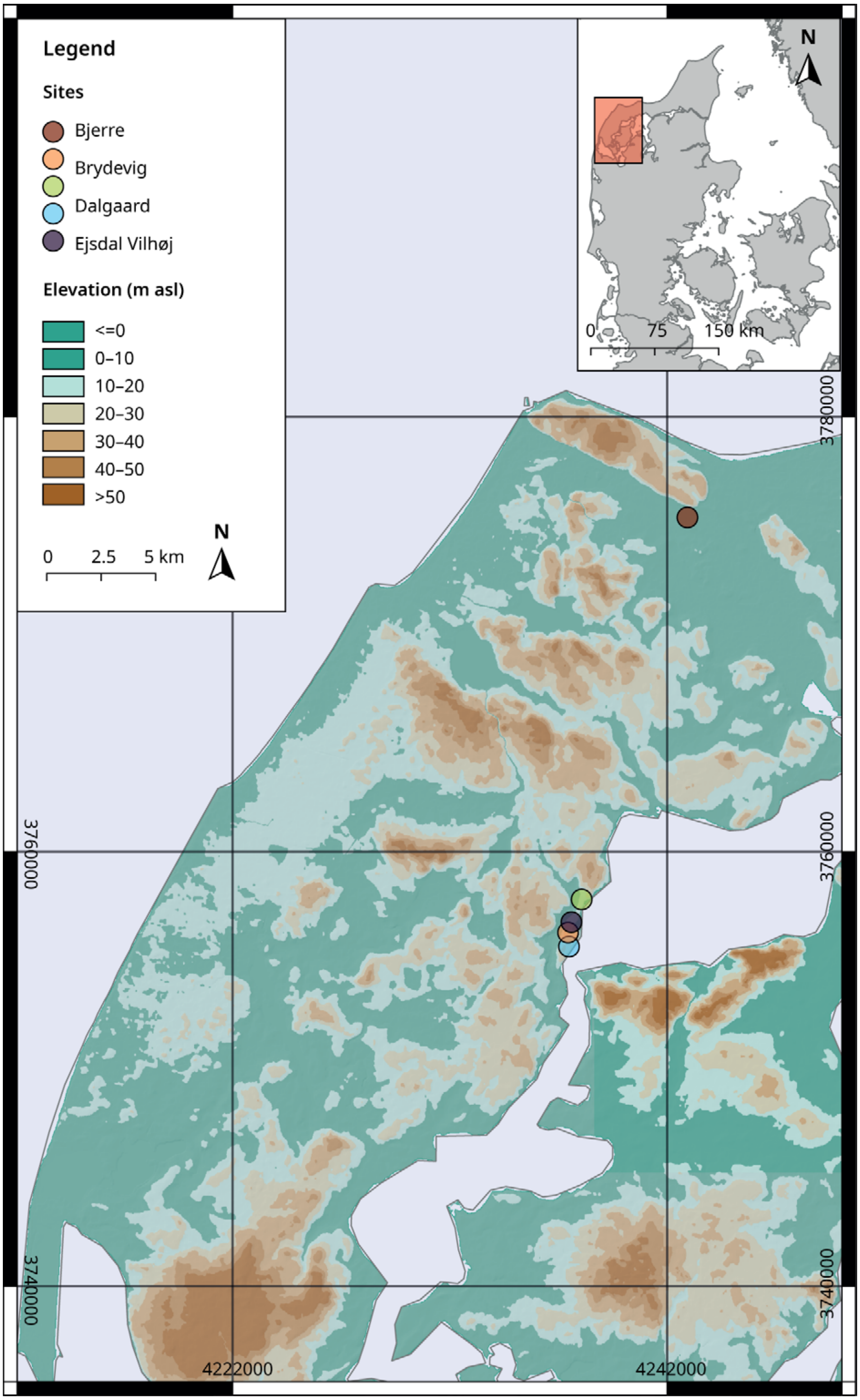


Figure 27. Location of the archaeological sites mentioned in Thy. Baseline elevation map from EU-DEM v.1.1. In the inset map the location of Thy is shown on a map of Denmark.

Site	Min. Houses	Max. Houses	Min Inhabitants	Max. Inhabitants
Brydevig (EBA III)	0.90	4.00	15.30	68.00
Brydevig (LBA)	1.20	3.00	13.59	33.97
Vilhøj	0.83	3.05	10.58	38.86

Table 12. Demographic estimates for the settlements in Aas.

Period	Min. Inhabitants/ settlement	Max. Inh./Settl.	Min. Total Inh.	Max. Total Inh.	Min. Density (p/km^2)	Max. Density (p/km^2)
EBA	19.11	83.54	57.33	250.63	14.33	62.66
LBA	9.60	44.05	38.41	176.18	9.60	44.05

Table 13. Cumulative demographic estimates in Aas.

Period	Min. Density (p/km^2)	Max. Density (p/km^2)
EN I	5.36	10.72
EN II	6.28	12.57
MN I – II	13.11	26.23
MN III – V	6.56	13.11
YN I	7.74	14.16
YN II	4.22	7.72
YN III	6.06	9.64
LN I	15.21	30.63
LN II	13.79	27.57
EBA	12.69	36.73
LBA	9.60	44.05

Table 14. Cumulative results for demographic estimates in core areas from the case study presented. In Chapter 6.4.2 these results are scaled to the models in order to be used for demographic purposes.

house) and up to 3.05 (55 houses for 50 years). Adjusting for relative chronology, there seems to be little difference between EBA III and the LBA, with 2-5 houses in the earliest period and about 4 per period during the LBA (11-13/3 = 3.67-4.33). The situation would change if we consider the single structure dated to period II, but in this case, there is the possibility of underrepresenting the period and it should be treated as if it was similar to period III.

In Brydevig, at least 10 longhouses have been found, with estimates suggesting a total potential number of 30-40, considering the local topography (Mikkelsen, 2018: 483, 488). One to two longhouses dated to the second half of period III, while the other 8-9 are dated to periods IV – VI (Mikkelsen, 2018: 483). In this case, the period of occupation is shorter (1200-500 BCE) and the number of houses is comparatively higher for the LBA. Considering 30-40 possible houses, we would expect 2/3-4/5 additional EBA III houses and 16/18-24/27 LBA houses. Considering the possible house lifespan, we would get: 0.9-4 houses for the second part of period III (0.9-3 considering 30 houses, 1.2-4 considering 40) and 1.2-3 during the LBA (1.2-2.25 and 1.6-3). The results do not differ much from Vilhøj and can be used as a proxy for the size of Dalgaard and Ejsdal. The results for the LBA are mostly consistent to the situation observed in Bjerre Enge, though the maximum estimates are generally lower for earlier periods. The results for the two settlements are summarised in Table 12. Considering the different settlements analysed and taking Aas as a region to calculate settlement density in Thy, we would get the results shown in Table 13.

4.3.4 Cumulative results

Having examined various case studies across the south-western Baltic region and the diverse chronological periods studied, we can now merge the results together. These estimates are then used to scale the results of the predictive models presented in Chapter 6. Certain periods (EN II, YN I and II) are not represented directly, due to lack of precise house and settlement data. However, their values can be interpolated using the average number of houses in the previous and following period and using the median house size for that specific time-frame. The results are shown in Table 14 and plotted in Figure 28.

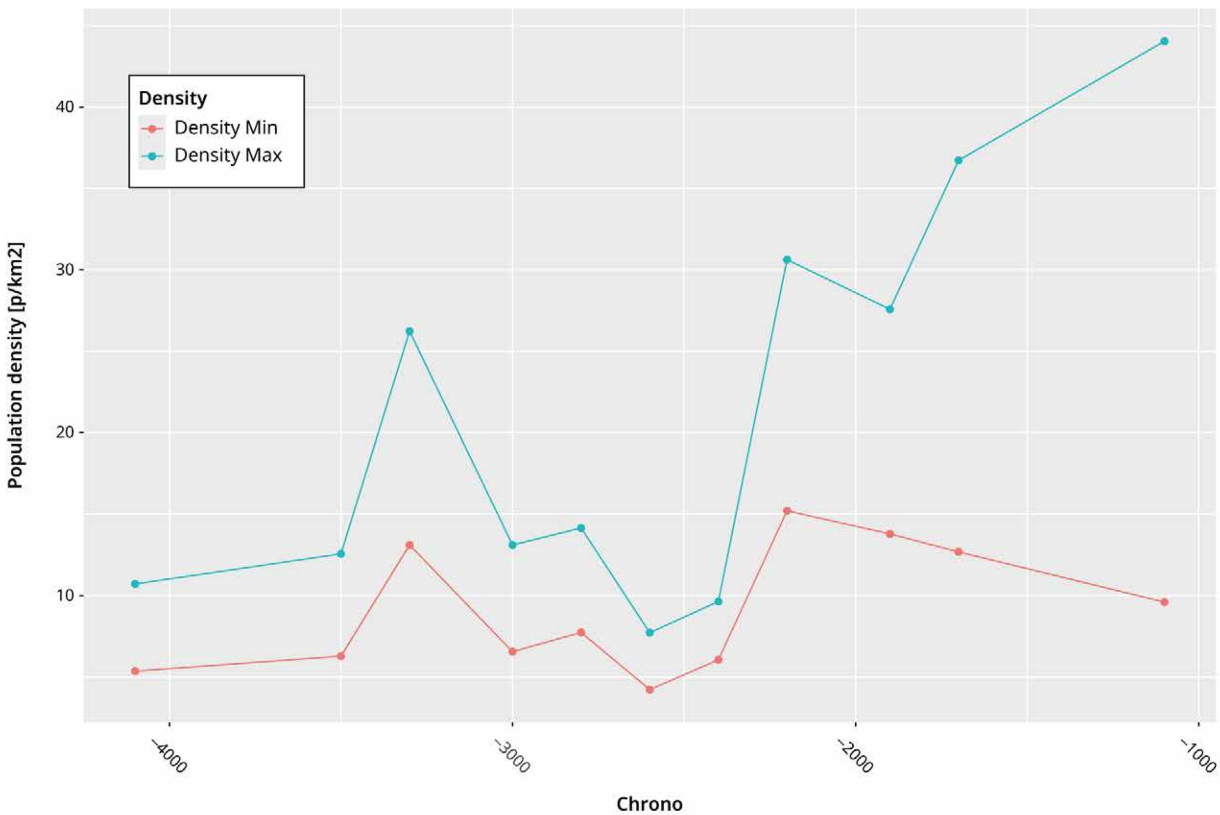


Figure 28. Population density results for the core areas presented here. The measurements used are drawn from Table 14.

5. Methods

In this chapter, I outline the methodologies employed to model population dynamics and historical land use in this thesis. The input data consist of the archaeological datasets obtained from regional and national databases described in Chapter 3. The methods presented here aim to address the challenges intrinsic to these datasets, particularly their inhomogeneity and uncertainty, which are among the main reasons why they are seldom used for formal analyses.

All the analyses described in this chapter adopt a fully documented approach and use Free and Open Source Software (FOSS). In this way, the methodology is completely transparent, even in secondary or minimal parameter selection, and can be easily improved. In addition, given a dataset of archaeological sites, radiocarbon dates from a region and a set of covariates, it is possible to reproduce the same analysis in any study region.

To overcome data uncertainty (spatial and chronological) I opted for a probabilistic model based on intensity areas. The workflow is divided into two main parts, the first dealing with chronological and representativeness uncertainty, and the second with population modelling.

The first part is structured as follows:

- Definition of key areas. The choice is made using a combination between expert knowledge and an intensity-based approach. This is simply done by comparing site density and the state of the art, as described in Chapter 3.1.4;
- Chronological uncertainty. Well-dated sites are binned into time windows of 200 years, which represents the average duration of a relative chronological period of the Nordic Bronze Age. The remaining sites with no precise date (*e.g.* labelled as 'Bronze Age') are assigned a simulated date with a varying probability depending on the summed density of locally available radiocarbon dates;
- The process is iterated 100 times. The number of times a site's chronology is simulated within any given time window represents the probability of a site being dated to that period. The higher the value, the more precise was the relative dating.

In the second part, the output is used to create the final model for each time window employing Point Pattern Analysis (PPA) to study the properties of the newly created dataset. In particular, the distribution of sites is analysed in relation to a range of environmental covariates and the distribution of other sites via cluster analysis, to determine occupation areas.

The results obtained through this approach serve two purposes. First, they provide insights into the factors influencing settlement choices and how these have evolved over time. Second, they facilitate the prediction of site density in under-explored areas, based on the PPA results. This methodology offers an advantage over traditional models,

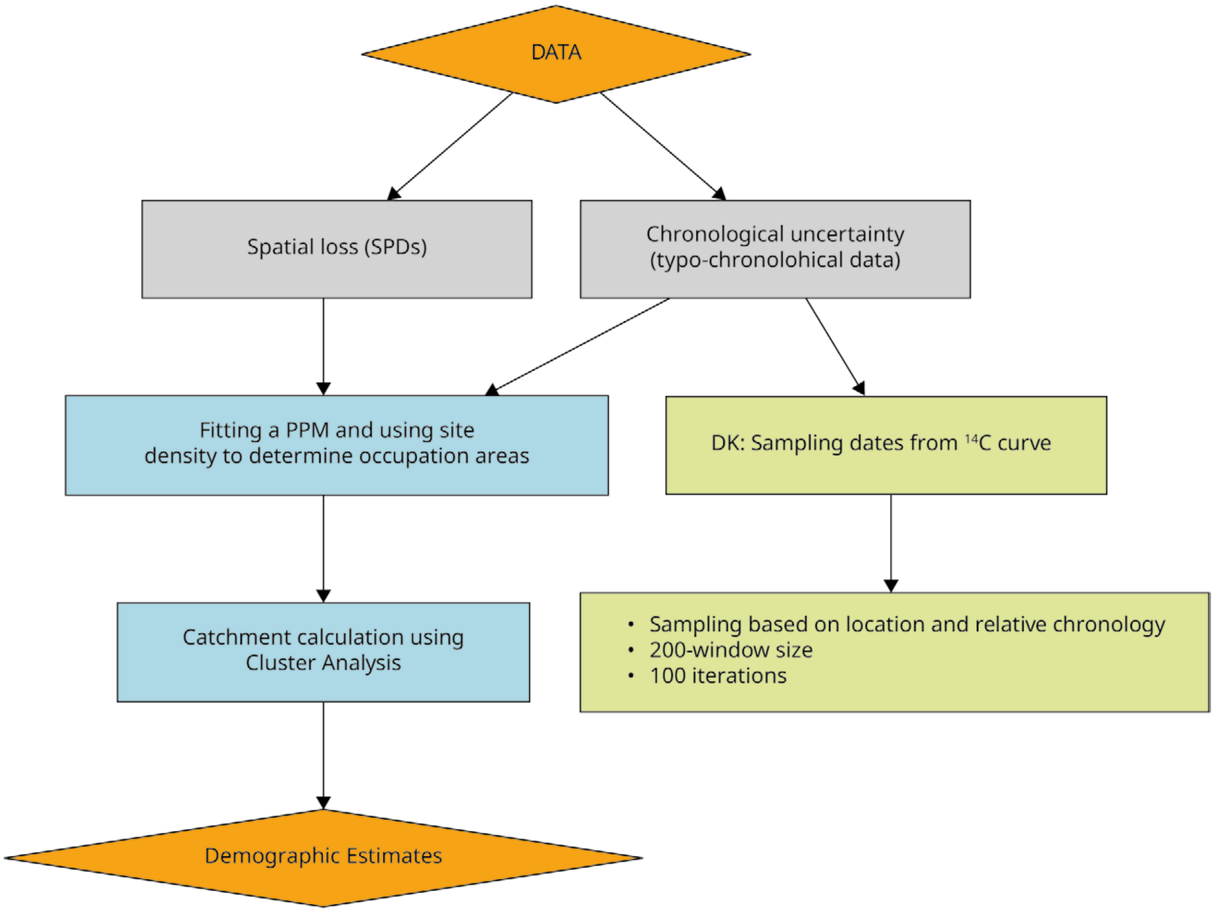


Figure 29. Flowchart showing the integration and combination of the different methods described in this chapter.

as it optimises the extraction of information from both key areas and the broader region, while also quantifying the associated uncertainties. The results obtained here are then compared to the current literature, including traditional models not dealing with uncertainty in the same way and other established methods for assessing human occupation intensity, such as SPD curves modelling. A visualisation of the combination of the different methods and the various steps is shown in Figure 29.

These analyses are conducted for each chronological window. In this study, all sites are considered equally, based on the premise that a site, regardless of its type, indicates the use of a specific location during a certain period (settlement, grave or stray find). This approach is not without implications and needs a more detailed discussion. Ideally, we would be able to infer population dynamics from the structure and distribution of settlements. Sometimes, this can be done accurately, but in most cases we lack sufficient data and the results would not be representative of real patterns or the number of case studies to which they can be applied would be limited. In particular, for cluster analyses, including burial sites appears to be a viable solution, especially given the presence of large and visible monuments. When both settlements and burials are available, it seems that most burial monuments were erected relatively close to inhabited areas, making them a reliable indicator of settlement zones, as shown for some regions in Figure 30. This is possible because the focus is not on the absolute number of sites in an area, but rather on its extent (catchment) during any given period. Certainly, the number of sites can be used as demographic proxy but this would not allow a proper handling of recovery and representativity biases. Thus, employing a Point Pattern Model in conjunction with cluster analysis is likely to yield a more comprehensive and robust outcome.

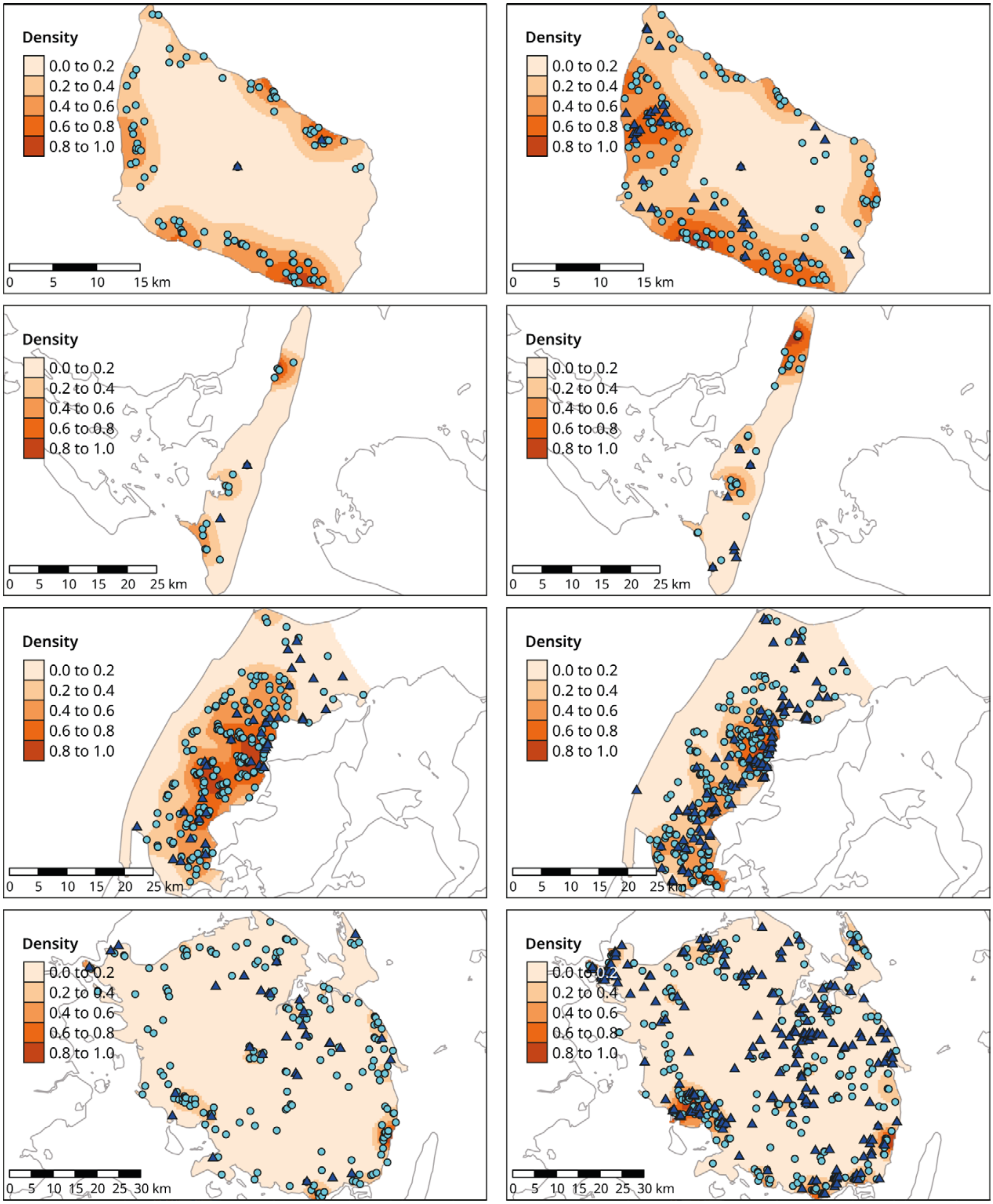


Figure 30. The density map shows Bronze Age settlements (in blue) and graves (in cyan) for different regions of Denmark (Bornholm, Langeland, Thy and Funen), with separate maps for the Early Bronze Age (EBA) on the left and the Late Bronze Age (LBA) on the right. Despite the near-complete absence of settlements in certain periods/regions, graves appear to serve as a reliable proxy. Neolithic sites are not shown as the number of dated settlements in this period is even lower than that of the Bronze Age. Density values are scaled to 1.

5.1 Chronological modelling

Modelling past population dynamics is not possible without an adequate management of chronological uncertainty. Various methods have been explored to attempt it, some of which, such as the Summed Probability Distributions (SPDs), have been previously mentioned (Chapter 4.1.1). Although extremely valuable for regional or large-scale reconstructions, they do not provide a satisfactory solution when we have a small amount of data or if we are interested in middle-to-small scale dynamics. Even the great possibilities offered by Bayesian modelling cannot operate at this scale. The resulting output of these methods is typically a unidimensional curve that homogenises the patterns across a fairly large area, which fails to effectively capture local variations.

The method outlined here aims to connect radiocarbon dates with archaeological sites. It employs a straightforward theoretical framework where a calendar date is assigned to each site within its relative dating range, drawn from the regional radiocarbon curve. These simulated dates are then categorised into predefined temporal windows. This process is repeated *n* times (in this case, n = 100), providing the foundation for further modelling. This approach allows us to estimate the likelihood of a site belonging to a different time window, effectively creating fuzzy boundaries instead of rigid chronological divisions. It is important to note that if all the available data are poorly dated (*e.g.* 'Bronze Age' or 'Neolithic'), the results essentially translate the radiocarbon curve into spatial data. This outcome, far from being redundant, could be used to represent the intensity of occupation for a set of radiocarbon dates or serve as a baseline model.

For simulating chronology, a method conceptually similar to the Composite Kernel Density Estimation (CKDE) is employed. CKDE is a statistical technique used for estimating the probability density of a set of ^{14}C dates. Considering the existence of other modelling methods, it is important to understand how they operate and why in this case the one employed is the most suitable one.

5.1.1 Radiocarbon calibration

The aim of this paragraph is to emphasise the impact that the initial choices regarding the calibration curve and algorithm have on the final results. In most cases, these decisions are necessary and should be based on a thorough understanding of both the processes involved and the relevant literature. However, direct control over these choices is limited to only a few instances. For a detailed discussion of the calibration technique and the history of radiocarbon dating, see Renfrew (1973), Taylor and Bar-Yosef (2014) and Taylor (1987).

Many of the issues discussed stem from the fact that ^{14}C concentrations vary among different reservoirs, a phenomenon resulting from its production in the atmosphere and subsequent decay (Bronk Ramsey, 2008). These processes are relatively constant over time, allowing the method to serve as an effective age estimation tool. However, the initial concentration of radiocarbon is not constant and can only be inferred based on our knowledge of past environmental conditions (Bronk Ramsey, 2008). It is important to note that production rates vary due to multiple factors that need to be carefully considered (Damon et al., 1995; Mak et al., 1999). Changes can be short- or long-term, with the former responsible for the spikes and fluctuations in the calibration curve that generally do not allow the dating of a single sample to within a century with 95.4% confidence (Bronk Ramsey, 2008: 251).

Furthermore, the ^{14}C content in the atmosphere is different from that in surface oceans. Notably, oceans have a slower mixing rate, leading to a longer exchange time for the isotope across various locations. Additionally, there is an active ongoing exchange with deep oceanic reservoirs. This phenomenon, known as the '*reservoir* *effect*', can introduce an offset of approximately 5% (around 400 radiocarbon years) in samples (Bronk Ramsey, 2008). Geography plays a significant role in this process, and estimating the local variation of the reservoir effect and accounting for it is crucial. However, these factors add complexity to the dating process, because the relationship between the surface ocean and the atmosphere varies both spatially and temporally (Ascough et al., 2007; Hughen et al., 2004; Stuiver et al., 1998). The situation is similar for freshwater reservoirs, like lakes and rivers, where our understanding of the exchange and mixing processes is even lower (Bronk Ramsey, 2008: 252-3). Additionally, there may be seasonal variations and interactions with both the geological bedrock and the atmosphere, allowing for the possibility of any intermediate ^{14}C content between 0 (the bedrock) and the atmospheric quantity (Bronk Ramsey, 2008).

Radiocarbon is assimilated into the biosphere through the photosynthesis of plants. Animals assimilate radiocarbon either directly (eating plants), as in the case of herbivores, or indirectly by consuming other animals. The exchange of radiocarbon ceases when a plant or animal dies, marking the start of radiocarbon decay (Bronk Ramsey, 2008). This cessation point is a snapshot of the radiocarbon content in the original reservoir, which is measured in radiocarbon dating (Bronk Ramsey, 2008). During dating, the measured aspect is the ratio of the radioactive carbon isotopes (14 and 13) to the stable ^{12}C isotope (Taylor, 1987). Up to this point, the method of carbon incorporation by the organism is irrelevant. However, it becomes relevant once we need to translate this ratio into calendar years by applying the calibration. Specifically, it involves identifying the reservoir(s) from which the radiocarbon originated and comparing it to samples with known ages (Bronk Ramsey, 2008: 260). Generally, assessing the reservoir for plants or animals is straightforward, with terrestrial species preferred as samples. The situation is more complex with humans, who may rely on varied sources despite living in similar environments. Stable isotope analysis and archaeozoology from excavations can aid in reconstructing diets and, therefore, determining the extent of a reservoir's representation in a sample (*e.g.* Lee-Thorp, 2008; Salazar-García et al., 2022). For the time frame of this study, we can assume the primary reservoir for humans was terrestrial, though this is not always the case, particularly in coastal areas or during the Mesolithic-Neolithic transition. It is evident that the choice of the sample has to be made carefully during the archaeological excavation, contamination has to be avoided and the laboratory procedure needs to be adequate (Bronk Ramsey, 2008: 256-7). It is evident that this process is completely out of my control, since inspection of every single date is not possible. Thus, published dates are presumed to meet the aforementioned standards, although this may be overly optimistic. The presence of some outliers ('bad samples') cannot be ruled out, but their impact is likely mitigated by the rest of the entries.

The following step involves comparing the isotope ratios in the sample to those in samples of known age. When this is not possible, it is assumed that the content of radioactive isotopes was constant over time. This was also Libby's initial assumption when the method was first introduced (Libby et al., 1949). This assumption has since been disproven, and without any reference material it is very difficult to estimate the uncertainty of the measured date (Bronk Ramsey, 2008: 261). Dendrochronologically dated wood is by far the best sample to calibrate atmospheric-derived radiocarbon samples (Reimer et al., 2004). It is from these data that calibration curves are built and used. Looking at Figure 31 a we can observe the difference between the IntCal20 and 13 calibration curve Reimer et al. (2020). Although the differences are not enormous, the figure shows that in only seven years of refinements some changes occurred. The discrepancy between the 'real' curve and a hypothetical constant ^{14}C value in the atmosphere over time is also shown in Figure 31 a. Both models are remarkably different from the calibration curves used for oceanic reservoirs (Figure 31 b), with the additional complication that the calibration curve for ocean

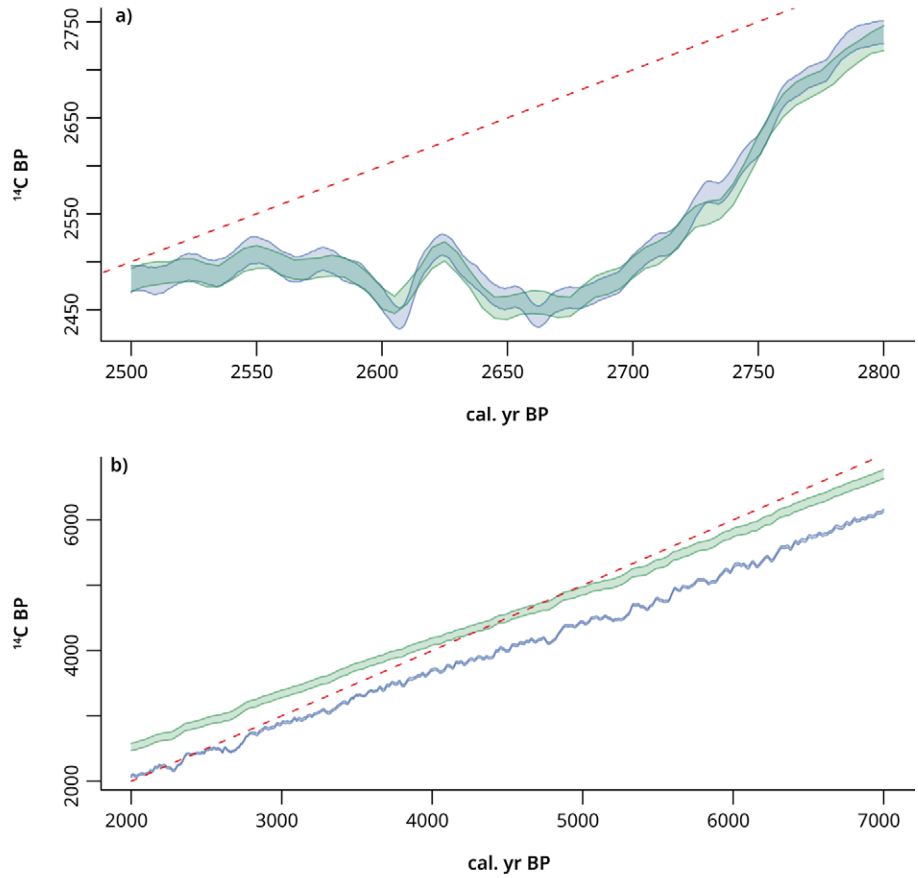


Figure 31. Example of calibration curves created with the IntCal package in R (Blaauw, 2022). The red dashed line represents the linear relation between radiocarbon and calibrated years if the content of ^{14}C were constant over time. a) Difference between the IntCal20 (blue) and IntCal13 (green) curve between 2800 and 2500 cal. yr BP (Reimer et al. 2013; 2020); b) Difference between the Intcal20 (blue) and the Marine20 (green) curve between 7000 and 2000 cal. yr BP. The Marine 20 is the calibration curve for the ocean surface (Heaton et al., 2020).

surface is, at best, an approximation (Bronk Ramsey, 2008: 262). At the time of writing, the latest calibration curve for atmospheric data was IntCal20, based on tree ring sequences extended to 13,900 cal BP, covering the entire chronology of this study (Reimer et al., 2020).

When multiple dates from a single site with reliable stratigraphic information are available, the error in estimates can be reduced to as little as a single generation span (*e.g.* Meadows et al., 2007). In cases with multiple tree-ring sequences, 'wiggle-matching dating' allows for grouping various dates into even more precise time spans (Bronk Ramsey et al., 2001). However, this technique is beyond the scope of this project and will not be explored further.

The last calibration issue addressed here concerns the algorithm selection. Research has shown that different algorithms can cause significant variations in models with a precision of less than 25 years ('sub generational'; Weninger et al., 2015: 561). This issue is particularly significant when handling multiple radiocarbon dates, as in this study. A solution adopted by some archaeologists is to limit inferences to a chronological precision greater than 200 years (Weninger et al., 2015: 561), or to develop methods for a null model that accounts for this issue (Timpson et al., 2014). A 200-year threshold can be highly problematic when dealing with historical or proto-historical periods, where generational changes can be tracked with different methods (*e.g.* high-precision chronotypology or written records; McLaughlin, 2019). However,

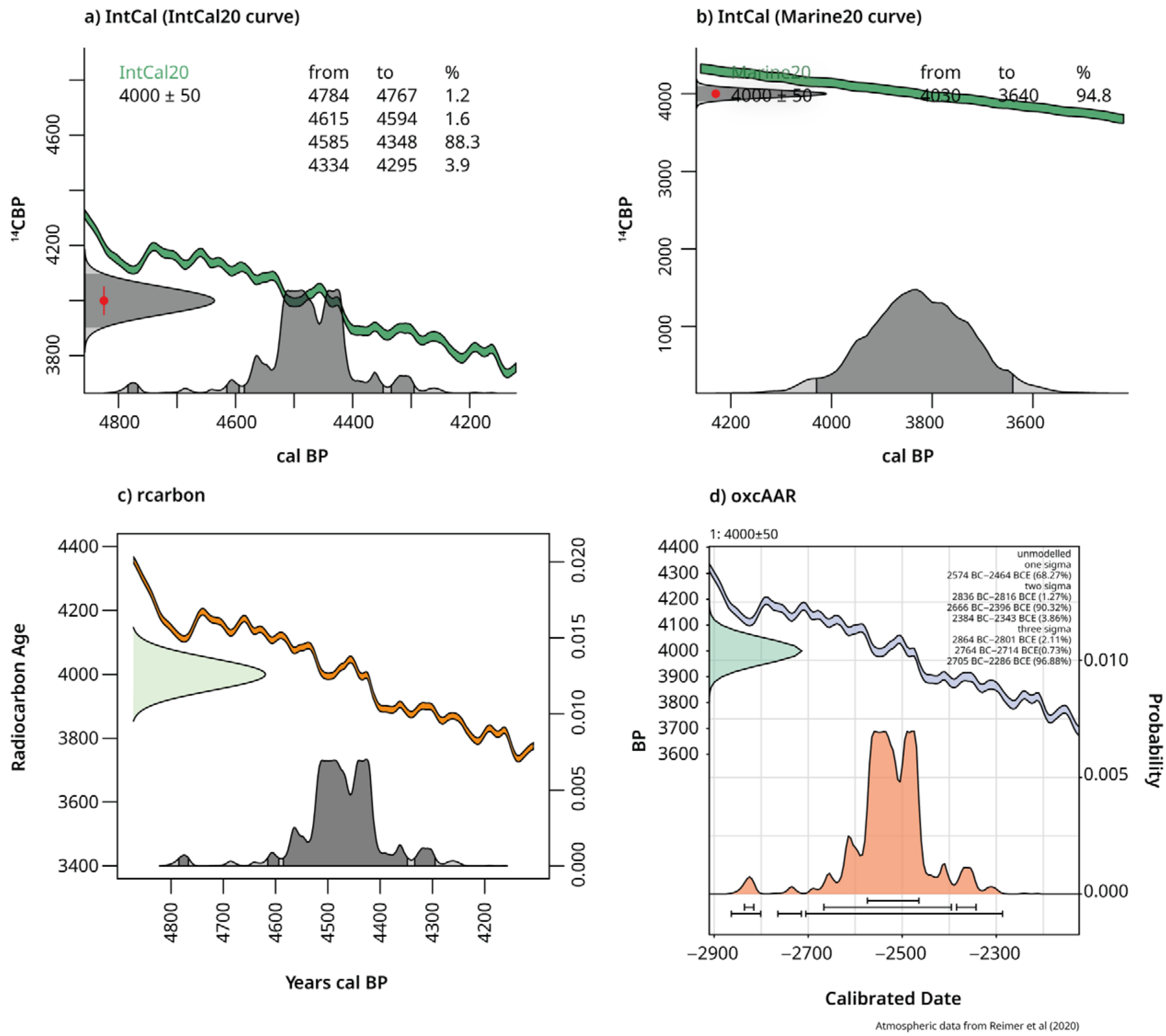


Figure 32. Radiocarbon calibration of a single date (4000 ± 50 yr BP) using different packages in R and different calibration curves.

this concern is generally not applicable to this study, allowing us to adopt 200 years as an adequate threshold.

Archaeologists commonly use the OxCal program or its adaptations as their primary tool for radiocarbon calibration (Bronk Ramsey, 2001, 2009), with an alternative represented by the CALIB 14C Calibration Program (Stuiver and Reimer, 1993). These programs share similar functionalities, and in most cases, one could use the calibration curve to calibrate dates on their own (McLaughlin, 2019). There are several packages available in R for radiocarbon calibration and I have tested them in order to find out whether there were substantial differences. Among these, there are the *oxcAAR* package, which replicates OxCal functions within R (Hinz et al., 2021); *IntCal*, a package that can be used to calibrate single dates but that was created to provide the calibration curves as support to other packages (Blaauw, 2022); and *rcarbon*, offering both simple calibration using OxCal functions and methods for summarising radiocarbon dates (Crema and Bevan, 2021). Summarising radiocarbon probability distributions is a key aspect in archaeology and it is necessary for the development of the method used in this work. For this reason, the latter package was used here.

Figure 32 shows the results of calibrating a single date (4000 uncal BP, sd = 50 years) using the different packages. While there may be slight variations in default plot settings (with the *oxcAAR* package providing better default readability), other differences are minimal or nonexistent. On the other hand, changes in the calibration curve can result in wide variations, as illustrated in Figure 32 (a and b).

5.1.2 Summed probability distribution

This method is arguably the most recognised and extensively employed in archaeology as a demographic proxy, as already discussed in Chapter 4.1.1. As the name suggests, the method is used to combine two or more calibrated dates (*i.e.* their probability density), by summing the probability for each calendar year. Whether the probability is normalised or not depends on various factors, both methodological and theoretical (see Crema and Bevan, 2021; Weninger et al., 2015).

The concept behind this approach is very similar to the construction of intensity histograms using uncalibrated or median calibrated dates. It is, in essence, a direct development of the original 'date as data' approach (Rick, 1987). The key distinction lies in the fact that in SPDs, the probability distribution of each calibrated date is summed to obtain a per-year probability representation of the entire dataset (Crema and Bevan, 2021). The resulting curve represents the intensity of probability for each calendar year and is often regarded as a proxy for human activity.

However, SPDs are not without their challenges. The most significant issue concerns the creation of artificial spikes, which are a direct consequence of the uncertainty of each measured dating and, if performed, the normalisation of the SPD (Bronk Ramsey, 2017: 1811; Weninger et al., 2015). In essence, low uncertainty can lead to spurious peaks, while high uncertainty in the dates, albeit providing a better representation of the distribution, would lead to a smeared result (Bronk Ramsey, 2017: 1811). To address this issue and obtain a more accurate representation of the summed distribution, it is important to have a large sample size and appropriate uncertainty levels, although there is not a standard (Bronk Ramsey, 2017: 1811). In addition, the calibration curve further complicates the results, as sharp drops in density and extended probability ranges beyond the actual dating range can occur (Bronk Ramsey, 2017: 1812). These effects are particularly pronounced in areas where the calibration curve exhibits plateaux, as shown in Figure 33.

In comparison to the Kernel Density Estimation (KDE) method, the probability distribution of each dating sample in an SPD is not determined by the kernel bandwidth but rather depends on the associated measurement error and the calibration curve for that specific range. Consequently, SPDs derived from different datasets are not directly comparable in terms of intensity (Bronk Ramsey, 2017).

To summarise, there are three major issues associated with summed distributions: (i) the lower the number of measurements, the greater the noise introduced; (ii) variation in uncertainty determines the presence of spurious peaks or a smoother curve; (iii) the calibration curve introduces noise in the model (Bronk Ramsey, 2017).

Certainly, it is possible to use various statistical methods, such as Bayesian modelling, to address these challenges and minimise false-positive attributions of signal to noise (McLaughlin, 2019). However, when applying this method to sample calendar dates, issues arising from spikes in data can persist. Although techniques like thinning and binning might offer a partial solution, it is important to note that these approaches are primarily designed to identify deviations from a null model. Consequently, they may not be ideally suited for randomly sampling dates to simulate site chronology (Crema et al., 2016; on the use of SPDs see, for example, Crema et al., 2017; Edinborough et al., 2017).

Nevertheless, these considerations do not undermine the value of SPDs as a suitable method for combining radiocarbon dates. In fact, they provide an excellent way to visualise temporal patterns between different sites and as a comparison with different proxies based on material culture or site counts (*e.g.* aoristic; McLaughlin,

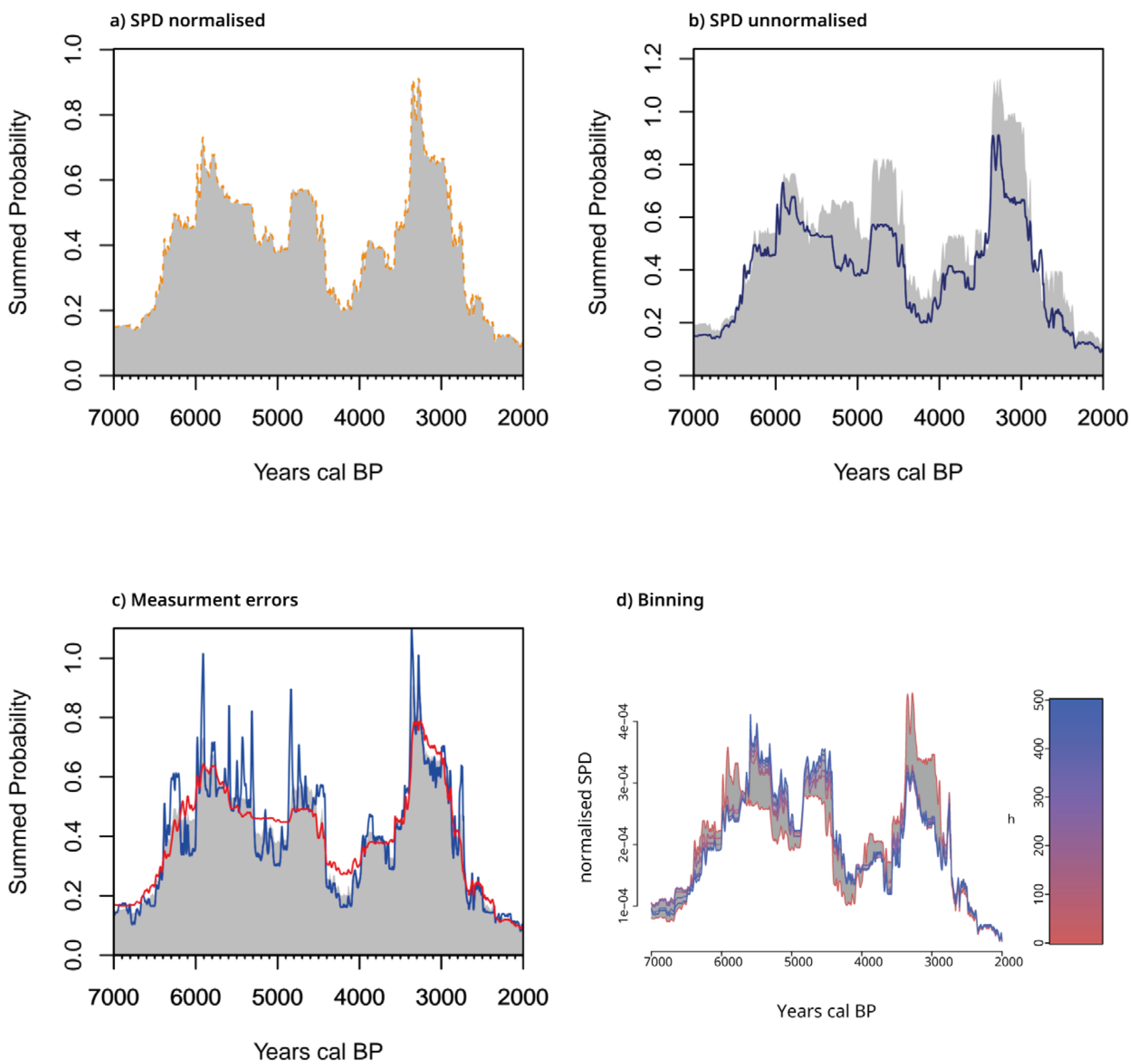


Figure 33. SPD plots for 2311 Danish ^{14}C dates to illustrate some of the aspects and issues described in the text. Dates from XRONOS database (Hinz and Roe, 2023) calibrated using the rcarbon package in R (Crema and Bevan, 2021). a) SPD normalised. The orange line represents a smoothing using a rolling mean of 200 years. b) SPD unnormalised. Note the difference with the blue line, representing the normalised SPD. c) Effect of measurement error on the final result. Here the original error has been manually doubled (red line) and halved (blue line). The original SPD is shown in grey. d) Impact of binning on the SPDs. A binning between 0 (orange line) and 500 years (blue) is carried out. The choice of the optimal value depends on several factors such as the nature of the archaeological data and the research questions.

2019: 482). Additionally, SPDs offer the opportunity to study overlaps and hiatuses in dated samples, which can be further explored through Bayesian modelling to enhance our understanding of the starting and ending of the processes under investigation (Bronk Ramsey, 2009, 2017).

5.1.3 Kernel density estimation

Kernel Density Estimation (KDE) shares the same objective as SPDs in determining the cumulative probability of events over time. However, KDE has the advantage of allowing a better smoothing of the underlying noise (McLaughlin, 2019). While it addresses the uncertainty of individual dates, including standard deviation and calibration issues similar to SPDs, KDE additionally models the uncertainty related to sampling procedures using a Gaussian distribution for the kernels. Although other distributions are possible, the Gaussian distribution is generally considered the most appropriate (McLaughlin, 2019). The choice of an appropriate bandwidth for the smoothing process is crucial in KDE. A small bandwidth would fail to eliminate noise caused by the calibration curve, while a large bandwidth would hinder the identification of genuine dynamics within the data. Thus, the selection of bandwidth involves a trade-off, and there is no one-size-fits-all value (McLaughlin, 2019). As previously discussed, a bandwidth of less than 200 years is generally not considered suitable, as it would introduce noise that could be misinterpreted as false positives (McLaughlin, 2019: 483). There is some debate in the literature over the decision of a bandwidth (or a bin in the case of SPDs), but it seems that this minimum threshold could be considered adequate (McLaughlin, 2019; Shennan et al., 2013).

Nonetheless, this may be a trivial issue when dealing with northern European prehistory, as the finest resolution available for the relative chronology is of about 200 years, representing a single Bronze Age period and some Middle Neolithic phases. As discussed earlier (see Chapter 5.1.1), achieving a precision of less than 100 years in a single calibrated date is usually not feasible, with observed fluctuations often attributed to the calibration curve (Bronk Ramsey, 2008: 251; McLaughlin, 2019: 482-483). Another important aspect in KDE is the selection of the point estimate for each calibrated date. The weighted mean is commonly used, but potential complications can arise from the calibration curve, especially in cases of plateaux (McLaughlin, 2019: 483).

In addition, one of the primary advantages of KDE is its long history of development and refinement, leading to a rich and more extensive body of literature compared to SPDs (Baddeley et al., 2016; Brown, 2017: 103-4; Diggle, 2013).

However, what should really be compared to an SPD is not a single KDE but the so-called Composite KDE (CKDE; Brown, 2017). This method involves sampling random calendar dates from each calibrated date and using them to generate a KDE with a specific bandwidth. The process is repeated multiple times, and each resulting KDE is combined to form an envelope (Crema and Bevan, 2021; McLaughlin, 2019). The CKDE offers advantages over SPDs when it comes to simulations, as it retains sub-population information, handles uncertainty more effectively and provides greater flexibility (McLaughlin, 2019). However, as its counterpart, it struggles when dealing with the sampling of the so-called ‘first’ and ‘last’ events, which tend to be sampled too early or too late compared to the real values (as discussed in Bronk Ramsey, 2017). In both cases, Bayesian modelling provides a solution, as implemented by Bronk Ramsey (2017) in OxCal.

Evidently, there is no ‘best’ method, and researchers must adapt and use the most suitable approach for their specific research questions and methods. However, the CKDE reduces calibration noise and false positives compared to other methods. In this study, I adopt a method that is similar to the one used to generate a CKDE. Specifically, I sample dates from the radiocarbon distribution, but instead of building a CKDE, I use the list of calendar dates to sample a possible dating for each site in the dataset, repeating the operation 100 times. Site chronologies are simulated based on their relative chronology and are later binned into 200-year windows. To illustrate this, consider a site dated to the Early Bronze Age, with a possible simulation date range from 1700 BCE to 1101 BCE. When a date like 1545 BCE is sampled, it would fall into the 1700-1501 BCE window (EBA I). If the probability curve were a straight line during the EBA, approximately one-third of 100 simulations would likely fall into each period. However, a site’s chronology is more likely to be sampled during years with higher sampling density. It is important to remember that with the relative chronology constraints

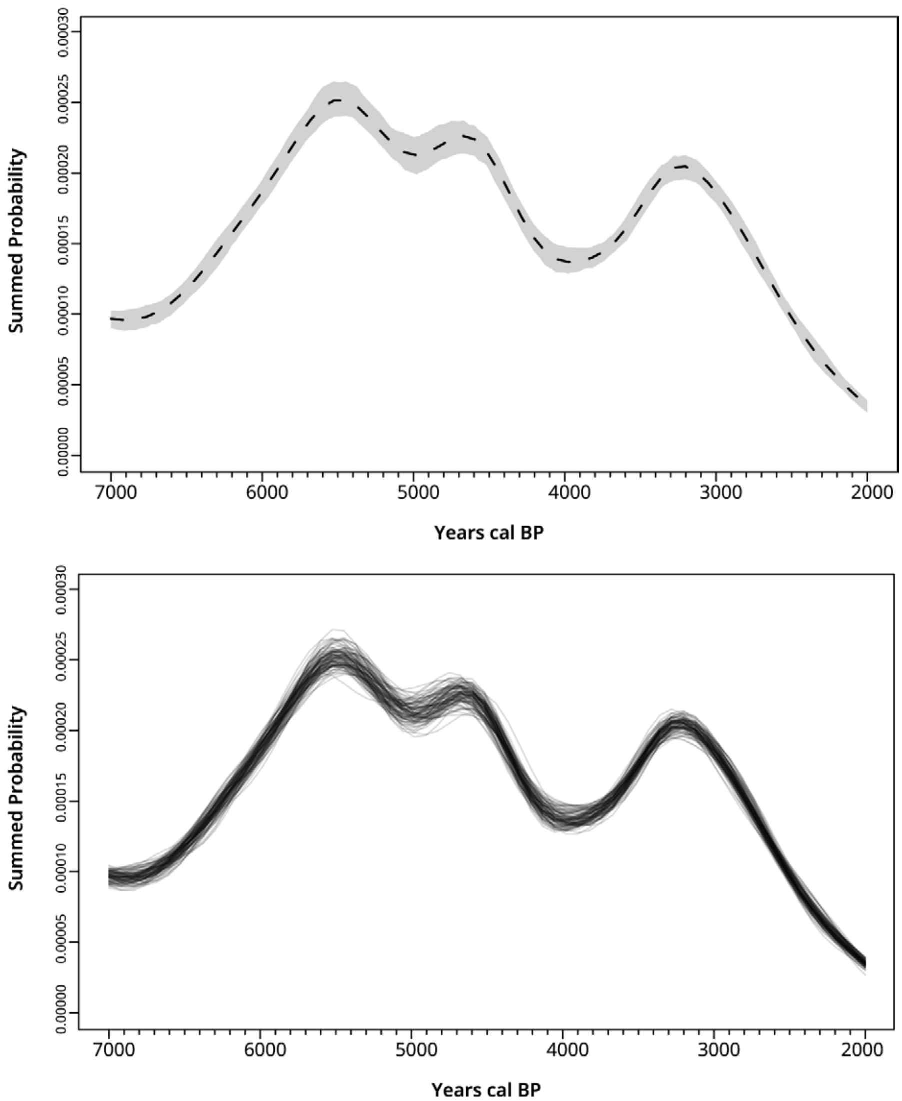


Figure 34. Example of CKDE calculated using the rcarbon package (Crema and Bevan, 2021). Each line in the plot on the right represents a KDE. CKDE generated using all the ^{14}C datings from Denmark available in the XRONOS database (Hinz and Roe, 2023).

and the binning, the unwanted noise is smoothed out of the model and therefore variation is assumed to reflect demographic patterns. The outcome represents the probability of each site being dated to a given period, based on the CKDE and constrained by the available relative dating. Because 100 simulations were conducted, the result also indicates the likelihood percentage of each point falling within a specific time window. The number of simulations was limited to 100 due to computational constraints.

In R, it is possible to generate a CKDE using the *rcarbon* package. First, the *sampleDates* function is used to generate a defined number of random dates. Second, each group of sampled dates is used to create the composite KDE using the *ckde* function (Crema and Bevan, 2021). An example, using the same data from Figure 33 is provided in Figure 34.

5.2 Point pattern analysis

A spatial point pattern is the representation in the space of a group of events. Point Pattern Analysis (PPA) is the study of the organisation of these events in the space (Baddeley et al., 2016: 3). It is a fundamental concept of spatial statistics and

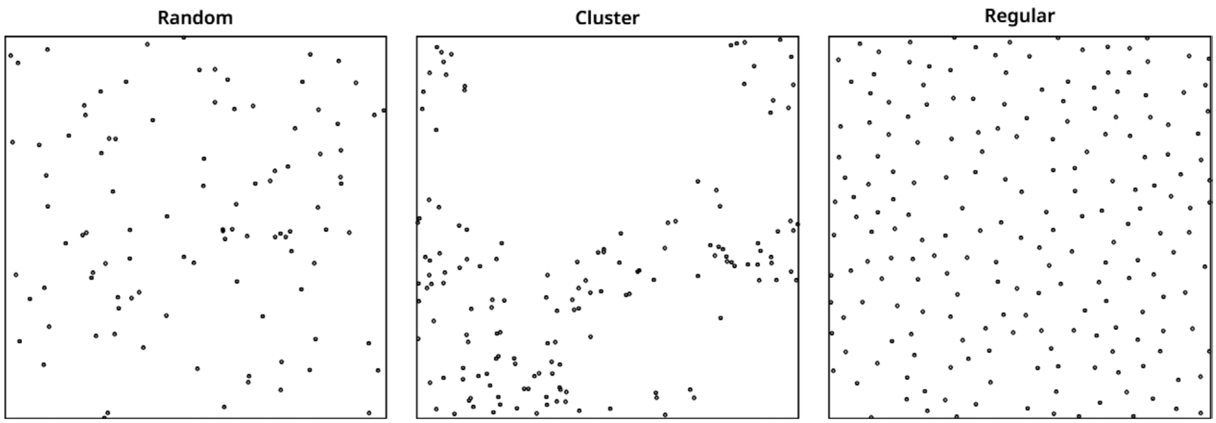


Figure 35. Visualisation of the characteristics of a point process. The points are randomly created using functions form the sptatstat package (Baddeley et al., 2016).

finds applications in many fields of research as diverse as Ecology or Criminology (Anselin and Rey, 2010; Legendre and Legendre, 2012; Leitner, 2013; Wiegand and Moloney, 2013). In archaeology PPA has increasingly been applied and it is now a fairly established method (Bilotti et al., 2024a; 2024b; Bilotti and Campeggi, 2021; Blankholm, 1991; Brandolini and Carrer, 2020; Carrero-Pazos, 2019; Crema et al., 2010; Kempf, 2021). The concept of point process and its application in probability theory is not new. The earliest applications dated to the late 17th century and were related to life tables and renewal theory (Daley and Vere-Jones, 2003: 5 ff.). Another important approach related to *Counting Problems* and probability theory and it is within this framework that the concept of Poisson distribution was introduced (Poisson, 1837). However, it was not until the mid-20th century that stochastic processes grew in theoretical foundation and application (Daley and Vere-Jones, 2003: 13; Møller and Waagepetersen, 2004).

The aim of PPA is to determine whether the spatial distribution of points is the product of some external variables or relation between points (Baddeley et al., 2016: 127). It is important to note that the focus has to be on the *processes* that generated the point distribution rather than on the point themselves, which are representing the initial observation and are fixed (Baddeley et al., 2016: 127). When studying a point process we are generally interested in two aspects: its intensity and the interaction between points. In the literature, we often refer to these aspects as first and second-order properties (Bailey and Gatrell, 1995; Gatrell et al., 1996).

A basic and fundamental concept in PPA is that of *point process*. A spatial point process is a mechanism that generates a pattern of points as its outcome (Baddeley et al., 2016: 128). This concept is essential in the formulation and testing of scientific hypotheses over the observed spatial patterns, which in our case are the archaeological sites. Our interest is not for the single site or set of sites but on their generalisation and the process behind, giving it a statistical framework (Baddeley et al., 2016: 128).

Point patterns can be defined according to their characteristic as random, clustered or uniform (Figure 35). A random process is the result of a homogeneous Poisson point process, that can also be called *Complete Spatial Randomness* (CSR) (Baddeley et al., 2016: 132). The key properties of a CSR are homogeneity and independence. Homogeneity means that there is no preference for any given region and points are expected to be distributed proportionately to the area of the region; independence means that the point distribution in one region (regardless of its dimension) does not help explaining distribution in any other region (Baddeley et al., 2016: 128; Møller and Waagepetersen, 2004, ch. 3). An additional characteristic of a CSR is orderliness, meaning that if we divide the area in small regions the probability of having more than one point in it is negligible (Møller and Waagepetersen, 2004, ch. 3). These

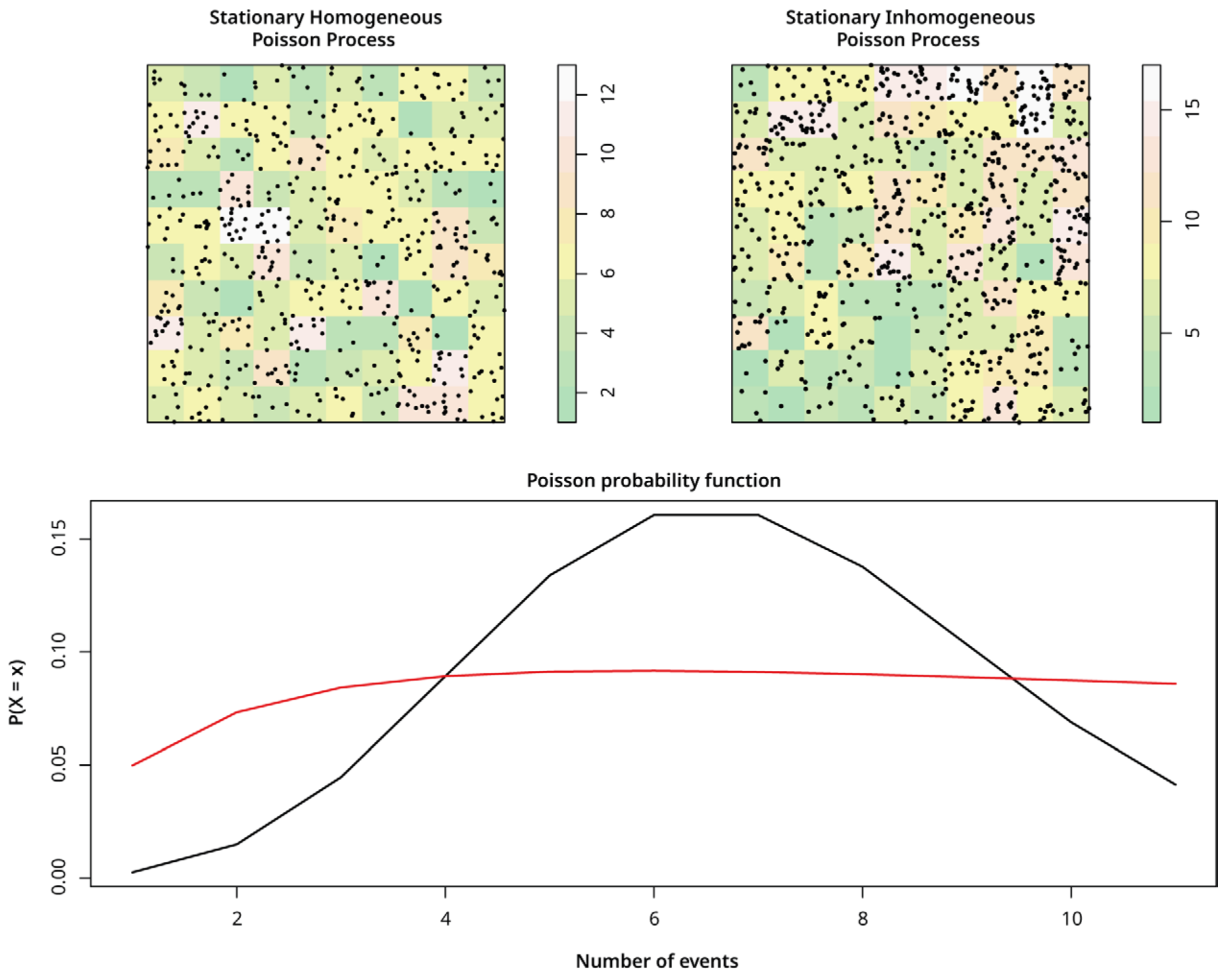


Figure 36. Example of a Stationary Poisson Process using random points generated using the spatstat package (Baddeley et al., 2016). Random points are distributed across a 10 × 10 grid, with the colours of each square varying depending on the number of points simulated within them. The Homogeneous Poisson Process probability function is shown in black while the Inhomogeneous is in red.

characteristics correspond to a homogeneous Poisson distribution (Kingman, 1993, ch. 1). The importance of CSR is that it is generally used as a null hypothesis to test an observed point pattern.

In practice, it is often more useful to deal with inhomogeneous Poisson point processes, the difference being that the average density of points varies across space following an intensity function (Baddeley et al., 2016: 137-138; Daley and Vere-Jones, 2003: 19-20). The other characteristics remain unchanged (independence and Poisson distributed points within any given region). The properties of a Poisson distribution and the generality of the intensity function make the inhomogeneous Poisson process models particularly useful in most cases (Baddeley et al., 2016: 137-138; Daley and Vere-Jones, 2003: 19-20). An example of the differences between the two Poisson processes (both stationary) is shown in Figure 36.

This model is represented as the intensity function describing the mathematical relation between the point pattern and a group of covariates that are assumed to have an impact in site distribution (Baddeley et al., 2016: 299). A Poisson distribution assumes that events are independent and that their mean intensity is constant. Furthermore, a process can be homogeneous or inhomogeneous, depending on the fact that the probability of an event is the same in every part of the region or not (Baddeley et al., 2016: 138; Daley and Vere-Jones, 2003: 19-20). In our case, it is generally adequate to treat point distributions as inhomogeneous Poisson processes (Baddeley et al., 2016: 138).

When the point process results from interaction between points, we are no longer in front of a CSR. Clustering is when points tend to be located at smaller distance from each other while we talk about regular distribution if the presence of points tend to inhibit the presence of neighbours within a certain radius (Figure 35) (Baddeley et al., 2016: 139 ff.).

5.2.1 Spatial intensity and kernel density estimation

Kernel Density Estimation is arguably one of the most widely used non-parametric methods for examining the spatial distribution of points. KDE is a data smoothing technique that measures the density of a population without prior knowledge on the mean density or the variance (Silverman, 1998: 76 ff.). Part of its popularity can be attributed to its straightforward application, as it only requires a smoothing parameter, known as kernel radius or sigma (Silverman, 1998: 76 ff.). During the analysis, a kernel of fixed bandwidth is moved across the study region, measuring the intensity of observations at each location using a quadratic equation. The resulting values are assigned to the centre of the kernel and the final result is a continuous intensity surface (Baxter et al., 1997; Bevan, 2020; Conolly and Lake, 2006; O'Sullivan and Unwin, 2010).

In this study KDE has been used in two distinct ways. On one hand, it served as an exploratory technique to visualise the distribution of points within a two-dimensional space. In this case it was computed using the *density.ppp* function from the *spatstat* package (Baddeley et al., 2016). On the other hand, KDE was used as an alternative to summed probability in handling radiocarbon dating, as discussed in Chapter 5.1.3.

The choice of the bandwidth determines the granularity and shape of the resulting KDE. When applied on two-dimensional point patterns, the function assigns higher weights to observations closer to the centre, as opposed to those farther away (Baddeley et al., 2016; Baddeley and Turner, 2005). The primary issue with this technique is the choice of an appropriate bandwidth (as shown in Figure 37). A bandwidth that is too small would result in an uninformative, noisy plot similar to the original point distribution. Conversely, a bandwidth that is too large would overly smooth out most of the variation within the dataset. Generally, as the bandwidth increases, the results become smoother, and the goal is to determine the threshold at which the resulting KDE provides informative insights at the desired scale (different values may be suitable for different patterns, as shown in Figure 37). Silverman (1998) proposed a formula to identify the upper limit for the choice of the optimal bandwidth on the assumption that the observations follow a normal distribution. Another possible solution has been developed by Diggle (1985), wherein the optimal smoothing parameter is calculated as the value that minimizes the '*mean-square error criterion*' based on Berman and Diggle (1989). This value can be calculated using the *bw.diggle* function from the *spatstat* package (Baddeley et al., 2016; Berman and Diggle, 1989; Diggle, 1985; Diggle, 2013). A possible alternative is provided by the *bw.ppl* function, available in the same package, which assumes an underlying Poisson process and aims at maximising the point process likelihood cross-validation criterion (Baddeley et al., 2016). The main advantage of this function relies on the fact that it is a formal method that can be directly applied to any case study. However, depending on the scope of the analysis, it may be beneficial to visually assess the impact of different bandwidths on the final KDE.

5.2.2 First-order properties

First-order properties refer to the intensity of a process relative to an external covariate, such as the number of sites in a particular area and an environmental explanatory variable. The location of a point is affected by the underlying area's structure but not by the location of other points (Wiegand and Moloney, 2004).

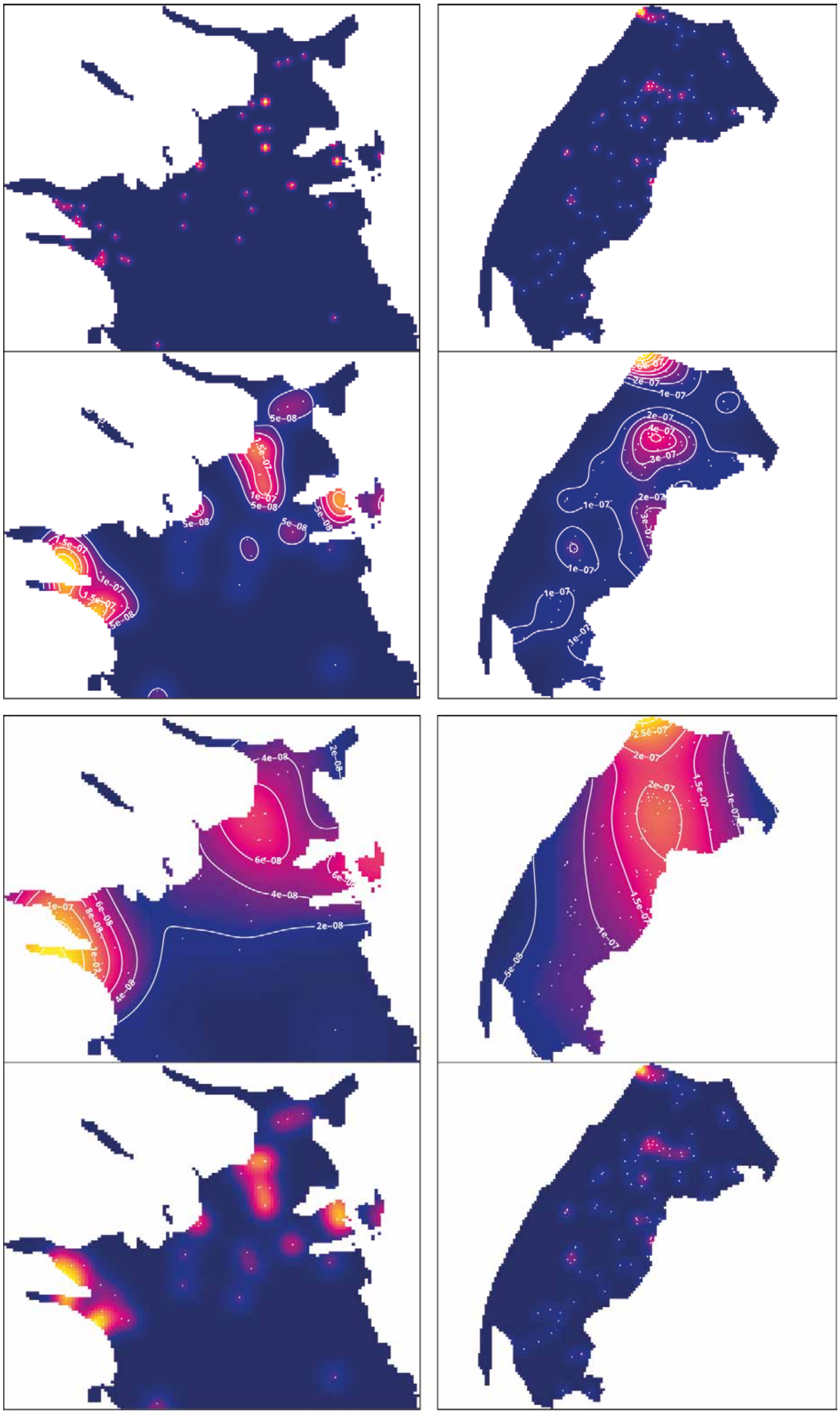


Figure 37. An illustration of KDE applied to Bronze Age burial mounds in NW Zealand (left) and Thy (right; both in Denmark). The choice of an appropriate bandwidth is crucial. In the sequence from left to right, KDEs are calculated with a sigma of 500, 2000 and 5000 m respectively. The final plot to the right shows the KDE using as sigma the output of the bw.diggle function: 1633 m for Zealand and 804 m for Thy. Evidently, the optimal bandwidth varies between the two case studies. A radius of 5000 m is informative of the pattern of the mounds in Zealand while it obscures the results for Thy. Sites are represented as white dots and density isolines are superimposed to the 2000 and 5000 m KDEs.

5.2.2.1 Rhohat

The *rhohat* function from the *spatstat* package is used to calculate the intensity of observations (archaeological sites), against environmental covariates (Baddeley et al., 2012). Sometimes, this relationship is called *prospectivity index* or *resource selection function*, due to its application for geological or ecological purposes. The method used to calculate it is nonparametric and does not assume as a prior any type of interaction (Baddeley et al., 2012; Baddeley et al., 2016; Baddeley and Turner, 2005).

By employing the rhohat function, it is possible to visualise the impact of environmental parameters on the distribution of points. These parameters can include variables like elevation, distance from water sources, or other factors relevant to the study. The function provides a measure of repulsion or attraction, allowing researchers to identify preferred ranges in relation to the available values within the study area. The use of continuous covariate data in the form of raster maps enhances the flexibility and accuracy of this analysis (Bilotti et al., 2024a; Kempf, 2021; Knitter and Nakoinz, 2018).

One of the advantages of the rhohat function is its ability to generate results accompanied by a confidence interval, typically set at 95% (Baddeley et al., 2012; Baddeley et al., 2016). This interval provides a measure of uncertainty, allowing for a more comprehensive interpretation of the intensity patterns observed. Moreover, the function enables researchers to combine their expertise and decision-making with objective analysis, resulting in a more nuanced understanding of the interplay between observations and environmental factors.

In summary, the rhohat function serves as a powerful tool for assessing the intensity of observations in relation to environmental covariates. Its nonparametric nature, visual representation, and inclusion of confidence intervals contribute to the robustness and reliability of the analysis. By utilising this function, researchers can gain valuable insights about the complex dynamics between archaeological sites and their environmental context. It can be used as an explanatory analysis, creating a predictive surface using the *predict* function on its results, or as a support for further investigation such as Point Process Models.

5.2.2.2 Point process models

A point process is a method used to describe the distribution of point patterns in an n-dimensional Euclidean space. It is often used to study point distribution and its hidden relation to external parameters such as soil fertility, proximity to resources, *etc*. (Baddeley et al., 2016; Bilotti et al., 2024a). While several probability distributions are possible, this work focuses exclusively on Stationary Poisson processes.

In R, it is possible to fit a Poisson point process model using the *ppm* function from the *spatstat* package (Baddeley and Turner, 2005). In order to work, a formula relating the points and the covariates has to be defined. Here, multiple covariates are used simultaneously and summed with equal weight. Then, the model is fitted to the different groups of points, grouped by chronology.

However, some covariates may not have explanatory power or they may be redundant. For this reason, I applied a stepwise model selection in order to optimise the model. This could in part be done using the *rhohat* function described earlier, but it would force one to manually select the covariates for each time period, making it a very long and less reproducible process. Moreover, even if manually selected, an optimisation may still improve the model. Here, I use the Akaike Information Criterion (AIC) to minimise redundancy in the model keeping the same predictive power (Venables and Ripley, 2010: 175 ff.). In R, this is done using the *stepAIC* function from the *MASS* package (Venables and Ripley, 2010) or the *step* function from the *stats* package (R Core Team, 2023).

5.2.3 Second-order properties

Second-order properties describe inherent spatial dependency, such as attraction or repulsion, and occur when a point's location is influenced by the presence or absence of other points (Eve and Crema, 2014; Wiegand and Moloney, 2013). However, in this study this group of analyses is not carried and will not be further discussed.

5.3 Cluster analysis

Cluster analysis is a statistical method used to group data into clusters based on their attributes, such as spatial location or material culture. It is an exploratory technique that provides information on the structure of the input data without prior knowledge of their grouping. The technique is fairly widespread in many disciplines such as biology, social sciences, marketing or computer science (Ahlquist and Breunig, 2012; Fielding, 2006; Kung, 2014). The origin of cluster analysis in the scientific literature can be found in the first half of the 20th century (Blashfield, 1980). In particular, one of the most influential works on the topic was written in 1939 by the behavioural psychologist Robert C. Tryon (1939). However, it is from the 1960s that most of the scientific literature on cluster analysis has been written and in particular after the publication of *Principles of Numerical Taxonomy* by the biologists Sokal and Sneath (Aldenderfer and Blashfield, 1984: 7-8; Sokal and Sneath, 1963).

Although there is not a single definition of what a cluster is, there is general agreement on the fact that clustering is the action of grouping objects (physical or abstract) into classes based on similarities (Han and Kamber, 2006: 383). The clustered object can generally be treated as a single entity, making clustering a form of data compression (Han and Kamber, 2006: 383). Classification is a basic concept in science and it has been carried out long before the formalisation of the statistical technique (Aldenderfer and Blashfield, 1984: 7). This is because classification is a common human activity, learned during childhood and continuously improved throughout our lives (Aldenderfer and Blashfield, 1984: 7; Han and Kamber, 2006: 383).

However, cluster analysis becomes a proper statistical technique when, in order to assign a specific object to a group, a degree of similarity is calculated and the distance between clusters measured (Aldenderfer and Blashfield, 1984: 8). Another important step concerns the identification and handling of *outliers*, *i.e.* distant objects in terms of similarity from all identified clusters (Han and Kamber, 2006: 383). If we look at the literature we find that there is not a single definition of clustering and even the terminology used is generally not consistent, when not contradictory (Aldenderfer and Blashfield, 1984: 9; Estivill-Castro, 2002). This diversity is reflected on the number of different algorithms used to detect clusters (Blashfield, 1980). As pointed out by Estivill-Castro (2002) 'clustering is in the eye of the beholder'. This variation partly depends on the method's origins and the diverse interests and backgrounds of its early developers. Later on, the number of applications multiplied and the initial lack of formalism resulted in the present situation (Blashfield, 1980). In fact, clustering algorithms are ultimately based on inductive principles, which essentially represent the mathematical formalisation of these specific interests and believes (Estivill-Castro, 2002). This is not an issue *per se*, because cluster analysis is an exploratory technique rather than confirmatory. The diversity of approaches and interpretation of the results (what may be considered noise by one person could be interpreted as a significant signal by another, Han and Kamber, 2006: 461) enriches the diversity, provided that the analyses are carried in a formal way and with an initial set of hypotheses to test (Estivill-Castro, 2002: 71).

For this reason, it does not make much sense to give a definition of cluster. It is more useful to describe the common grounds on all the techniques and how clustering methods are used. Following Aldenderfer and Blashfield (1984) we can say that there are four main goals in cluster analysis:

1. Developing a classification;
2. Investigating conceptual schemes for grouping;
3. Formulate hypotheses (after all it is an exploratory technique);
4. Hypothesis testing, aka trying to verify if the identified clusters are present in a data set.

The first point is the one that attracted the most interest of scientists (Aldenderfer and Blashfield, 1984: 9). Despite the variability in aims, disciplines and data involved, it is possible to divide into steps the procedure of creating clusters as follows: (i) data selection, (ii) definition of the attributes to be used to (iii) compute similarities, (iv) create clusters out of similarities and (v) validation of the results (Aldenderfer and Blashfield, 1984: 12), which should be supported by graphical display (Rousseeuw, 1987). In the next section, the concept of cluster analysis in archaeology is introduced alongside a more detailed description of the different clustering algorithms.

5.3.1 Cluster analysis in archaeology

The first systematic approaches of cluster analysis in archaeology can be traced back to the emergence of the New Archaeology and the advent of computational analysis in the 1960s and 1970s (Clarke, 1972; Doran and Hodson, 1976; Hodder, 1977; Shennan, 1997). However, anthropologists were among the pioneers of the techniques, trying to identify homogeneous cultural areas using matrix manipulation methods (Aldenderfer and Blashfield, 1984: 7). Nonetheless, as for most of other disciplines, classification and division into groups was an essential part of archaeology. In fact, grouping the material culture was among the central tasks of archaeologists until the late 1950s and it still bears importance. In this early period, archaeologists relentlessly tried to establish a chronological and typological framework based on the available material culture in order to create sequences (cultural and chronological). Examples of these early attempts are abundant and one of the better-known examples is certainly Flinders Petrie and his pottery seriation in Egypt (Petrie, 1921). Another example worth mentioning is the seriation and classification used by Vere Gordon Childe as the backbone for building global narratives for prehistoric patterns (Childe, 1951, 1958).

Finding similarities and interpreting differences in our dataset still holds a key role in archaeology and cluster analysis provides a more robust solution than manual classification (Fletcher and Lock, 2005: 129 ff.). Everything can be grouped, from single artefacts, to features or sites. Recently, Carlson (2017) wrote an account of the most important methods used in archaeology for classification (analogical and computational) and described in further detail the two he thinks are most valuable for archaeologists, notably k-means and hierarchical clustering (Carlson, 2017: 318 ff.). Among the methods worth mentioning and adopted over time by archaeologists there are:

- Monothetic divisive. Every entry is differentiated using one attribute per step. For example, we could classify pottery starting from the shape and then moving to

decoration and temper. This makes the technique dependent on the order of the attributes and the arbitrary end and start points;
- Type specimen. In this method, a first group is formed around a chosen element of the data set. Subsequent elements are compared to this initial specimen, either joining its group or forming new groups around new specimens;
- Polythetic divisive. This works similarly to the monothetic method, but considers the attributes simultaneously. It recursively partitions the dataset based on the best splitting criteria (usually some similarity indices).

It is important to note that all three of these techniques are forms of *divisive clustering*, which is part of hierarchical clustering (Ezugwu et al., 2022). In this work, I am mostly interested in the spatial relation of data points, therefore using the coordinates as the attributes and separating sites beforehand by their type or chronology (*e.g.* megalithic graves or burial mounds). Thus, methods such hierarchical clustering, which are more suitable for multi-dimensional datasets or those with multiple attributes (*e.g.* language relatedness, phylogenesis, *etc.*), which typically produce a dendrogram as a result, are not discussed. Other methods, such as intensity-based clustering, are not widely used in archaeology but are included here as they can be beneficial in our discipline.

5.3.2 Clustering algorithms

There are several families of clustering algorithms and many researchers have tried to group them into classes of similarities (*metaclustering*?). Recent works on this topic showed that it is possible to differentiate between two broader classes: hierarchical clustering and partitional clustering algorithms (Ezugwu et al., 2022). The first class has been already mentioned and is not addressed here.

Within the partitional clustering algorithms, I will only consider hard/crisp clustering and in particular, density-based clustering (DBSCAN and OPTICS), model based clustering, and square error clustering (k-means and k-medoids). There are some more typologies of cluster analysis that may prove useful in archaeology (*e.g.* fuzzy clustering) but they were developed to deal with a very high number of attributes, which is not the case in this work. For a complete taxonomy of clustering algorithms see Ezugwu et al. (2022). Other authors classified clusters differently, *e.g.* Venables and Ripley (2002). However, it is only a matter of labelling and this does not affect the content of the present work.

The key parameters used to evaluate the performance of different algorithms in archaeological case studies include:

- Identification of clusters with arbitrary shape. Not all clusters are spherical but some algorithms are more likely to identify these because of the distance measures they are based on (Han and Kamber, 2006: 385);
- Dealing with outliers and noisy data;
- Prior knowledge required to define input parameters. In some cases, we have to determine some parameters in advance. This is not ideal for scalability and usability.

On how to judge a clustering algorithm see Han and Kamber (2006). Although primarily focused on data mining, most concepts are applicable to every field.

5.3.2.1 Square error clustering

K-means

K-means is one of the better-known and most-used clustering algorithms. Its popularity mostly relies on its simplicity, computational speed and interpretability.

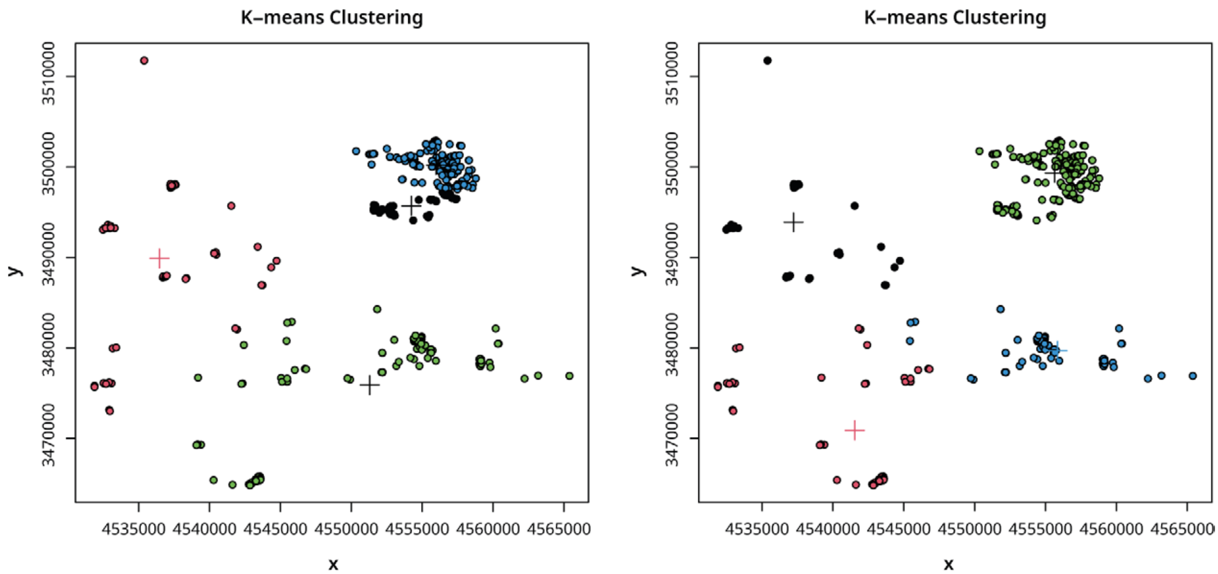


Figure 38. Two examples of k-means clustering based on Bronze Age burial mounds on the island of Rügen. The figure shows how different runs can lead to different results. K is set to 4.

It divides the data points into a number of predetermined clusters defined by the user (Venables and Ripley, 2002: 318 ff.; Carlson, 2017: 321). Every data point is iteratively assigned to the centroid of the nearest cluster and at each step the centroids are updated based on the means of the points belonging to each cluster. The workflow is as follows (after Carlson, 2017):

1. Centroids are defined. They can be set manually by the user but are more generally randomly chosen;
2. Each point is assigned to the closest centroid. Distance is usually Euclidean but it is possible to use different methods (*e.g.* Manhattan). It is important that the variables are scaled so the attribute distance is appropriate (Hartigan, 1975: 85);
3. The centroids are updated based on the mean of the points belonging to each cluster (iterative reallocation);
4. Steps 2 and 3 are repeated until centroids become stable or the iteration limit set by the user is reached.

In R, k-means can be easily performed using the *kmeans* function from the *stats* package (R Core Team, 2023) using the algorithm based on Hartigan and Wong (1979). An example of its application is shown in Figure 38.

The aim of the algorithm is to minimise the overall distance within each cluster (Hartigan and Wong, 1979). However, the k-means has a number of limitations. The most important is that it is very sensitive to the initial selection of centroids, which means that its results are not deterministic and vary between different runs due to the random initialisation of centroids (Conolly and Lake, 2006: 171). Furthermore, it is very sensitive to outliers and it may be necessary to manually remove them before running the analysis (Carlson, 2017: 321). A possible solution could imply iterating the k-means and manually selecting the best results (Carlson, 2017: 321) or applying fuzzy k-means (Ezugwu et al., 2022). Nevertheless, this method scores low in the three parameters previously defined, as it works best with spherical clusters, it is not robust to outliers, and prior knowledge about the dataset is required.

K-medoids

K-medoids, also known as Partitioning Around Medoids, is a clustering algorithm similar to the k-means but with some improvements (Kaufman and Rousseeuw, 1990: 68-125):

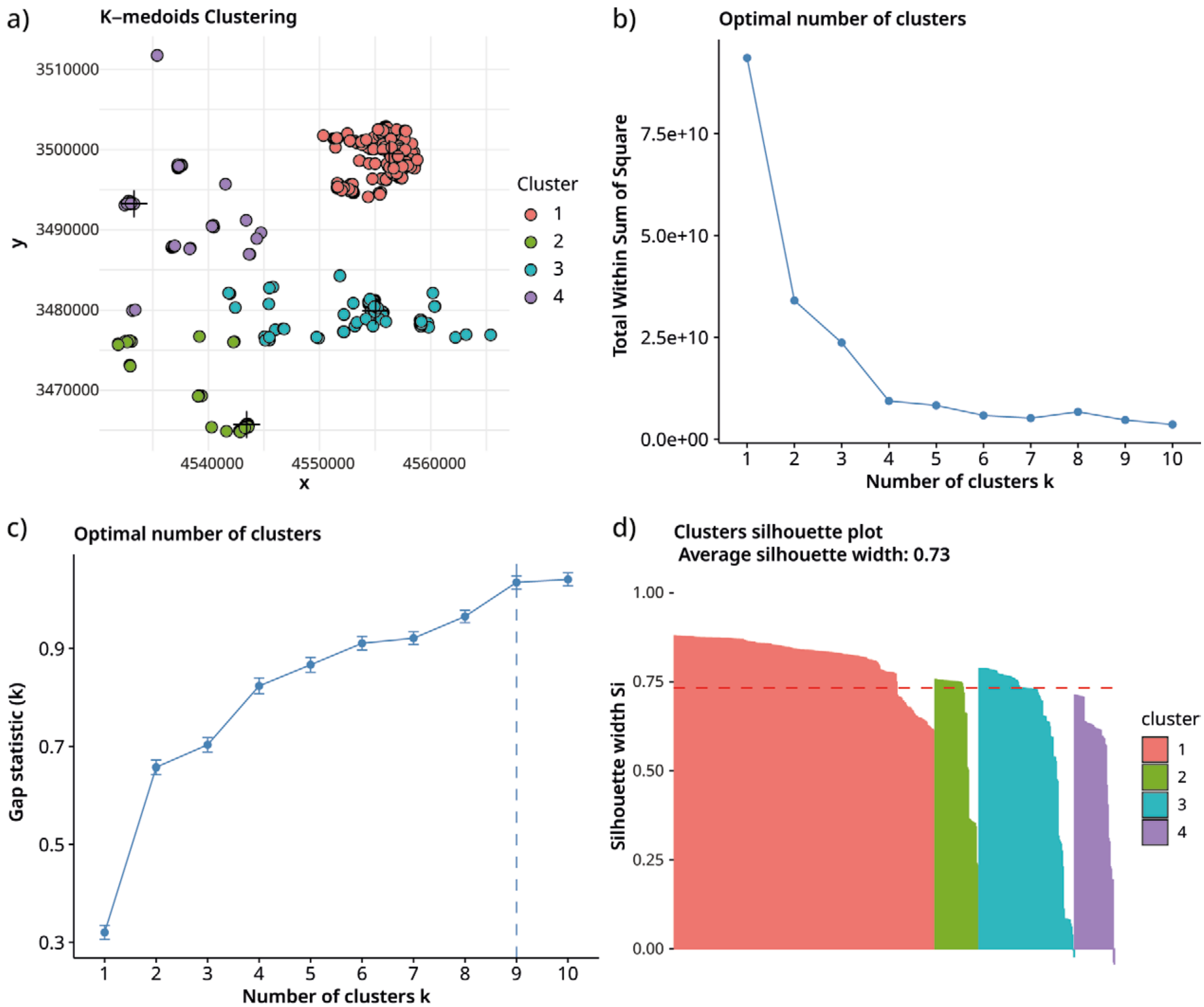


Figure 39. a) An example of K-medoids clustering of Bronze Age burial mounds in Rügen. Note the fact that the centroids are real points; b) Within Sum of Squares (WSS) and c) Gap Statistics methods used to find the optimal number of clusters; d) Silhouette plot to evaluate the goodness of the selected K and membership of each point.

- Real points belonging to the initial data set are chosen as centroids (known as *medoids*);
- Using real points as centroids makes the algorithm more robust to outliers. This is because distances are computed between real points, thus it is less likely that an outlier influences the choice of a centroid;
- It is easier to implement it using different dissimilarity measurements (k-means mostly works with distance).

A downside is that it can be computationally more expensive. The workflow of k-medoids is the same as that of k-means. The only difference is that the initial centroids are randomly sampled from the real data points (Figure 39 a). In R, this method can be implemented using the *pam* function from the *cluster* package (Maechler et al., 2022). Unfortunately, the algorithm does not solve the lack of determinism nor the issues connected to the choice of the initial number of clusters. Similar to k-means, k-medoids can also be implemented using fuzzy logic.

Summary of square error clustering

Square error clustering methods try to minimise the sum of squared distances between data points and their respective cluster centroids. Their popularity mostly relies on their computational efficiency. Their main issue is that they require an initial definition of the optimal number of clusters.

The ideal number of K (clusters) can be assessed using the within sum of squares (WSS). This can be easily performed using the *factoextra* R package and will visualise the variation with the increase of K (Kassambara and Mundt, 2020; Figure 39 b). It is assumed that the optimal number of K occurs when the curve bends making an *elbow*. However, this works only with well-defined clusters and it is difficult to automatise (Conolly and Lake, 2006: 171). Another possible method to estimate the optimal number of K is using *gap statistics*. This method compares the within-cluster data dispersion with that of a null model at varying K. The optimal number of K is identified at the point where the logarithm of the ratio (within-cluster/reference) is maximised, indicating a stronger clustering structure than in the original dataset (Figure 39 c). This can be measured using the *clusGap* function from the *cluster* package (Maechler et al., 2022). Finally, the goodness of membership to a cluster (and ultimately the number of K) can be assessed using the silhouette method (Rousseeuw, 1987; Figure 39 d).

In conclusion, if correctly set up, models based on Square Error clustering can provide insightful results. However, the difficulty in usability on very different dataset, their not ideal handling of outliers and the requirements of prior knowledge of the dataset make them difficult to use for our case studies.

5.3.2.2 Density-based clustering

This family of algorithms defines clusters based on point density, with the assumption that low-density regions separate clusters. Points falling in these lower density regions are treated as outliers (Ezugwu et al., 2022). The fact that they are based on density variation allows the identification of clusters with arbitrary shape. Sometimes this class of clustering functions is called '*natural clusters*' because they are thought to be suitable for case study such as spatial data, or cluster of points in physical space (Kriegel et al., 2011: 232).

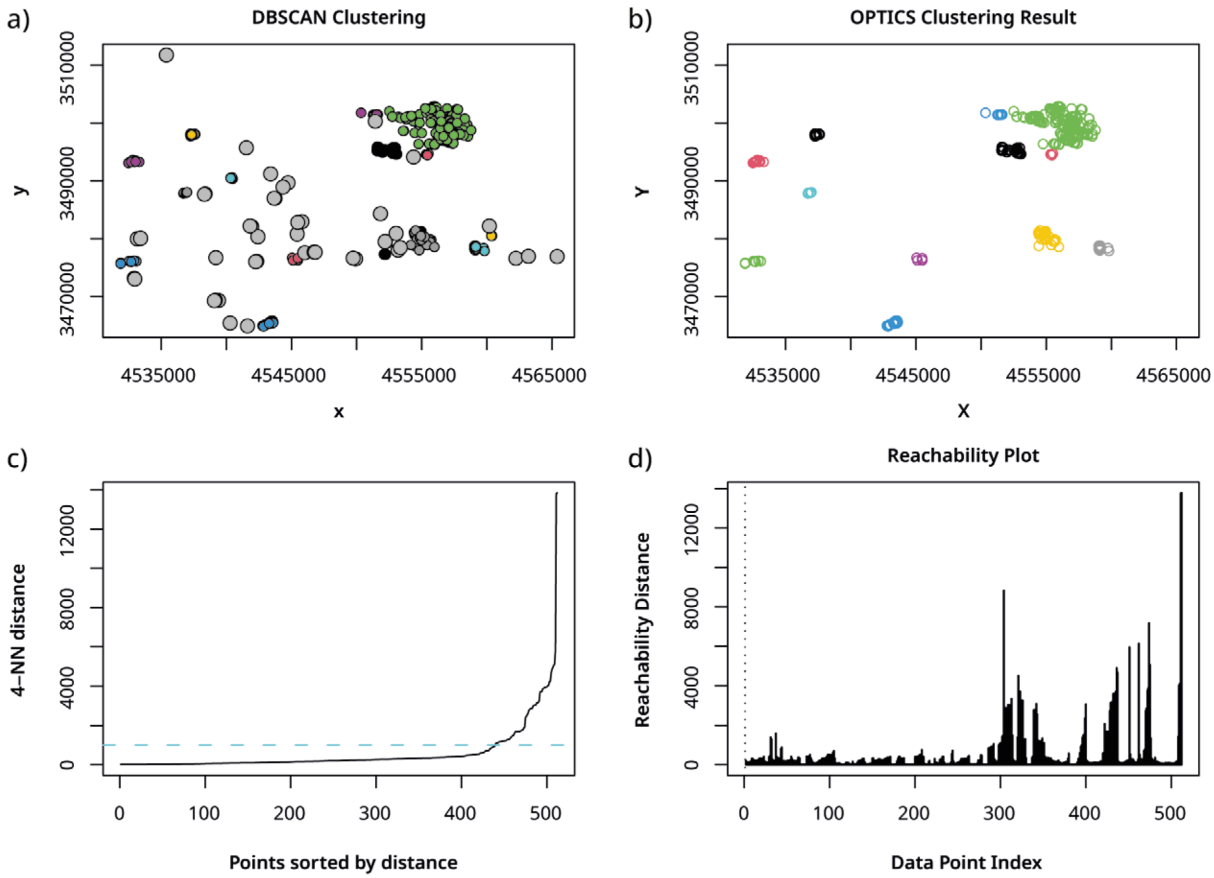
DBSCAN

Density-based spatial clustering of applications with noise, or DBSCAN, is the most popular density-based clustering algorithm. The algorithm requires two parameters: a distance threshold (r or ε) and a minimum number of points in a cluster (*minPts*). In simple terms, it requires parameters defining how far to look for cluster members and what would be the minimum density allowed per cluster (Hahsler et al., 2019).

Each data point is classified as a core point, a border point or *noise* depending on its characteristics. A core point is a point that has > minPts within the defined radius. Border points do not fill the neighbouring argument but they fall within the radius of a core point. Noise points do not fulfil any of the two (Kriegel et al., 2011: 232). When core points are within the distance threshold then they have a direct density connection; a third core point connected to one of the two is then indirect density connected to the second point (Kriegel et al., 2011: 232). A non-core point can be directly connected to any other point but can be density connected if and only if the point to which it is connected is a core point and is density connected to another point. This structure allows for the creation of density-based hulls in the clusters (Kriegel et al., 2011: 232).

A cluster is defined as a group of maximally connected points, each within a distance < ε from at least one core point, although it is possible to introduce the minimum number of core points as a parameter, in which case these clusters become spurious (Kriegel et al., 2011: 232). As in most cases, clusters are computed iteratively. In R, it is possible to calculate density-based clusters using the *dbscan* package and the function *dbscan* (Hahsler et al., 2019).

The optimal cluster density does not need to be manually set, which solves one of the main concerns of DBSCAN. A low number of points in a cluster (2-3) would only integrate noise points and generate unsuitable clusters. A too large threshold, on the



other hand, would make the identification of smaller clusters difficult. Sander and colleagues argued that a '*reasonable* k' should be 1 < k < 10 in a 2-dimensional space (Sander et al., 1998: 182). The optimal number is then defined as $MinNum = k + 1$ with $k = 2 * Number\ of\ Dimensions - 1$. In our case, the number of dimensions is 2 (x, y), thus the optimal minimum number of points should be 4.

Figure 40. An example of a) DBSCAN and b) OPTICS output at 1000 m radius of Bronze Age burial mounds in Rügen; c) 4th Nearest Neigbhour plot; d) Reachability plot. Note that outliers are not plotted in the OPTICS plot.

The optimal radius is more difficult to define, and it works similarly to the way the optimal number of clusters is defined for the square error clustering algorithms (Chapter 5.3.2.1). In this case, we identify the ideal radius when the n^{th} nearest neighbour curve forms a *knee*, with $n = minPts$ (Figure 40 c). Despite this issue DBSCAN is a very useful and powerful tool for cluster analysis, especially when we deal with noise and complex cluster shapes.

OPTICS

One issue of the DBSCAN is the definition of a suitable density thresholds distance. Additionally, DBSCAN struggles with datasets that have clusters of variable densities. In some cases, this problem can be solved using hierarchical clustering but, as will be described here, a more suitable solution is provided by ordering points to identify the clustering structure (OPTICS; Kriegel et al., 2011: 236).

The OPTICS algorithm is based on DBSCAN for the density estimation but it calculates the *reachability* distance at which a point could be added to a cluster provided the number of points is > minPts. The smaller the value of the reachability, the higher the density of points around it. This implementation makes the OPTICS algorithm more a hierarchical clustering, *i.e.* the data is not partitioned but characterised based on their density structure (Kriegel et al., 2011: 236-7). However, instead of a classic dendrogram it is visualised and studied using a reachability plot

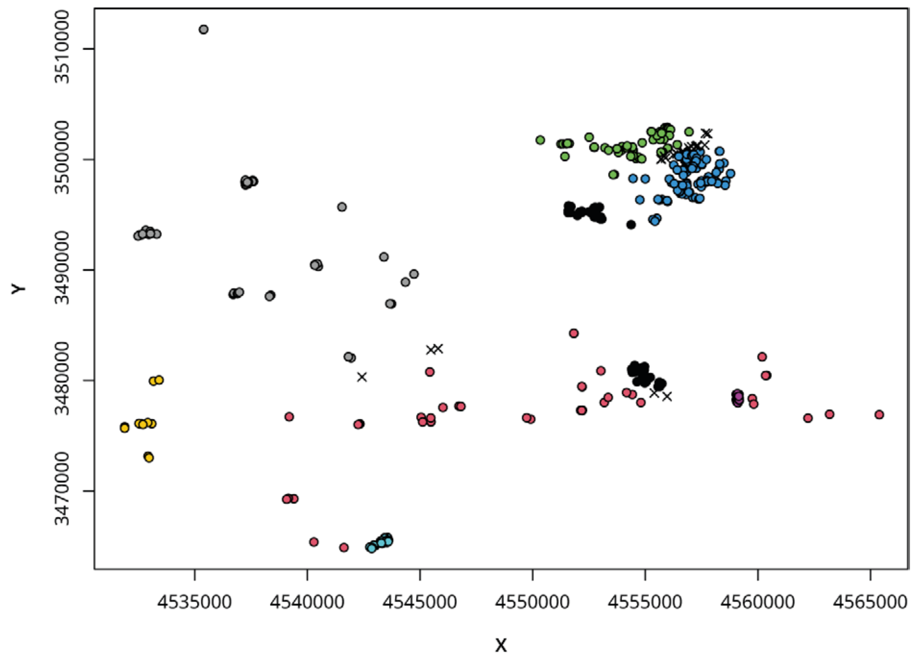


Figure 41. Model-based clustering with > 50% uncertainty. A Gaussian distribution is assumed in this clustering method (Fraley and Raftery, 1998; Scrucca et al., 2016).

(Figure 40 d). Troughs in the reachability plot represent high-density regions and the longer bars correspond to low density areas. The deeper the troughs the higher the density (Kriegel et al., 2011: 237).

The result of the OPTICS algorithm is not an explicit cluster of a data set, but an '*ordering of the database representing its density based clustered structure*' (Ankerst et al., 1999). In other words, OPTICS allows for a very flexible cluster extraction by specifying the desired parameters (minimum density and radius) or setting a threshold on the reachability. This allows one to extract clusters of varying sizes and densities in a very effective and neat way (Ankerst et al., 1999). The noise points would be the ones that have a reachability level above the defined ε.

Compared to DBSCAN it is computationally more expensive as it estimates the reachability at several scales rather than at a specific value. However, with the data used in this study this issue is marginal. In R, it is possible to perform the OPTICS in the *dbscan* package using the *optics* function (Hahsler et al., 2019). As we can see from Figure 40, the results do not differ very much between the two algorithms but in some other instances the differences can be noticeable.

Model-based clustering

This is the last group of clustering algorithms considered here. In this model type, it is assumed that the observed pattern is the result of the probability distribution of the clusters constituting the dataset (Ezugwu et al., 2022: 11). The algorithm tries to estimate the various parameters that constitute the observed pattern and explain the distribution (Ezugwu et al., 2022: 11).

The most common method is the Gaussian Mixture Model (GMM), where it is assumed that the distribution of the clusters is Gaussian (Fraley and Raftery, 1998; Scrucca et al., 2016). The procedure to assign a point to a cluster is similar to the other clustering methods described here and works iteratively, assigning at each step the point to the most likely cluster based on the parameters, until there is convergence. This process, known as the EM (Expectation-Maximization) algorithm, can be computed in R using the *mclust* package (Scrucca et al., 2016).

Its flexibility and ability to handle complex data structures, including outliers, make it particularly useful (Figure 41). In this case, each point is classified in a cluster (sharp/crisp clustering) but it is also assigned an uncertainty, due to the possibility of it belonging to a different cluster or being an outlier. However, there are a number of issues with the approach; convergence can be very slow, especially with poorly defined mixtures and the complexity increases with a high number of components (Scrucca et al., 2016). In addition, it cannot handle clusters with very low numbers of data or if variables are collinear, which cannot be excluded in our case, since we are dealing with bidimensional coordinates. The model can be implemented using Bayesian or Stochastic model selection (Ezugwu et al., 2022; Fraley and Raftery, 1998).

In general, this model works very well but it is probably overcomplicated for the type of data used here, which only have 2 variables (coordinates) and the risk of having very small clusters. For this reason, I opted for the DBSCAN and OPTICS for the final models. Nonetheless, both model- and density-based algorithms perform better compared to square error clustering in terms of flexibility, outlier handling and unsupervised choice of parameters.

6. Results

In this chapter the results of all the analyses are illustrated, divided by type of analysis and case study. In addition, the script used is discussed and presented. For a thorough discussion of the consequences of the presented results, computational issues, and possible solutions, I refer to the last chapter.

6.1 Chronological modelling

The main challenge regarding chronological simulation lies in the accuracy of dating for certain regions. Dating is especially challenging for the German and Swedish case studies due to the structure of their respective databases (see Chapter 3). This necessitates the selection of very specific case studies derived from publications or separate data collection, rather than relying on the original dataset. As previously discussed, this presents significant challenges in integrating data from diverse sources, thereby affecting reproducibility and coding standardisation.

A potential concern arises from the chronological subdivision. While it aligns with the relative chronology from the Late Neolithic to the Bronze Age (2100-500 BCE), with each window corresponding to distinct phases or sub-phases, this is not true for the Younger Neolithic. During this period, the time windows (2900-2700, 2700-2500, 2500-2300 and 2300-2100 BCE) do not precisely match the relative chronology and they overlap with the MN (2900-2800 BCE) and the LN (2200-2100 BCE). Although not inherently problematic, this overlap might introduce additional noise or uncertainty into the model due to the inclusion of sites from potentially different phases. In some cases, notably East Holstein, the Middle Neolithic chronotypology allows for a more precise sequencing than the chronological windows. Therefore, the relative chronology is used for this case study.

6.2 Point pattern analysis

A detailed discussion of the rhohat results is omitted for two reasons. First, the volume of the results is incredibly high, including over 1300 plots, making a comprehensive description impractical. Second, these results have a marginal role in this work, serving as a support in the covariates' selection for the predictive models. For this reason, their description can be found in the Appendix, which is available in the GitLab online repository (https://gitlab.com/bilottigiacomo/pswb-demo-appendix). The code is documented and accessible, and readers are encouraged to recreate the results themselves. Finally, distance from rivers has not been used for Bornholm, as it lacks major rivers.

6.2.1 Point process models

In this paragraph, the focus is on the outcomes of the point process model (PPM). The discussion here centers on the PPM itself, setting aside its implications for demographic analysis, which will be covered in a separate section.

Before describing each case study, some general observations are necessary. Often, especially for consecutive time frames within the same phase, predictive models exhibit many similarities. However, notable variations in peak probability can occur, influenced by factors such as precision in relative chronology (*e.g.* the presence of well-dated artefact typologies), the radiocarbon curve, or a combination of both. These variations are crucial in modelling, as they form the foundation for studying underlying population dynamics. Additionally, the intensity and the direction (positive or negative) of each covariate's impact in the predictive power can vary. As for the rhohats, also in this case the number of plots is very large and only a subset of them is shown here. Nevertheless, the code in the repository enables recreation of every model.

One of the challenges to be dealt with when creating the PPMs was that the functions required for their creation do not support marked planar point patterns ('*marked-ppp*'). In particular, this is the case of the *ppm* function used as the basis to create the final predictive models. Consequently, *ppp* objects representing the probability of each point belonging to a specific time frame were converted into regular *ppp* by duplicating each point according to its probability within each chronology. For example, a site with a 100% probability for a particular 200-year window was represented by 100 points in that period. If the probability was 50%, 50 points would be allocated to that period while the remaining 50 would be assigned to other periods based on their probabilities. Evidently, this process generates a larger dataset, greatly increasing computational times. The final predictive models combined the fitted PPMs, generated using the *predict.ppm* function on each PPM, with the KDE of the sites for each time frame. To minimise potential biases and the impact of site density on the models, I assigned a higher weight to the fitted PPMs than to the KDEs (⅔ to ⅓). Prior to combination, all models were scaled to a 100% maximum, with the highest value representing the peak observed across all time frames in each case study, calculated as follows:

$$(localmax/globalmax) * 100$$

The same scaling procedure was applied to the KDEs. Consequently, the resulting summed models did not sum up to 100%, as this would only occur if the highest site density and predictive intensity coincided in the same time frame and raster cells. However, this discrepancy is not problematic as the value is arbitrary and meant to standardise different time periods for cross-chronological comparisons. This scaling process is not applicable for comparing all study regions due to variations in point process intensities across different areas.

6.2.1.1 Bornholm

The main divide in the results for Bornholm is observed at the onset of the Bronze Age (Figure 42). During the Neolithic there is a generally low predictive intensity, with peaks consistently under 20% of the regional maximum (20.75% for the 2700-2900 BCE time frame) but often even lower. Low predictivity may derive from low-intensity occupation of extended areas (with varying characteristics) or inaccuracy in the choice of the covariates for this case study.

During the 4100-3900 BCE window, areas with slightly higher predicted probabilities are situated along the southern coast, to the north-east and west. A similar pattern persists in the subsequent time frame, with a slight uptick in intensity, likely due to an increased number of simulated sites. The predictive model maintains a similar appearance in the subsequent time windows, with a relative density peak during the 2700-2500 BCE period. However, from this period, central areas of the island start exhibiting a lower predictive probability, with the south-central part of the island returning lower site probability and occupied by fewer simulated sites. The trend of low predictive intensity persists throughout the entire LN period, with most predicted areas concentrated along the coastline, primarily in the south and west (Figure 42).

The Bronze Age marks a notable shift in the models (Figure 42). During the EBA I, the intensity of the predictive model swiftly increases, with the highest probabilities observed in the north-west and the south-south-west of the island. The northern coast also emerges as an important area. It is worth noting that, although many sites are simulated, their predictive probabilities remain generally low, only showing a significant increase in the subsequent time frame (1500-1300 BCE). In the latter period, while the intensity increases, the predicted areas remain mostly unchanged, with a slight uptick in predictivity on the western coast of the island. The situation during the Late Bronze Age sees minimal variation, with the main difference being a decrease in site density in the north-east.

In summary, there appears to be a peak in occupation on Bornholm during the Bronze Age. In this period, Hammeren, located at the north-western tip of the island, seems to emerge as a central hub. This region is the closest to the mainland (Sweden) and held historical significance, as it hosted an important castle during the Middle Ages (Hammerhus). The area likely played a central role in seafaring, serving as a hub connecting the northern and southern shores of the central Baltic. Additionally, there are unique geomorphological features in that area not observed on the rest of the island, including cliffs, caves and rock outcrops. A similar pattern is observed for the south-western coast, consistently showing high probability throughout prehistory, possibly due to its proximity to the southern Baltic shores and, in particular, the island of Rügen.

6.2.1.2 North-western Zealand

Due to urban development in the Copenhagen region and the differential research intensity in the area, the results for Zealand need to be carefully examined and had to be limited to its north-western part (as described in Chapter 3).

At the beginning of the Early Neolithic period, we observe that the predicted sites are predominantly inland, with a higher probability of site locations in the western and central part of the study region. However, the number of simulated sites belonging to this time frame is relatively low. During the following period (3900-3700 BCE), we notice a similar trend, but with higher probability in the predictive model and larger and more intensely predicted areas. There appear to be a clear preference for the western sector, with an expansion towards the coast. The previously less-occupied northern area now has more predicted sites, albeit lower in intensity. This pattern continues during the subsequent periods (3700-3500 BCE and 3500-3300 BCE), although the overall probability of predicted areas is generally lower due to fewer sites being simulated. This could be attributed to the lack of ‘index fossil’ artefacts compared to the EN I.

The model output remains relatively stable during the initial stages of the Middle Neolithic (Figure 43), with the main difference being a higher probability associated with sites from this period, probably linked to higher chronological resolution for some sites and the peak in the radiocarbon curve. However, from 3300-3100 BCE there is a tendency towards decreased probability intensities in the central part of the region, while the eastern inland area remains relatively stable. This decreasing pattern is maintained and reinforced also at the passage between the 3rd and the 2nd millennia BCE.

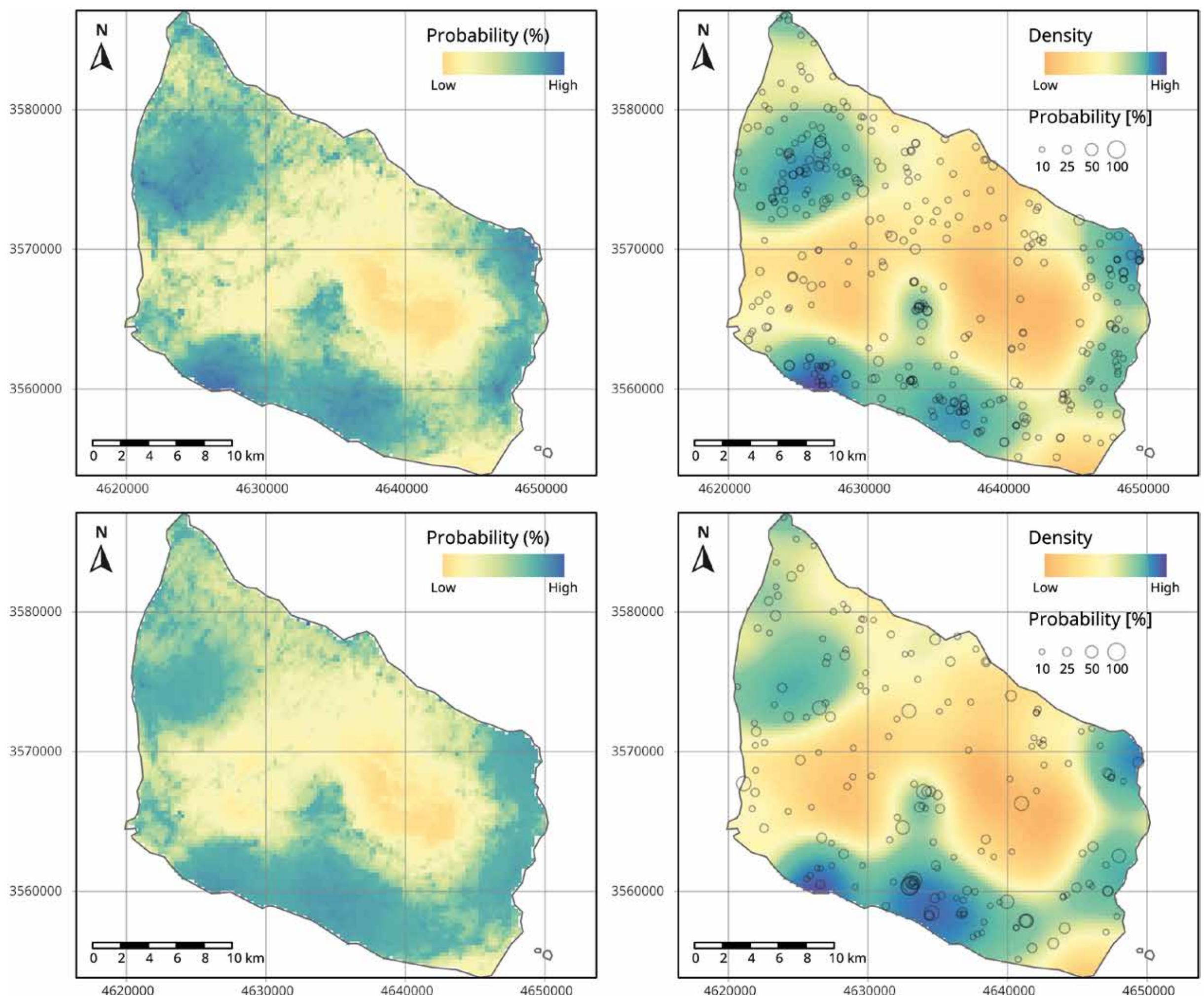


Figure 42a. Results of the point process modelling (left) and KDE (right) for Bornholm at different time frames. From top to bottom: 5450-5250 BP and 4650-4450 BP. See the code and supplementary information for the complete set of results. Sites are plotted over the KDE on the right plots and the size represents the probability of each site of being dated to the chronological window.

In general, we observe that between 3700-3500 BCE and 2700-2500 BCE the step function selects the same covariates for the best fitting predictive model, which could explain the similarity in intensity distribution. Nonetheless, the impact of each single covariate varies in each time window, especially during the last time frame, when a shift towards the coastline, especially in the west, becomes evident (Figure 43).

A significant increase in predicted probability occurs between 2100-1900 BCE, corresponding to a higher number of simulated sites. This may reflect a greater abundance of sites or more distinct artefacts during the Late Neolithic compared to other periods. While there is a slight increase in density in the radiocarbon curve during this period, the trend in the predictive models begins to diverge from it, possibly due to improved relative chronology data. The end of the LN II aligns with the previous time frame, with the same covariates serving as the best predictors for the model (Figure 43).

At the onset of the Bronze Age, important changes are observed in the predictive model. The probability is relatively low compared to the previous period, but higher-intensity areas now appear in the northern part of the region, including the island of Orø. The two westernmost areas around the Kalundborg fjord also show higher density, a pattern only partially observed before 2700 BCE. Between 1500-1300 BCE and 1300-1100 BCE, the predictive map maintains similar areas but with increased intensity, reaching a global peak, likely due to a higher number of well-simulated sites and their improved chronological precision. Between 1100 and 900 BCE, the intensity along the northern shores of the Kalundborg fjord and the south-central

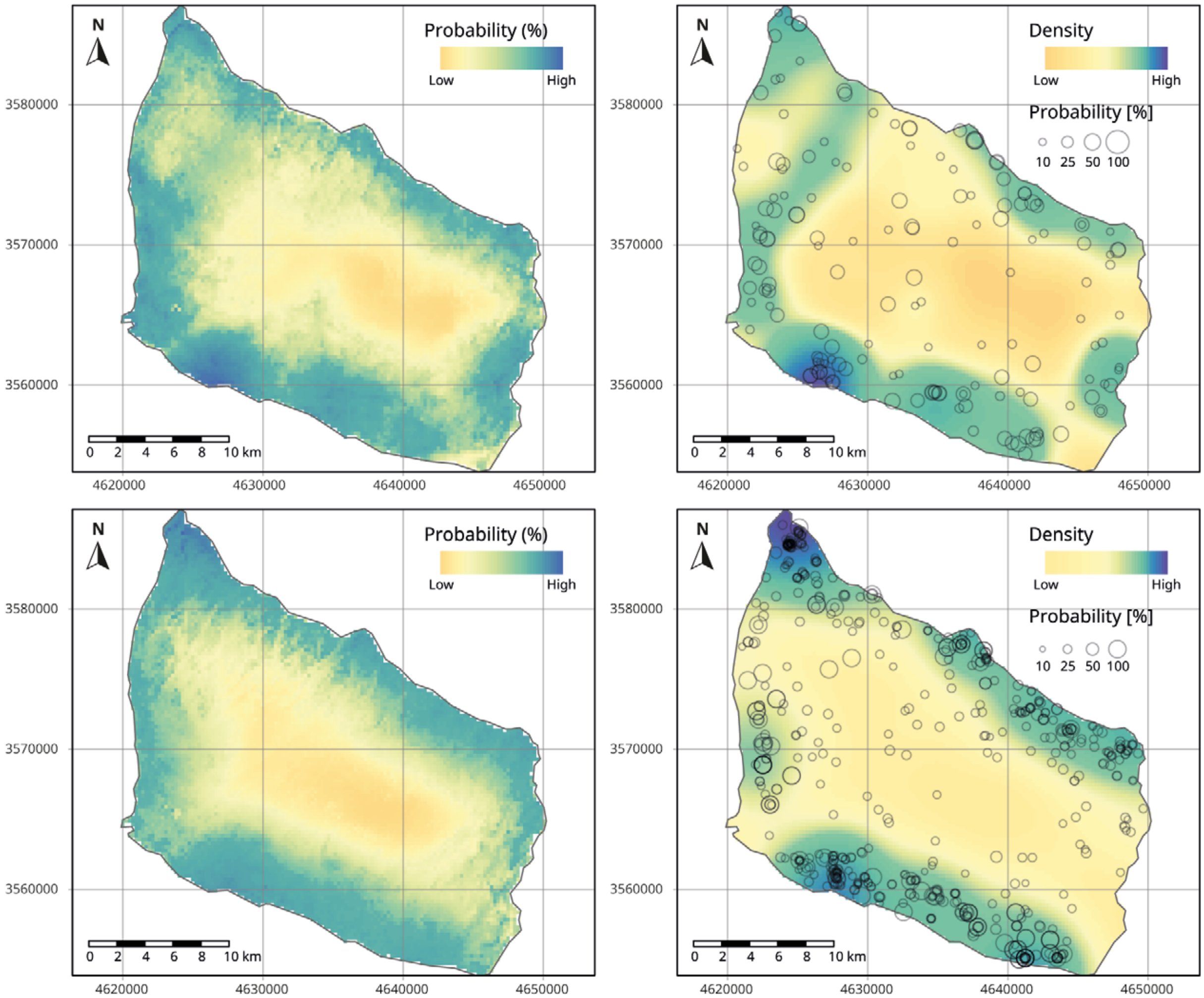


Figure 42b. Results of the point process modelling (left) and KDE (right) for Bornholm at different time frames. From top to bottom: 3850-3650 BP and 3050-2850 BP. See the code and supplementary information for the complete set of results. Sites are plotted over the KDE on the right plots and the size represents the probability of each site of being dated to the chronological window.

part of the Sejerø bay increases (Figure 43). Throughout the later phases of the Late Bronze Age, this pattern persists, but the intensity of the predictive map gradually decreases, possibly due to the lowering of the radiocarbon curve during this period, especially between 700 and 500 BCE.

6.2.1.3 Thy

As previously discussed, the Thy region stands out as one of the most significant areas in northern Europe during the Early and Middle Bronze Age. This prominence is clearly reflected in the model's output, similar to the pattern observed for Bornholm. However, Thy features a larger number of sites, leading to less pronounced differences between the highest and lowest peaks across the simulated time frames. A preliminary examination of the simulated site count, using the 'merged_ppp' object as a proxy (see the script), shows this trend. This analysis can be used as sort of aoristic count of archaeological finds in the area (Figure 44).

A common feature across all predictive models in Thy (Figure 45) is the consistent presence of the highest-density area in each time period, situated to the east (near the town of Ås), just north of the nearest part of Mors Island (Vildsund), facing the Limfjord. The explanation behind this phenomenon could be attributed to its geographical proximity to Mors and its association with the traffic routes through the Limfjord during prehistoric times or the crossing of the fjord. However, it is important to note that in northern Europe, especially during

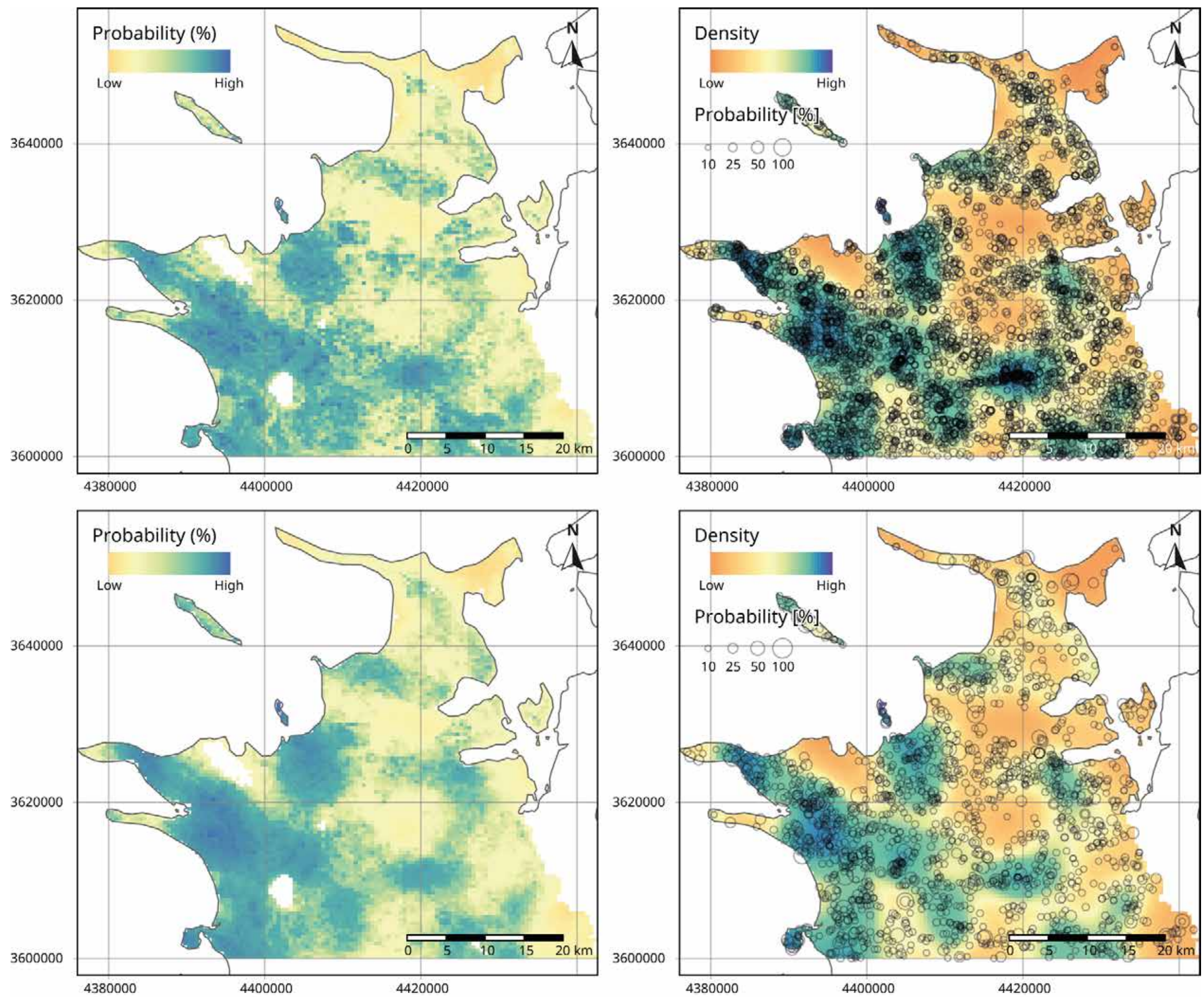


Figure 43a. Results of the point process modelling (left) and KDE (right) for north-western Zealand at different time frames. From top to bottom: 5450-5250 BP and 4650-4450 BP. See the code and supplementary information for the complete set of results. Sites are plotted over the KDE on the right plots and the size represents the probability of each site of being dated to the chronological window.

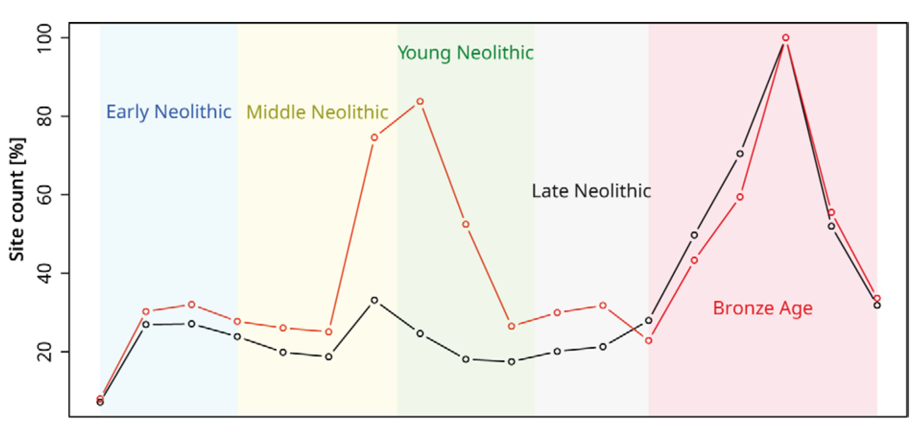


Figure 44. Site count for Thy and Central Jutland expressed in percentage in relation to the highest value. Thy sites are in black, Central Jutland in red.

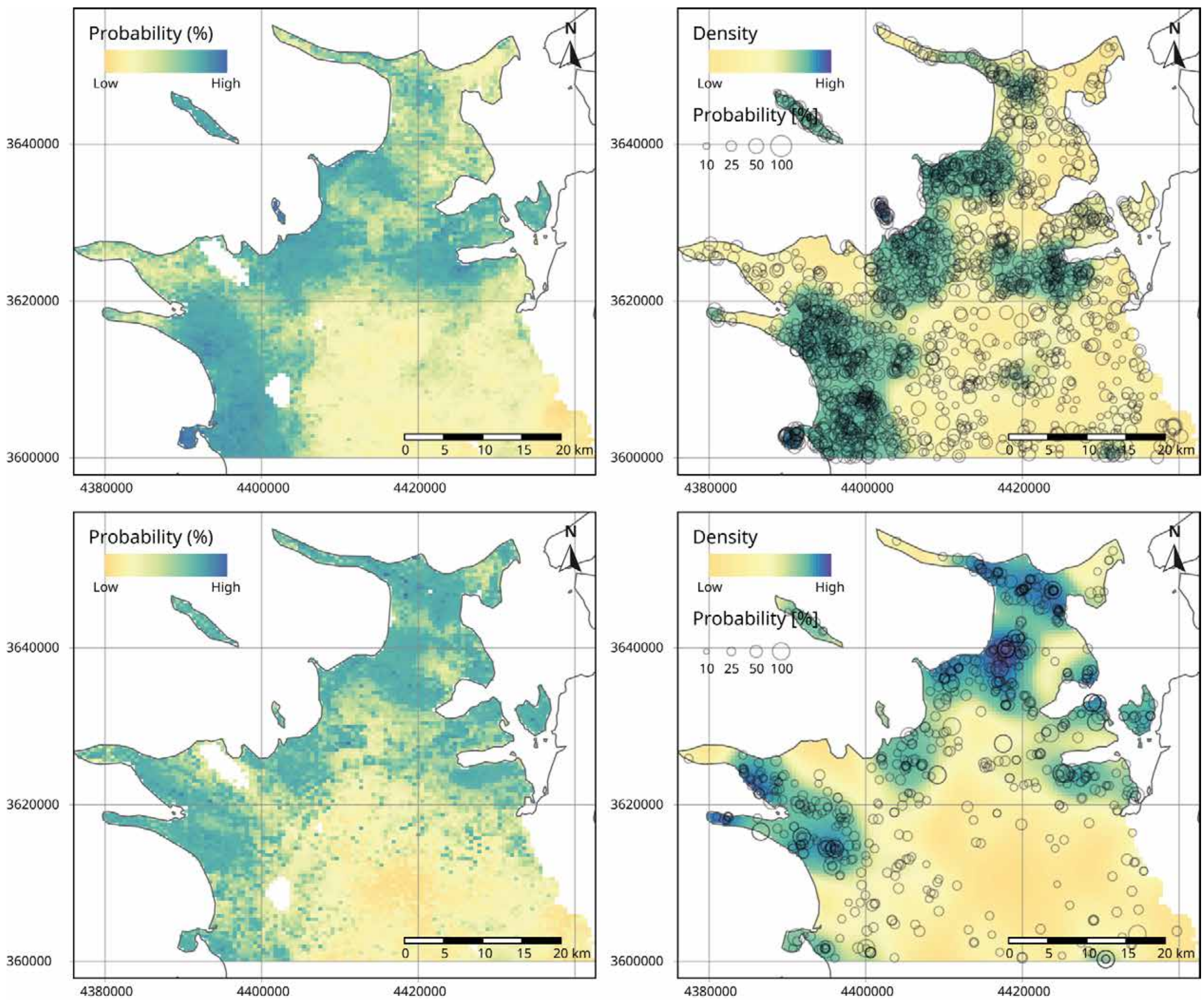


Figure 43b. Results of the point process modelling (left) and KDE (right) for north-western Zealand at different time frames. From top to bottom: 3850-3650 BP and 3050-2850 BP. See the code and supplementary information for the complete set of results. Sites are plotted over the KDE on the right plots and the size represents the probability of each site of being dated to the chronological window.

the Early Holocene, isostatic movements and sea level changes may have had a significant impact, especially in regions characterised by low elevations (the highest point in Thy is *ca.* 88 m asl). Furthermore, the proximity of this area to Thisted, the main urban centre in the region, may have led to its overrepresentation in the archaeological record.

In the first time window, aside from the aforementioned high-density area, the model exhibits relatively low intensity, with some predicted areas to the south and towards the west, but notably absent along the west coast, a trend consistent throughout the chronological focus. During the subsequent time frame (3900-3700 BCE), the predictive model displays a similar pattern but with slightly smoother contours, possibly due to a larger number of simulated sites. The central and eastern areas are characterised by higher prediction probabilities. Minimal changes are observed in the models for the remainder of the Early Neolithic period.

At the onset of the Middle Neolithic, a slight increase in probability is noticed in the central area, to the north-west of the high-probability region (Figure 45). During the transition from the Middle Neolithic to the Younger Neolithic (2900-2700 BCE), there is an increase in site density in the central and southern areas. In the following time frame, global probability slightly drops, with the predictive model showing a higher intensity towards the south and south-central areas, with a decrease in predicted sites to the north. Within the 2500-2300 BCE window, this pattern persists, but the predicted areas now have a higher probability. The main area shifts slightly southward, nearing the tip of Mors Island, strategically positioned at the narrowest

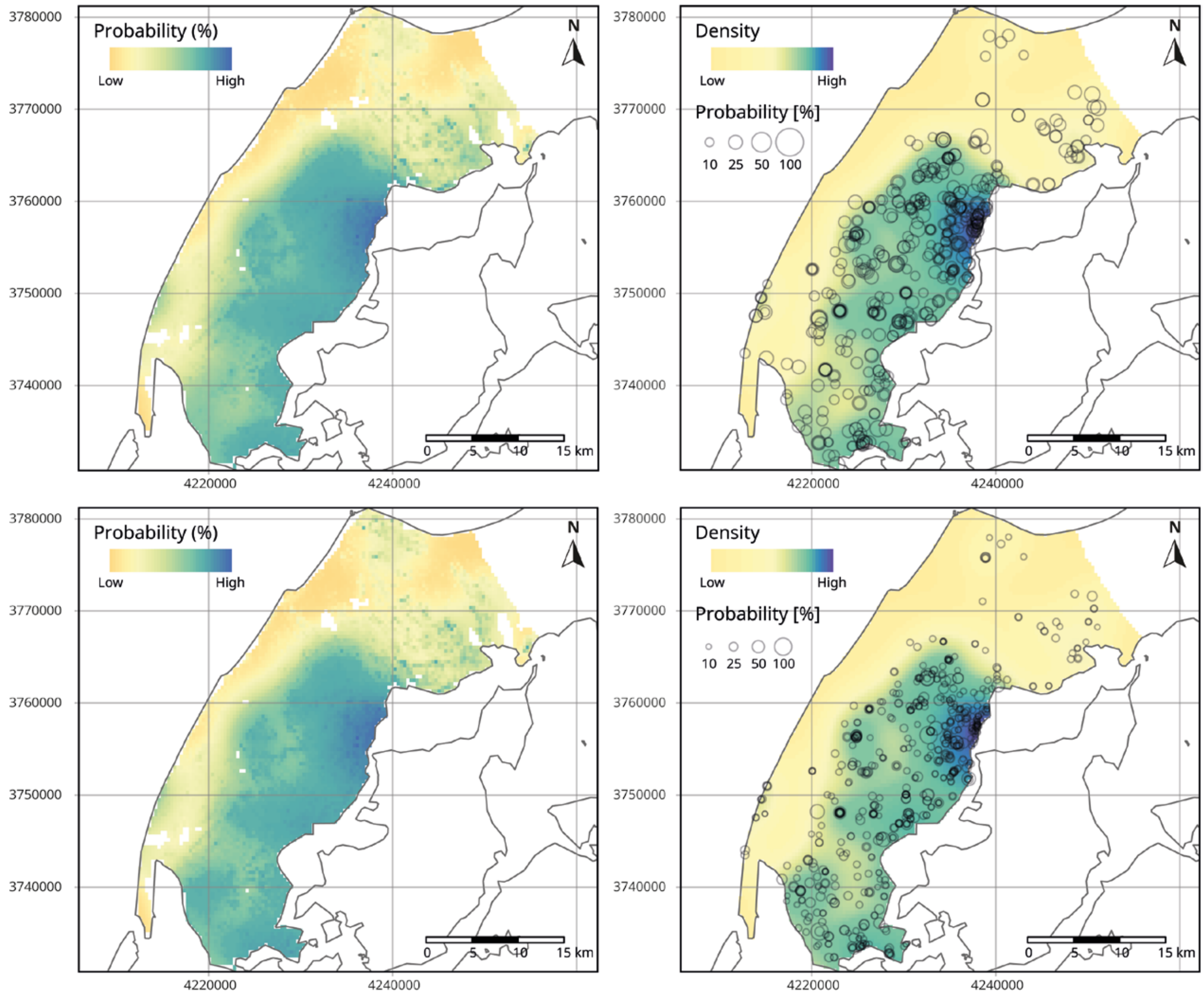


Figure 45a. Results of the Point Process Modelling (left) and KDE (right) for Thy at different time frames. From top to bottom: 5450-5250 BP and 4650-4450 BP. See the code and supplementary information for the complete set of results. Sites are plotted over the KDE on the right plots and the size represents the probability of each site of being dated to the chronological window.

crossing point of the Limfjord. During the Late Neolithic, the situation remains consistent, with a further decline in maximum probability to the global minimum (approximately 15%), aligning with a notable dip in the radiocarbon curve for middle and northern Jutland. Throughout the Neolithic, we observe one or two additional areas with higher site density, the first located just to the south-west of the higher density region and the second farther south. The latter is not always well-represented in the models (Figure 45).

During the Bronze Age (Figure 45), the predictive models exhibit an increase in probability values, possibly attributed to the rise in the total number of sites, higher chronological precision and an increase in radiocarbon density. However, this increase is gradual, with the EBA I not significantly exceeding the earlier periods but roughly doubling its maximum probability compared to the LN. The central and eastern regions remain the areas with the highest probability, with additional high-probability areas predicted to the south, south-east, and, for the first time, to the north and north-west. The primary probability area shifts slightly northward and expands concentrically. Aside from the aforementioned increase in probability, the EBA II pattern resembles the previous period. In the EBA III, we observe an expansion of the highest probability area to include central Thy. Other areas with relatively high probability are noted to the north and north-east, potentially indicating an expansion in site occupation. During the LBA IV, the peak in probability intensity is reached, but without noticeable changes in the pattern, besides a more evident north-south division in the predicted areas. For the remainder of the Bronze Age, there are no

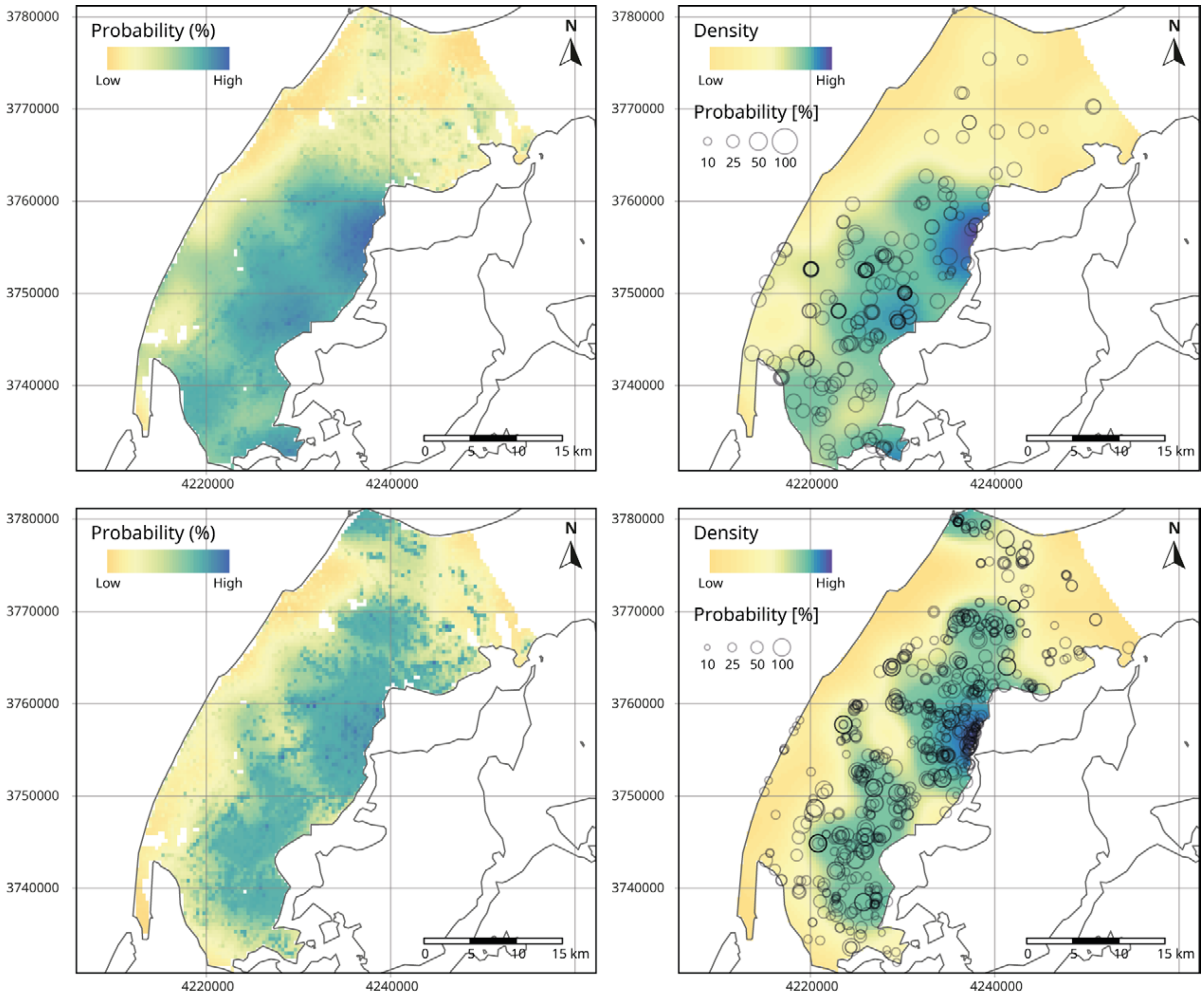


Figure 45b. Results of the point process modelling (left) and KDE (right) for Thy at different time frames. From top to bottom: 3850-3650 BP and 3050-2850 BP. See the code and supplementary information for the complete set of results. Sites are plotted over the KDE on the right plots and the size represents the probability of each site of being dated to the chronological window.

substantial pattern variations, but there is a decline in probability, likely linked to the decrease in the radiocarbon curve, which is, however, countered by the higher number of relatively dated sites.

6.2.1.4 Central Jutland

The first time frame in Central Jutland exhibits a notably lower number of sites when compared to the other periods, similar to Thy, the closest region analysed here (Figure 44). There is a minor uptick in site numbers following the onset of the EN, followed by a slight decline in the early MN. Nevertheless, Central Jutland experiences a significant increase in site occupation during the 2900-2500 BCE period, followed by a rapid drop in site numbers between 2300 and 2100 BCE. From the LN onward, the pattern closely resembles that of Thy, with the peak in simulated site count observed during the Bronze Age's Period IV.

Throughout the Neolithic period, the predictive model for the region is largely unchanged in terms of predicted areas (Figure 46). However, the intensity of the probability does vary and, in some cases, the individual regions scoring the highest probability within the model. This variability occurs despite the fact that the covariates selected by the step function in the point process model creation are not constant over time. During the EN period, higher probability is observed in the following areas: Fur island (with the highest score), the two shores at the mouth of the Hjarbæk Fjord, the area south of the Lysen Bredning, a secondary fjord or bay

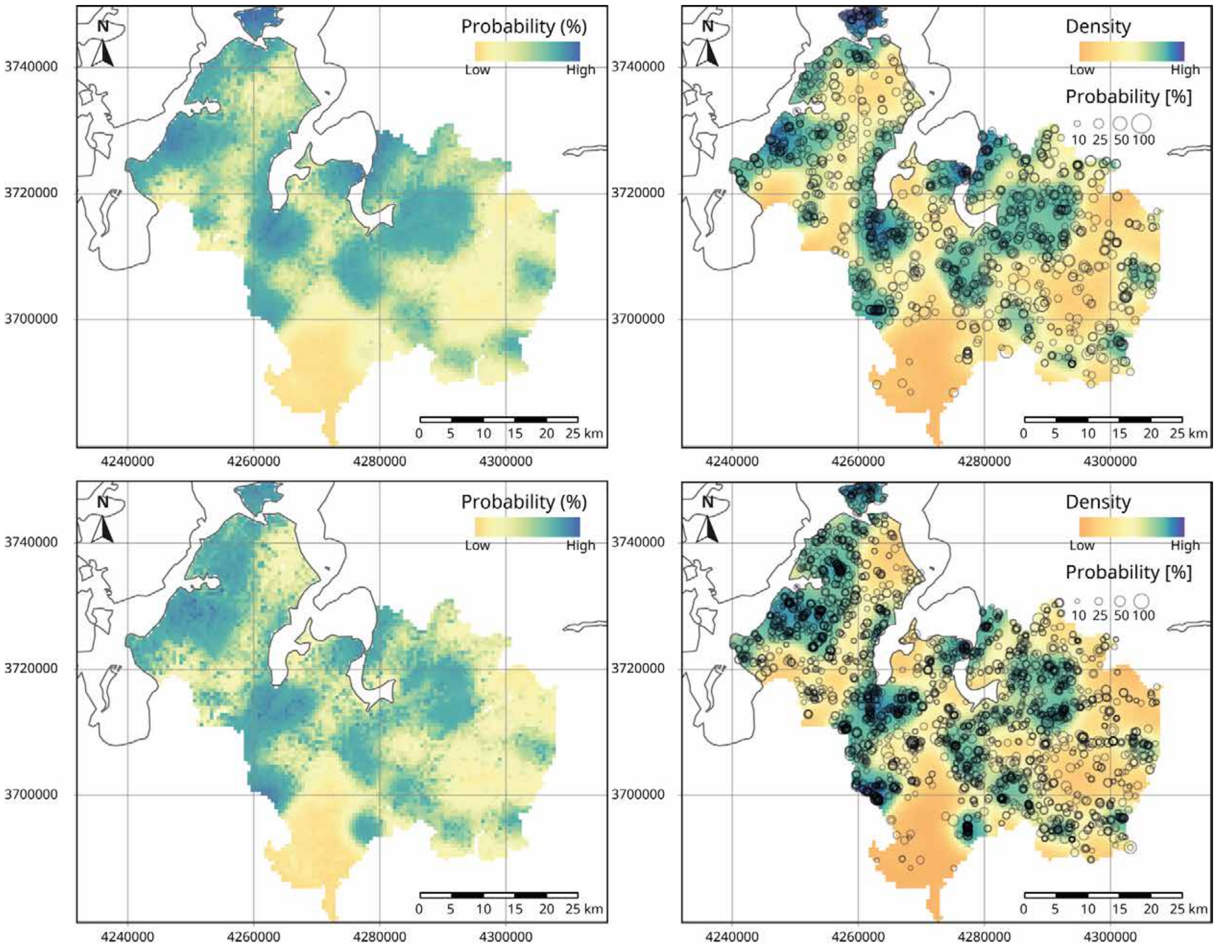


Figure 46a. Results of the point process modelling (left) and KDE (right) for central Jutland at different time frames. From top to bottom: 5450-5250 BP and 4650-4450 BP. See the code and supplementary information for the complete set of results. Sites are plotted over the KDE on the right plots and the size represents the probability of each site of being dated to the chronological window.

situated in front of the closest passage to Mors Island and the end of the Skive Fjord. Additionally, there are regions with higher site density, such as the north-west and central east areas, albeit peak site density during the EN remains relatively low (23% between 3900 and 3700 BCE).

Between 2900 and 2700 BCE, the primary focus shifts toward the southern part of the Lysen Bredning, the end of the Skive Fjord and the south-western edge of the study area. The central-eastern and south-eastern parts of the region also exhibit higher site density compared to earlier periods. This is the period of the MN-YN simulated site count peak (Figure 44), which declines again during the 2300-2100 BCE period. In this phase, areas with the highest probability include the mouth of the Hjarbæk Fjord, the north-western coast along the Salling Sund (the closest point to Mors) and Fur island.

During the Bronze Age (Figure 46), a clear division emerges between the north-west and south-east, with the highest site density concentrated along the Limfjord coastline facing Mors. Although some regions in the west show higher probability areas, this pattern remains relatively consistent until the EBA III. In the LBA IV, the central part of the study region gains prominence, with the southern coast of the Hjarbæk Fjord becoming the densest area and expanded inland to the south and south-east. The north-western region remains a significant hub, particularly the area between the Skive and Hjarbæk fjords. This period registers the highest probability in the models (84%). Subsequent periods of the Late Bronze Age maintain a similar pattern but with progressively lower probabilities.

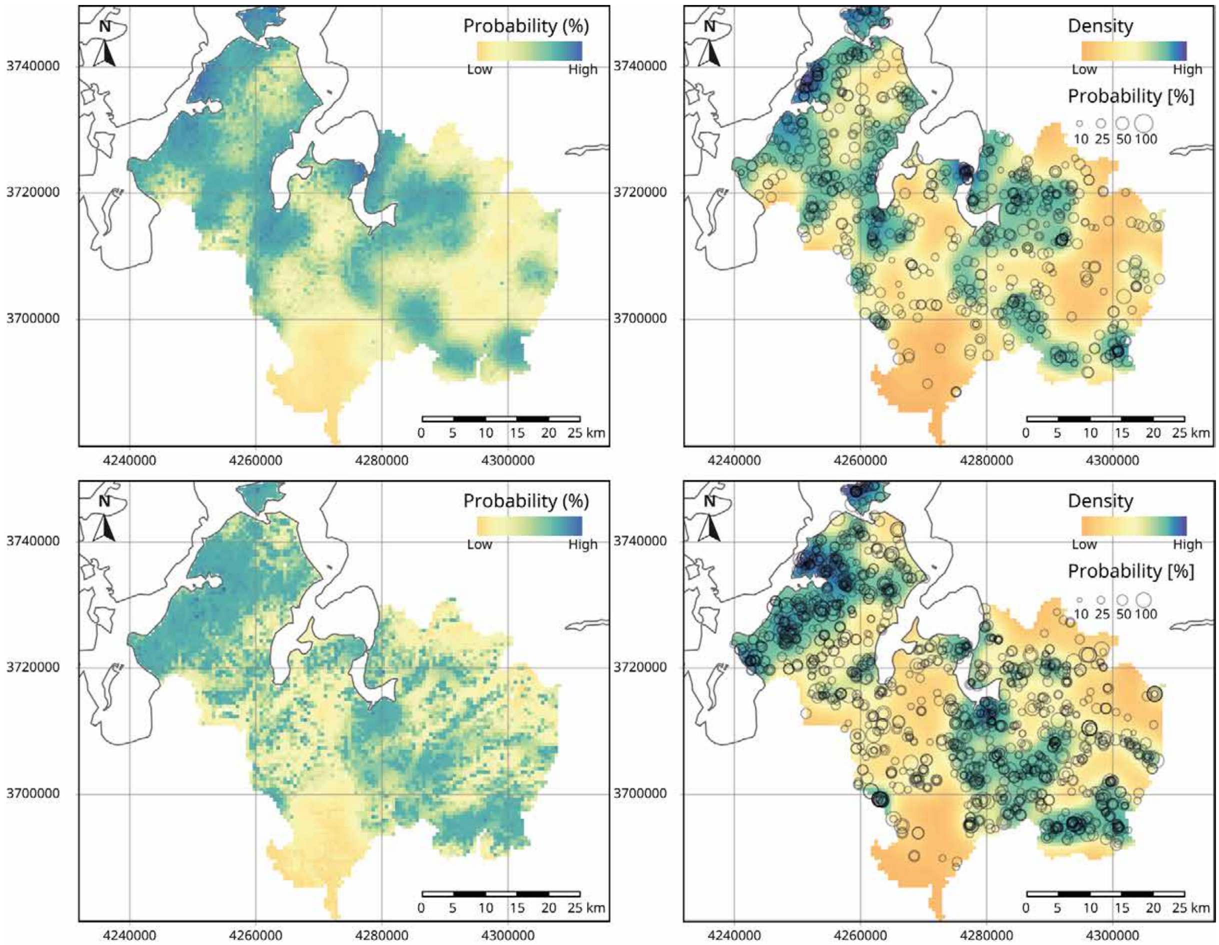


Figure 46b. Results of the point process modelling (left) and KDE (right) for central Jutland at different time frames. From top to bottom: 3850-3650 BP and 3050-2850 BP. See the code and supplementary information for the complete set of results. Sites are plotted over the KDE on the right plots and the size represents the probability of each site of being dated to the chronological window.

6.2.1.5 East Holstein

In the case of East Holstein, the point process model and the resulting predictive model followed a more traditional approach (Figure 47). Sites in this region were not simulated and the models are solely based on the relative chronology. It is worth noting that due to the relatively limited number of sites in East Holstein (less than 200), compared to the simulations (thousands or tens of thousands of sites), the step function had a more significant role in selecting the covariates.

Within the MN period, the number of sites in East Holstein does not exhibit substantial variation. The difference between the period with the most sites and the period with the fewest sites is approximately 20% (MN III – IV and MN I). In all cases, the area with the highest predictive probability is located in the north-western part of the study region, to the west of the Weißenhäuser Brök at the mouth of the Oldenburger Graben.

During the MN I, other regions with high site density include the area between the Weißenhäuser Brök and Oldenburg in Holstein, as well as the eastern coast near the other end of the Oldenburger Graben (Figure 47). In the MN II, the situation is mostly similar, but with a noticeable increase in density observed along the northern coastline and in the north-easternmost part of East Holstein, facing the island of Fehmarn. This region may represent a point of contact between this part of northern Germany and the Danish Isles, via Fehmarn and Lolland. Conversely, the area between the Graben and this north-eastern region, as well as the western part of the area, exhibits very low predictive power. The southern coast also has higher site probability (Figure 47). This

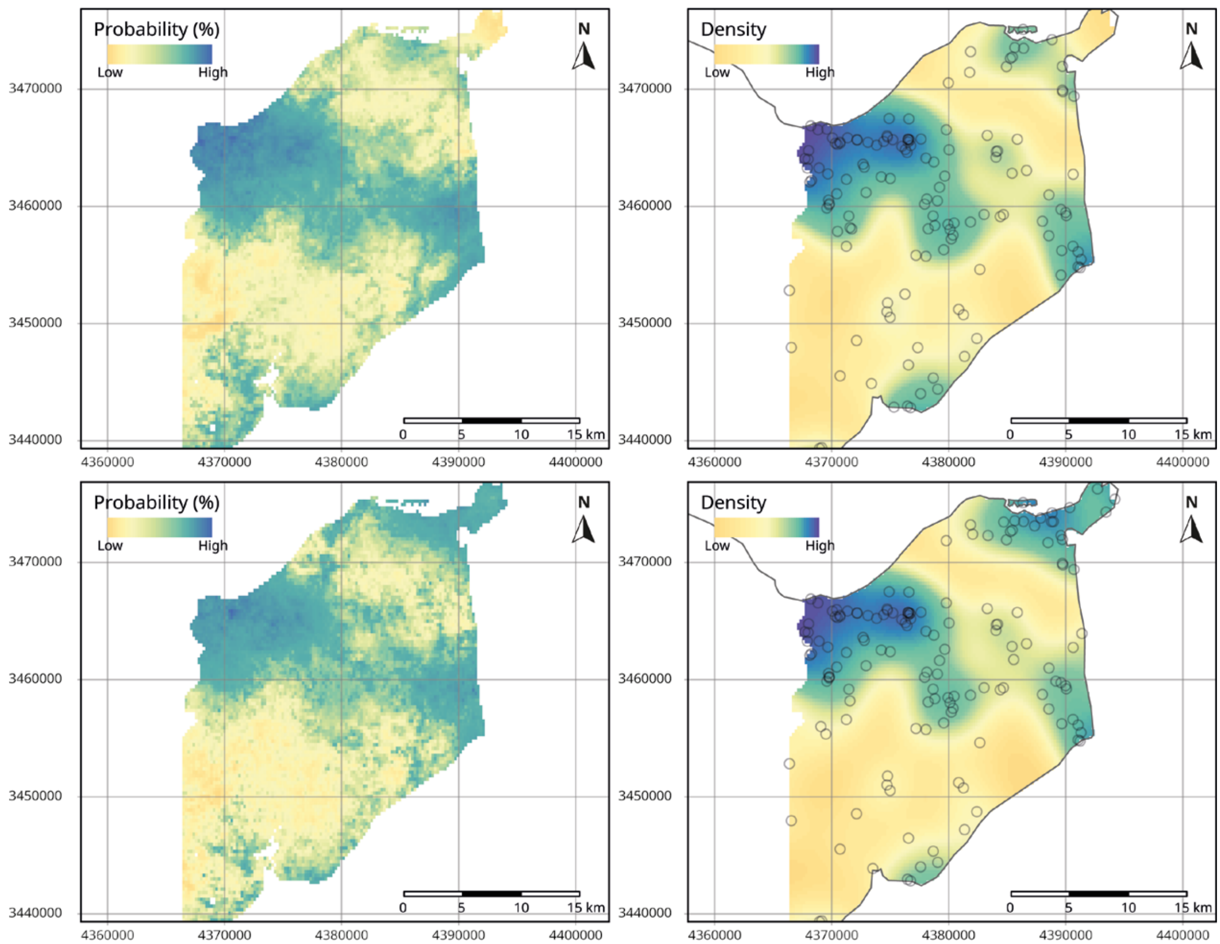


Figure 47a. Results of the point process modelling (left) and KDE (right) for eastern Holstein during the MN I (top) and MN II (bottom). Sites are plotted over the KDE on the right plots.

pattern persists during the subsequent MNIII – IV time frame, with the primary cluster shifting slightly to the east compared to previous periods (Figure 47).

However, in the following and final time frame, this pattern changes. Besides the high-density areas at the two ends of the Oldenburger Graben, the northern coast gains an even higher probability (Figure 47).

6.3 Cluster analysis

In this section, the results of the cluster analysis are described for each case study. Besides the five regions already presented, for this period also the Swedish and the other German regions are presented. The majority of monuments used cannot be precisely dated to specific sub-phases and are typically associated with entire periods. Nevertheless, when possible, a higher chronological precision has been already achieved with the predictive modelling previously presented.

6.3.1 Bornholm

During the Funnel Beaker period, megalithic graves in Bornholm (n = 71) are generally located along the coastline, with the majority to the south, in line with the results of the predictive model described earlier. The best reachability threshold from the OPTICS algorithm in this period seems to be between 3.5 and 4 km. In both cases, there are 6 identified clusters, with the only difference being the

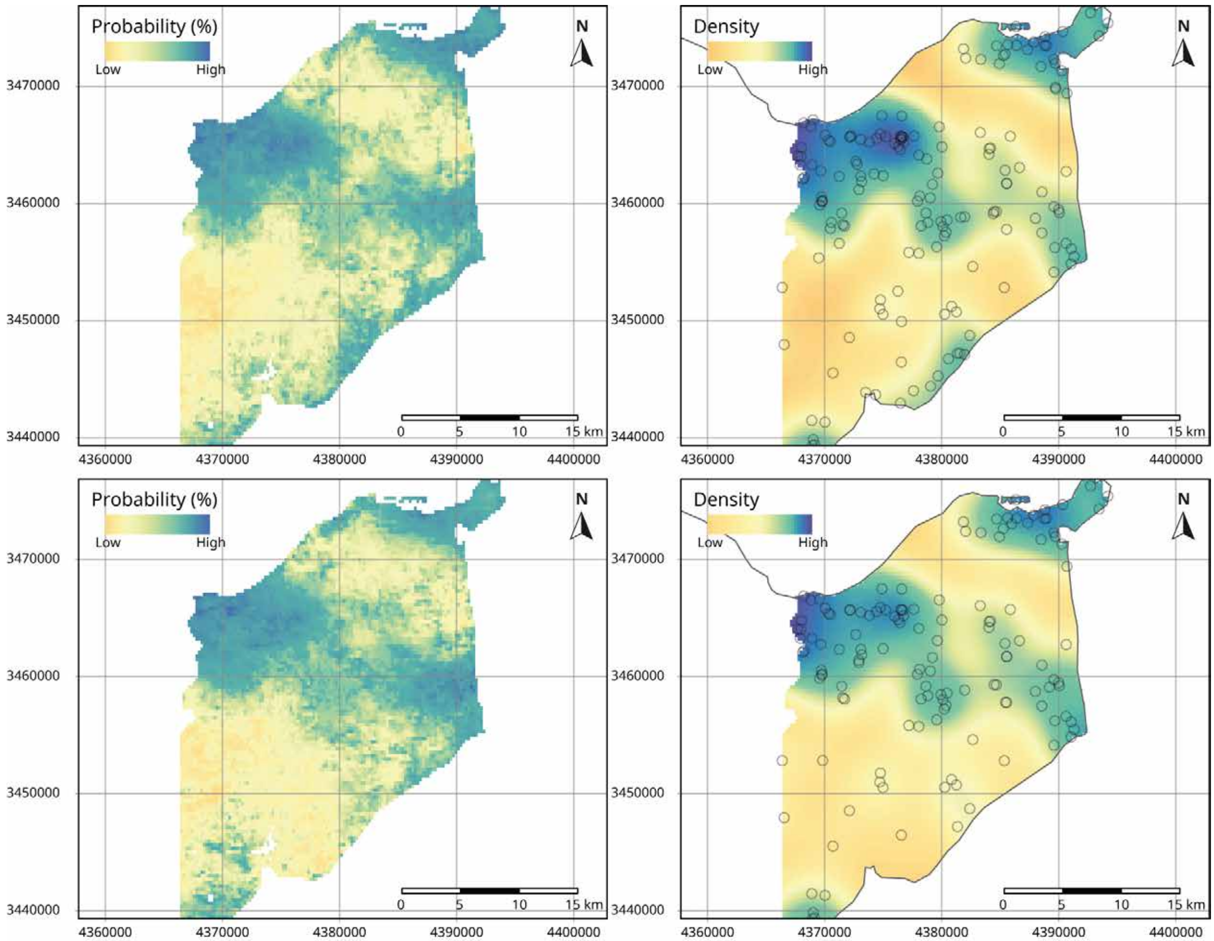


Figure 47b. Results of the point process modelling (left) and KDE (right) for eastern Holstein during the MN III - IV (top) and MN V (bottom). Sites are plotted over the KDE on the right plots.

handling of a few possible noise points (11 or 6). As these points look rather isolated, the 3.5 km can be taken as an appropriate threshold (Figure 48 a). During the Bronze Age, an epsilon value above 2.5-3 km results in a cluster containing all sites (n = 493). Compared to the previous period this depends on the larger number of sites, a more widespread diffusion of sites (although still mostly within short distance from the coastline) and, in general, the small size of the island. For this period, a reachability of 2 km results in 7 clusters, with two very large ones, including all monuments along the northern and southern coast respectively (Figure 48 b).

6.3.2 North-western Zealand

The number of Neolithic monuments in Zealand is very high, reaching one of the highest concentrations of monuments in northern Europe. In the north-western part of the island there are 1542 monuments, with a density of *ca.* 8.89 sites/km^2, higher than any other region included in this study. This is reflected in the cluster analysis results, with a very large number of clusters at small radii (82 at eps = 1 km). An appropriate reachability threshold appears to be between 1.5 and 2 km, with 43 and 19 clusters and 82 and 39 noise points respectively. At a 2.5 km radius, all sites located in the western part are assigned to the same cluster. Due to the lower number of noise points and clusters, a 2 km radius was chosen (Figure 48 c).

The situation during the Bronze Age is very different, with the number of sites dropping to a very low value (n = 360). The distribution of the sites themselves reflects what has been described for the predictive models, with most sites located along or near the coastline. The direct consequence of the lower site density is the increase in the optimal reachability distance. For this period, it could be set between 3 and 3.5 km. In this case, the 3.5 km threshold seems more suitable, as it reduces the noise and returns some clusters also for the inner area (Figure 48 d). However, the main consequence is that the clusters in the Odsherred peninsula are no longer separated, as those around the Kalundborg fjord. This differentiation may have a socio-political or at least cultural character. However, in terms of modelling palaeodemography this choice does not affect the final results. The difference in optimal epsilon between the different periods is also an indicator, if not demographically, then structurally, possibly indicating a more structured occupation of the landscape during the TRB period.

6.3.3 Thy

The structure of TRB monuments in Thy exhibits a particular structure, where both low and high epsilon values (1 and 3 km) tend to obscure many of the underlying patterns. Consequently, a significant portion of sites are either labelled as noise or grouped into a single cluster, reducing the possibilities of identifying internal variations. The main cluster located along the eastern coast shows a high degree of internal integration (already at 2.5 km), while the number of sites (n = 274) in the area or their distribution is not creating a well-defined structure akin to what can be observed in Zealand. For Thy, the optimal epsilon during this period is 2 km (Figure 48 e).

A comparable situation is observed during the Bronze Age, where an even lower threshold is necessary to integrate the majority of sites into a single pattern. In this period, the optimal reachability value falls between 1.5 and 2 km. The difference between the two clustering radii mirrors what was previously noted for Zealand, where some of the smaller clusters either merge together or become incorporated into one of the main clusters. In both instances, the principal clusters are situated in the east-central and southern region, although the largest one varies depending on the radius chosen (at 2 km, the southern clusters merge and form the largest cluster). However, the 2 km threshold has fewer noise points in the clusters and is therefore preferred here. This configuration aligns closely with the patterns observed in the predictive models (Figure 48 f).

6.3.4 Central Jutland

The number of sites in this area is comparable to that in northern Zealand (n = 1297), with a density of approximately 6.13 sites/km^2. While the sites are distributed relatively evenly throughout the entire region, the highest concentration is located to the west, in the Salling peninsula. On the other hand, the southern and eastern parts of the area have fewer Neolithic monuments. At a threshold of 2.5 km most of the sites are aggregated into a single cluster (n = 1122). At a reachability of 1.5 km, the number of clusters becomes very high (n = 64), but with the Salling peninsula already standing out as a nearly unified cluster (with 5 additional small clusters to the south and north-east). However, the number of noise points is high and a threshold of 2 km seems more appropriate, considerably reducing their number (Figure 49 a).

During the Bronze Age, the number of monuments is significantly lower (n = 307). Yet, akin to the Neolithic period, the highest concentration of sites remains in the Salling peninsula. At a reachability threshold of 2 km, the sites within the peninsula are organised in several clusters, indicating a well-structured landscape in that area. On the other hand, the sites located to the east and central regions of the study area do not exhibit the same

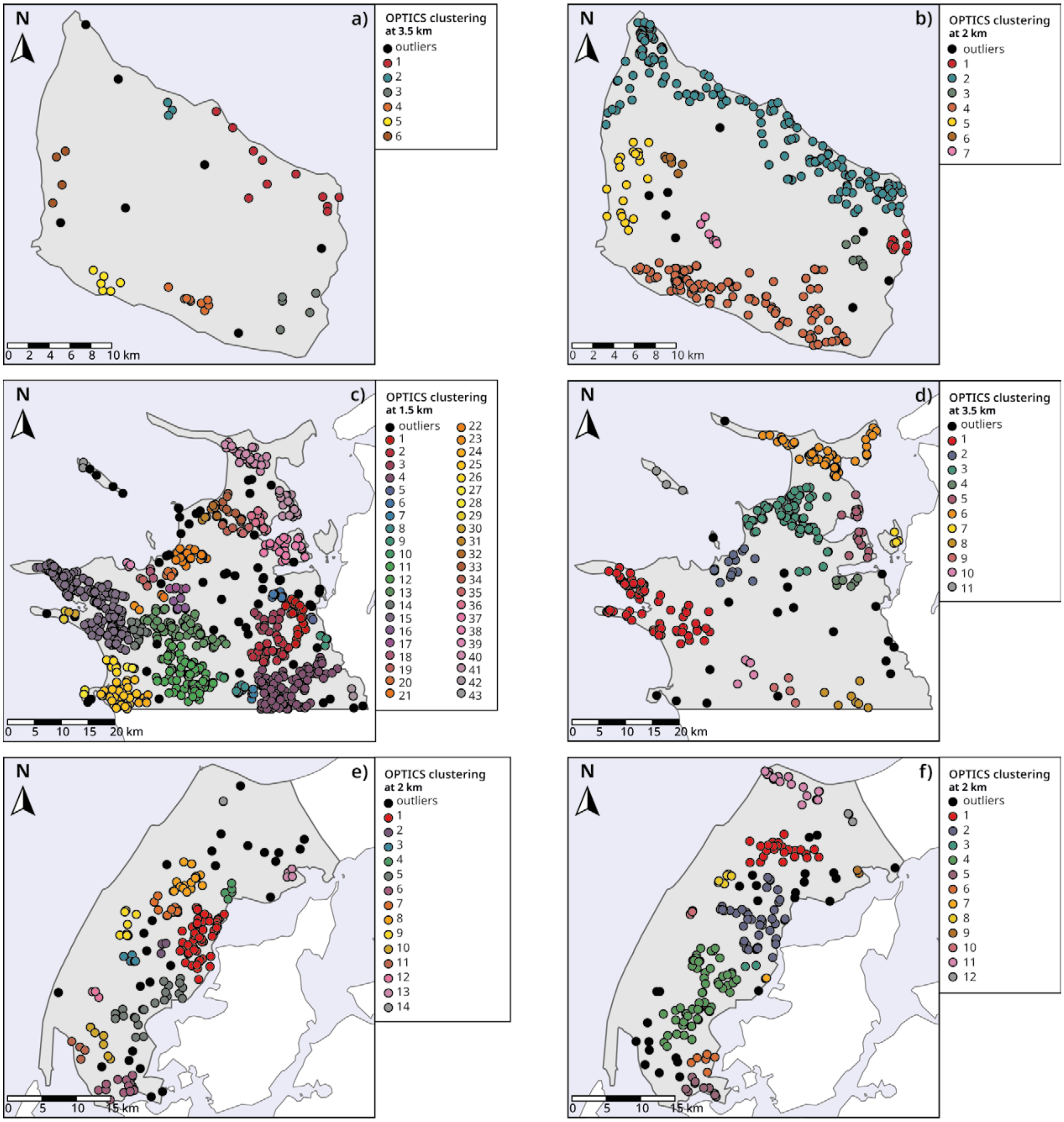


Figure 48. OPTICS (ordering points to identify the clustering structure) algorithm results for Bornholm (a, b), north-western Zealand (c, d) and Thy (e, f) during the Neolithic and the Bronze Age. Only the results for the optimal Eps values are shown.

level of integration. Therefore, the most appropriate radius when considering the entire region appears to be at 3.5 km. At this threshold, 19 noise points and 15 clusters are observed, two of which are located within the Salling peninsula (Figure 49 b).

6.3.5 East Holstein

For eastern Holstein, only the Middle Neolithic period was modelled and the graves are derived from Brozio (2016). The number of graves in the area is relatively low (n = 39), as is the number of possible clusters identified at different reachability thresholds (up to 3). This limited sample size can introduce potential limitations regarding the reliability of the output, and it is a factor that should be considered. Additionally, site number and organisation influence the choice of the optimal threshold, which for the case study is around 4.5 km. Values lower than this threshold

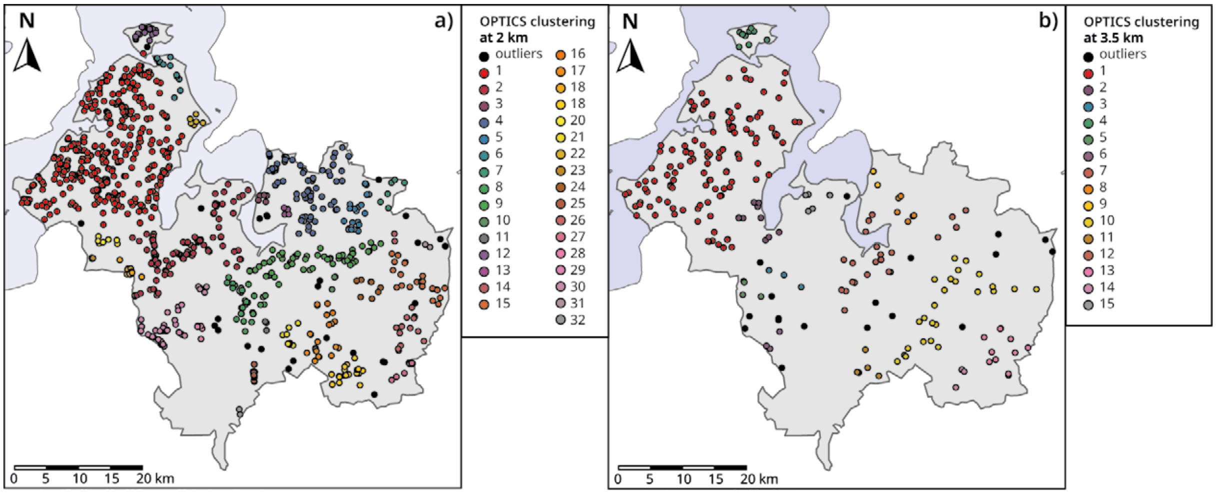


Figure 49. OPTICS (ordering points to identify the clustering structure) algorithm results for central Jutland during the Neolithic and the Bronze Age. Only the results for the optimal Eps values are shown.

tend to generate smaller and isolated clusters, with a large number of noise points. At a 4.5 km threshold, 3 clusters are observed, with 5 noise points. These clusters align with the high intensity areas identified in the predictive model. In particular, the largest cluster is situated to the west of the Weißenhäuser Brök, while the others are located along the Oldenburger Graben and on the peninsula facing Fehmarn and the Fehmarnsund (Figure 50).

6.3.6 Rügen

The most evident feature of the megaliths in Rügen is the near absence of these structures in the western and central regions of the island. This pattern is only partially reflected in the distribution of burial mounds, which can be found on the island's inland areas. In general, three areas always appear to be well-separated from each other at all clustering scales:

1. The southern part. The number of clusters in this area varies depending on the scale, with the largest cluster located in the eastern section and others situated along the south-eastern coast and further inland. At a 3 km threshold, all these clusters merge into a single one (218 sites), with 2 noise points in the Mönchgut peninsula;
2. The Jasmund peninsula, with a rather large cluster of monuments and only a few outliers. At 2 km thresholds the cluster has 37 sites and 3 outliers while at 3 km there are 38 sites and 2 outliers;
3. The Wittow peninsula, with two small and isolated clusters, merging at 3.5 km threshold. At shorter reachability distances, these two clusters contain 6 and 8 monuments, with a single outlier to the south.

Considering site distribution, clusters and outliers, it seems that the most suitable reachability threshold for this period is at 2 km. At this threshold, 4 medium or large clusters are already visible in Jasmund and southern Rügen, while 6 smaller ones are located inland, facing the Kleiner Jasmunder Bodder (Figure 51 a). It is worth remembering that during this period the Jasmunder Bodder was likely open sea, and Wittow and Jasmund were islands. The formation of larger clusters at a 3 km threshold may indicate the existence of meso-regional dynamics, similar to what has been described by Renfrew (1973) for Easter Island or the Orkneys.

The situation appears to be very different during the Bronze Age. The number of mounds is approximately double that of the megaliths (there are 512 mounds and 278 megaliths). However, more than half of these are concentrated on the Jasmund peninsula (303). During this period, the western and inland parts of the island exhibit occupation, albeit with fewer sites compared to the eastern and

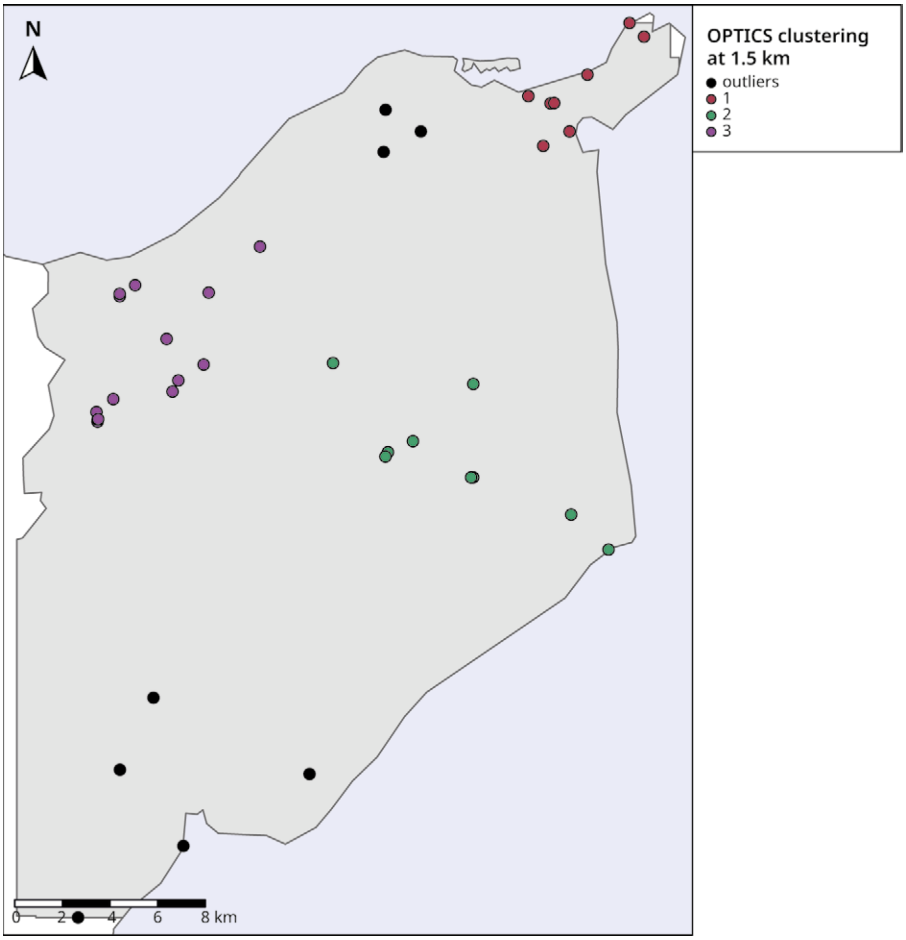


Figure 50. OPTICS (ordering points to identify the clustering structure) algorithm results for East Holstein during the Middle Neolithic. Only the results for the optimal Eps value are shown.

southern parts of Rügen. Conversely, the Wittow peninsula is almost completely abandoned, with only one mound, while the Zudar peninsula at the south-eastern extremity of the island is now inhabited. In addition, the south-eastern coast has fewer monuments (less than 60). Similarly, there are no clusters observed around the Kleiner Jasmunder Bodder, with only some isolated points. During this time frame, the 3 km threshold seems to be the most representative, with only 20 noise points and very well-defined clusters (Figure 51 b). Overall, it appears that the Bronze Age occupation of the landscape is more structured, characterised by an increased number of well-defined clusters when compared to the Neolithic period.

6.3.7 South-eastern Schleswig (Dänischer Wohld)

The study region is fairly small compared to some of the other case studies. This characteristic is evident in the fact that the majority of sites fall within a single cluster at a reachability distance of 1.5 km. Short distances and well-defined clusters at smaller thresholds suggest high connectivity between clusters and possibly reflect a well-organised landscape, especially in the central and north-eastern sectors. At a reachability of 1 km, there are 32 noise points (whereas only 13 are observed at 1.5 km), generally located in marginal areas, such as the western and to eastern parts of the region (Figure 51 c). For this reason, the 1 km threshold is preferred for the Neolithic period.

During the Bronze Age, there is an increase in cluster organisation. At 1.5 km, sites are organised in multiple clusters, while at a reachability of 2.5 km only two clusters are observed, one of which encompasses the majority of the sites (213 sites).

Unlike other case studies, here the number of sites remains relatively constant between the different periods, with 227 megalithic tombs and 252 burial mounds. Therefore, the shift in clustering patterns cannot be attributed to variations in site numbers but probably reflects changes in their spatial structure. During the Bronze Age, the western part gains significance, with a relatively large and stable (across varying radii) cluster situated there. This region has long been identified as critical for mobility and transportation routes (Nakoinz, 2012; Figure 51 d). A clear north – south division emerges in this period, with two large clusters separated by an 'empty' area at a reachability of 2 km. However, the southern cluster does not appear as cohesive as the northern one, as it fragments into smaller clusters at decreasing thresholds. Considering all these factors, the 1.5 threshold has been selected for this period.

6.3.8 South-western Scania

The organisation of monuments in this area during the Neolithic period exhibits a considerable degree of heterogeneity. Despite the relatively low number of sites (n = 49), there is discernible variation in site intensity. The southern part of the area demonstrates higher site intensity, while in the north and south-east, sites are more sparsely distributed. There, few sites are located close to each other, forming small clusters already at a threshold of 2 km. However, the majority of sites only form clusters at a 3 km threshold. On the other hand, the majority of sites in the south are already grouped in a single cluster at a reachability threshold of 1.5 km. Moreover, there is a tendency for sites not to be located inland. At 3.5 km threshold 4 clusters are observed, with two separate smaller clusters in the south-eastern area (Figure 51 e).

The situation during the Bronze Age is very different. The number of sites in this period is considerably higher (n = 354) and with a high site density (5.46 sites/km^2). Compared to the previous period, there is a higher presence of sites inland in the northern and central regions. However, the south-eastern inland part continues to exhibit lower site density. Higher site density is reflected by the fact that already at a reachability of 1.5 km, the largest cluster covers a significant portion of the northern and central part of the study area, including 237 monuments. However, a lower threshold would result in the fragmentation of this large cluster into numerous smaller ones, leading to a considerable number of outliers (122, more than one-third of the total number of sites). At a reachability of 2.5 km, the majority of sites are incorporated into the primary cluster, including those in the southern region, totalling 337 sites. At a threshold of 2 km, the large cluster already begins to include some sites from the south-central part, but is also representing the most suitable threshold for the period. This aspect potentially signifies a high degree of integration in the landscape occupation during this period (Figure 51 f).

6.3.9 Western Scania

Western Scania is the area with the highest number of megalithic tombs in southern Sweden, with 65 out of 193. For this reason, it is probably the most suitable area for cross-temporal comparison in Scania. The most evident characteristic of the region is the presence of an area nearly free of TRB monuments to the south and south-east of the city of Landskrona. This pattern is further emphasised by the fact that the clustering at a 5 km threshold shows a marked division of sites located in the two different parts. Although the number of sites during the Bronze Age is considerably higher (n = 900), at a threshold of 2.5 km the two parts are still clearly organised in different clusters separated from each other. An evident feature of the megalithic tombs during this period is that those located in the north tend to cluster together. This pattern is observed at thresholds above 1.5 km.

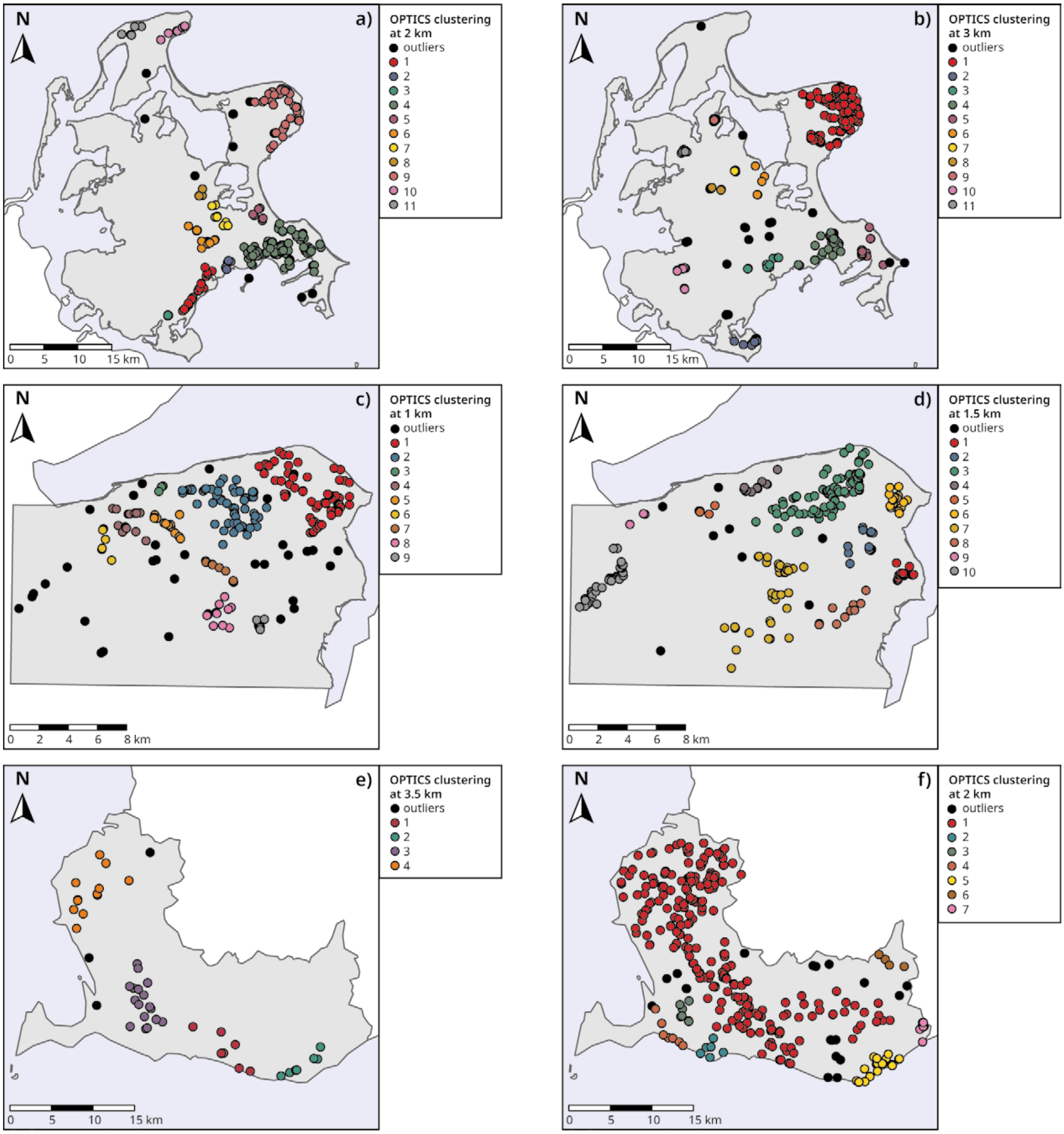


Figure 51. OPTICS (ordering points to identify the clustering structure) algorithm results for Rügen (a, b), the Dänischer Wohld (c, d) and south-western Scania (e, f) during the Funnel Beaker period and the Bronze Age. Only the results for the optimal Eps values are shown.

To the south, sites are somewhat more dispersed but form larger clusters at increasing reachability (3 km or more). At 3.5 km, they merge into a single cluster (Figure 52 a).

During the Bronze Age, the landscape becomes more densely populated, with only a few areas exhibiting fewer or no sites. These are primarily located inland and in the previously mentioned central part of the area. At small distances, numerous clusters emerge, and in the north, they tend to merge into larger ones already at a reachability distance of 1 km. In the south, this pattern is observed at 1.5 km. The island of Ven now exhibits a large number of sites forming an independent cluster at most of the analysed thresholds. An appropriate reachability distance for the Bronze Age seems to be 1.5 km. At this threshold, the larger clusters are already established but there are also numerous smaller ones. The inland area lacks proper clustering,

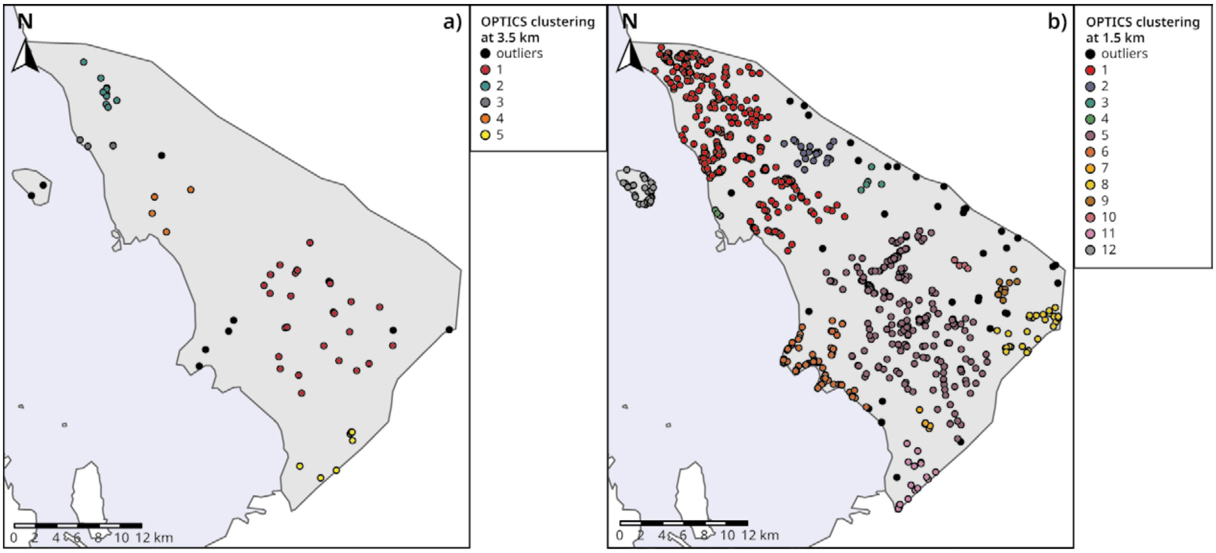


Figure 52. OPTICS (ordering points to identify the clustering structure) algorithm results for western Scania during the Funnel Beaker and the Bronze Age. Only the results for the optimal Eps values are shown.

potentially indicating a buffer zone or an area characterised by lower population density (Figure 52 b).

6.3.10 Bjäre peninsula and North-eastern Scania

There are no Neolithic monuments in Bjäre, while there are only 13 in north-eastern Scania. For this reason, only the Bronze Age is discussed for these two case studies.

In north-eastern Scania the number of Bronze Age monuments is the highest for Scania (n = 1224). The highest number of sites and the most pronounced clustering structure is located in the southern part. Here, clustering is already strong at 0.5-1 km thresholds. Additionally, well-structured areas are observed in the central part of the region, with a large number of sites clustering at 1.5 km. For this reason, the 1.5 km threshold has been chosen for this case study (Figure 53). In contrast, the northern part of the region shows less integration and more noise points. At a reachability of 2.5 km, approximately 83% of the sites (1021) belong to one of the two main clusters, with the southern one comprising 737 sites. At 3 km, most of the sites belong to the same cluster.

The Bjäre peninsula is a relatively small region but it has a significant number of Bronze Age monuments (n = 978), resulting in an exceptionally high site density (44.66 sites/km^2). Given this concentration, at 1 km radius, most sites already belong to a single cluster, making the 0.5 km the most informative threshold for the region (Figure 54). This suggests a highly structured landscape in the peninsula, likely influenced by its strategic position in relation to maritime and, perhaps, terrestrial routes connecting western Sweden to the south. The significance and intensity of its occupation are further highlighted by the abundant presence of rock art on the peninsula, predominantly dating to the same time frame.

6.4 Demographic model

In this section, the outcomes of the cluster analysis and predictive models are integrated to estimate the areas inhabited by past populations within different time frames. However, certain case studies have limited results due to data constraints previously outlined (Chapter 3). For instance, in south-eastern Schleswig and Rügen,

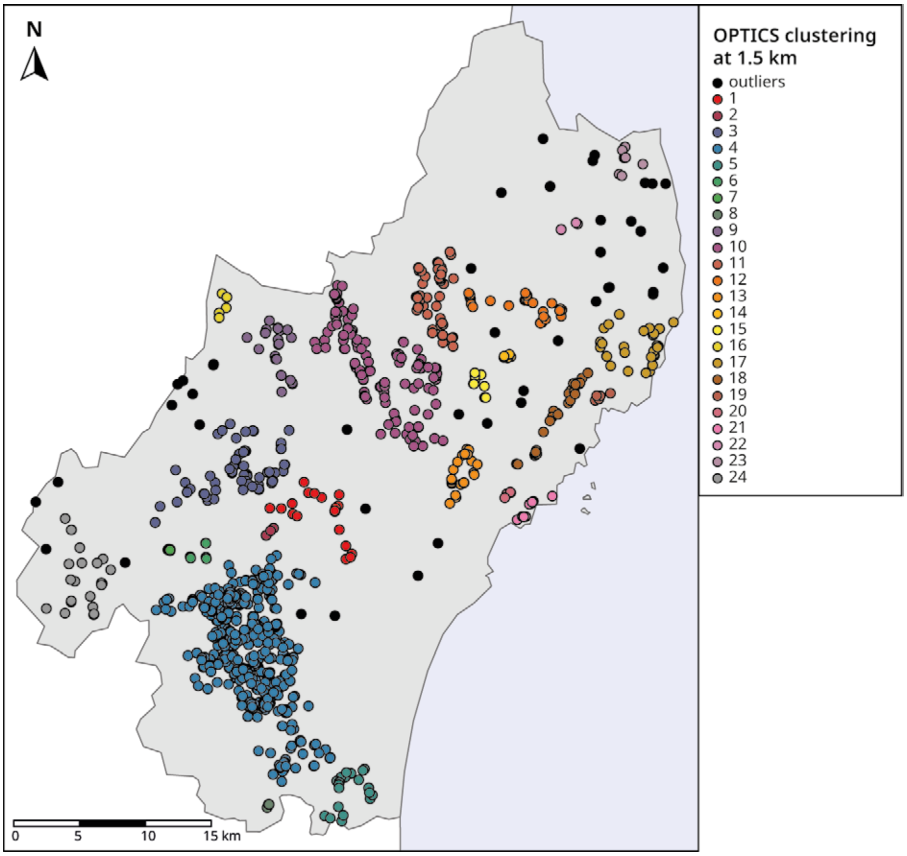


Figure 53. OPTICS (ordering points to identify the clustering structure) algorithm results for north-eastern Scania during the Bronze Age. Only the results for the optimal Eps values are shown.

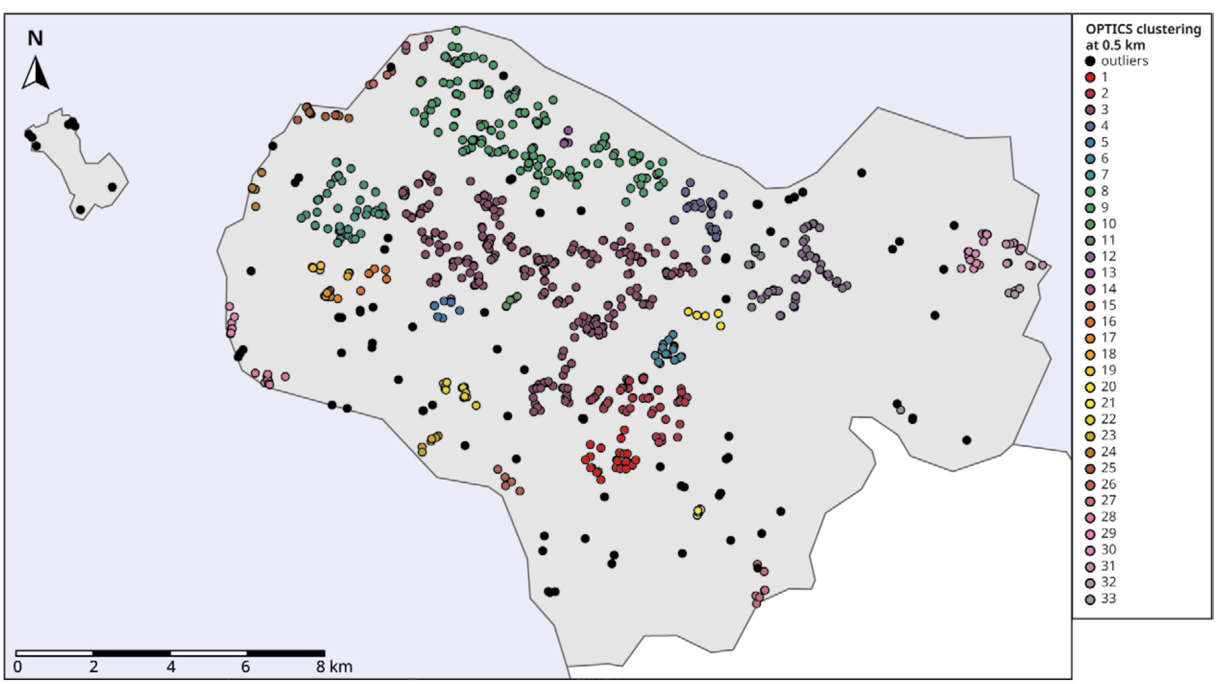


Figure 54. OPTICS (ordering points to identify the clustering structure) algorithm results for Bjäre during the Bronze Age. Only the results for the optimal Eps values are shown.

the results are confined to the Funnel Beaker period and the Bronze Age due to limited data availability for more precise modelling. The Swedish case studies allow for broader period considerations, as they are based on specific classes of artefacts with broader chronological relevance. However, the limited quantity of Late Bronze Age data in Scania, consisting of only 48 bronze objects, affects the reliability of that period's analysis. In particular, this affects north-eastern Scania and Bjäre, as they are modelled only for the Bronze Age period. Additionally, the Battle Axe period is not well represented in south-western and western Scania, resulting in a drop in demographic estimates for that period which may simply reflect a research bias. For this reason, the period was left out of the analysis in these regions.

The presented models serve to estimate two different quantities. First, they are used to calculate the maximum and minimum carrying capacities, based on ethno-historical and experimental data following Kerig (2016). Based on his account, it seems that the land requirement of a typical subsistence householdranged from 2-3 ha to 4-5 ha. If animal traction was employed, using 1-2 oxen or cows, the necessary land increases to 10-20 ha (Kerig, 2016). The minimum and maximum estimates used are 2 ha and 20 ha+. At this stage, it is not possible to provide a more refined estimate nor to model technological differences. Nevertheless, carrying capacity provides a simple indication of the landscape affordance over time. The maximum available area is defined as the extent of the clusters at the defined reachability, while the minimum is the result of the intersection between the clusters and the predictive models.

The second value is an absolute demographic estimate based on a mixture of the available archaeological data, the average house size variations over time and the results of the settlement densities from the case studies described Chapter 4. As for the carrying capacities, a maximum and minimum range for each estimate is provided. Should more reliable data be available in the future, they can be easily integrated into the existing model (or an adaptation).

6.4.1 Carrying capacity estimation

The results of the carrying capacity estimations are shown in Figure 55 and 56. The values derived from the cluster analysis remain rather constant and, in general, variation is only observed between the Neolithic and the Bronze Age, as this was the only possible chronological distinction. The minimum values tend to be rather homogeneous, likely because they yield a very low estimate.

The graph for Bornholm (Figure 55) shows an initial increase in the carrying capacity during the EN I, from a median value of around 7 p/km^2 to *ca.* 12. The median value declines until a value of 9 p/km^2 during the 2900-2700 BCE time frame and reaching a second relative peak at 11.2 p/km^2 during the following time frame. The lowest median values are reached during the YN, with a carrying capacity oscillating between 4.8 and 5.8 p/km^2. After the 2300-2100 BCE window the median carrying capacity increases steadily, until it reaches the global peak of 17.98 p/km^2 during the 1100-900 BCE time frame, after which the estimation slightly declines.

In north-western Zealand (Figure 55), the carrying capacity remains remarkably stable from 4100-3900 BCE to 3100-2900 BCE, fluctuating very slightly around 17.9 p/km^2. A slight decrease is observed in the following three time windows (2900-2300 BCE) reaching a median of around 15.4 p/km^2 but reaching the pre-2900 BCE levels during the LN. A significant drop is observed at the onset of the Bronze Age, with an estimated carrying capacity of 4.2 p/km^2, the lowest level of this region. The pattern is then very wavy, with a partial recovery in the following Period II to about 10 p/km^2, a second decline and recovery (Period III and IV) and a new decline during the second part of the LBA, with a median carrying capacity of 7.3 p/km^2 at the end of the LBA. This trend is mostly due to the fact that sites during the Neolithic are abundant and scattered across the entire region, while they tend to be more concentrated near the coast during the Bronze Age.

The median carrying capacity for Thy (Figure 55, Thisted) is at 10.58 p/km^2 during the 4100-3900 BCE window and experiences a slight increase, reaching a peak of around 11.17 p/km^2 in the early phases. Over the next time frames only modest variations are observed. However, there is a noticeable dip around 2700-2500 BCE, to approximately 9.45 p/km^2. Levels above 10 p/km^2 are reached again in the following time window. A more significant growth in median carrying capacity occurs between 1700-900 BCE, when the values grow from 12.81 to 14.39 p/km^2. Towards the end of the Bronze Age, a slight decline is observed, yet at values well above the median of the Neolithic period (13.68 p/km^2).

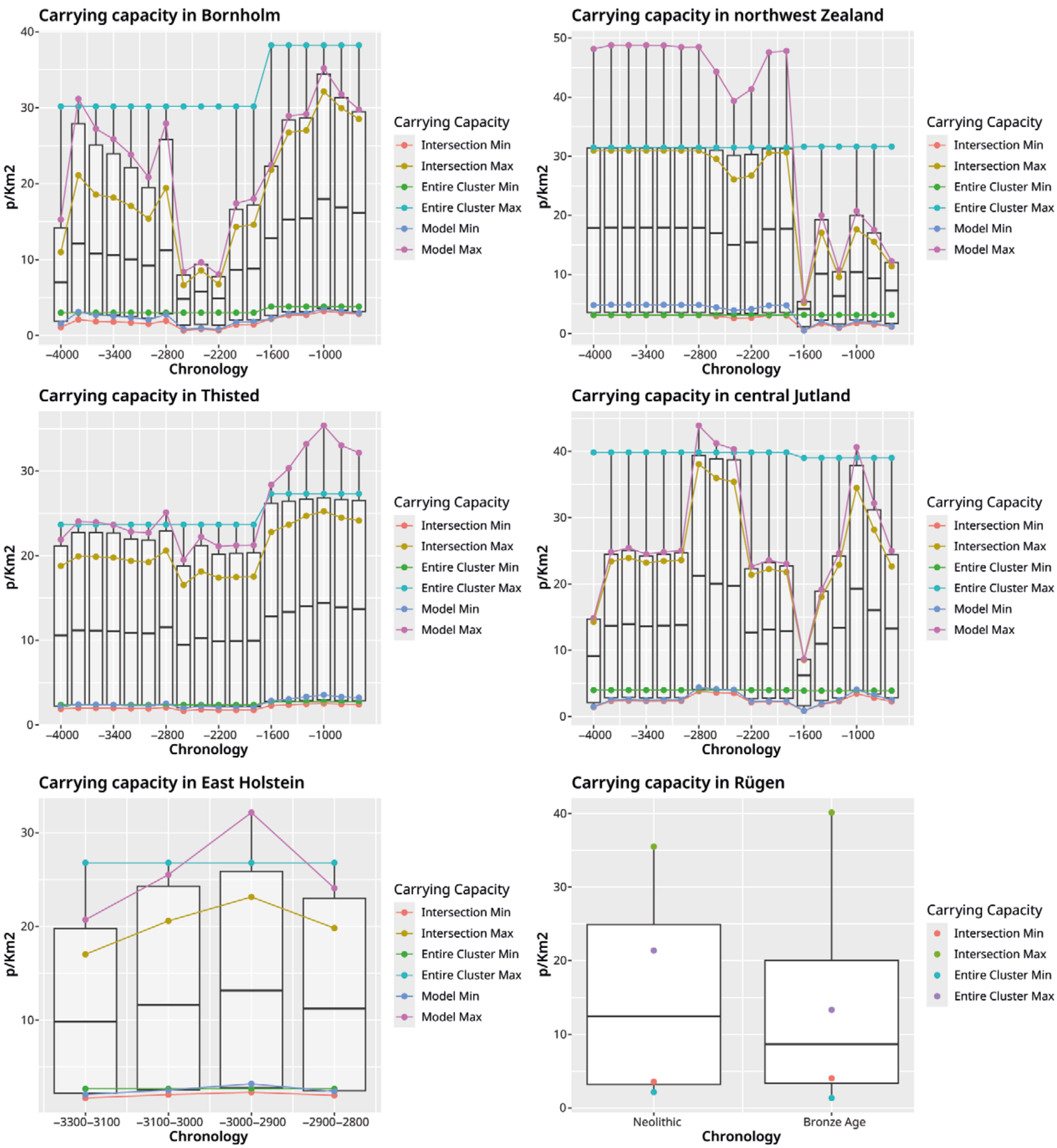
Analysing the plot for central Jutland, we can observe that cluster values tend to be homogeneous throughout the different periods, with the predictive model providing much of the observed variation (Figure 55). The initial carrying capacity has a median value of 9.14 p/km^2. It then experiences an upward trend, reaching higher median values that peak at approximately 13.95 p/km^2 by 3700-3500 BCE. The measurement is stable until 3100-2900 BCE, spiking abruptly in the following time window (2900-2700 BCE) and reaching the highest point at approximately 21.23 p/km^2. This peak is followed by a slight decline but maintains values above 19 p/km^2 until 2500-2300 BCE. After this period, values drop to a level generally lower than the EN – MN (around 13 p/km^2). At the beginning of the Bronze Age, the median carrying capacity reaches its lowest median at 6.21 p/km^2. However, during period IV of the Bronze Age, there is a 'recovery', with values near the YN peak (19.28 p/km^2). This upwards trend is followed by a decline at a median value of 13.28 p/km^2 at the end of the Bronze Age.

In East Holstein (Figure 55) the carrying capacity starts at a median value of 9.85 p/km^2. During the MN II, the median increases to 11.63 p/km^2. This rise is mostly due to the increase in the surface of the modelled area, as it is the case for the following periods. The peak in the carrying capacity estimation is reached during the MN III – IV, at approximately 13.18 p/km^2. Towards the end of the MN, a decrease to a median of 11.25 p/km^2 is observed, in line with most of the trends described for Denmark, where the YN usually represents a contraction, with the exception of central Jutland.

In the case of Rügen and south-eastern Schleswig, the only possible chronological division was between the Neolithic and the Bronze Age (Figure 55). The Neolithic estimates are probably reflecting the peak of megalithic construction in the Funnel Beaker period (between 3500 and 3000 BCE), whereas the burial mounds are most likely reflecting the situation of Period II – IV of the Bronze Age. For Rügen, the median is higher during the Neolithic period, with a value of 12.46 p/km^2 compared to 8.67 in the Bronze Age. However, the minimum values are very similar in both periods and the highest estimate (38.23 p/km^2) dates to the Bronze Age. A very similar trend is observed in south-eastern Schleswig, albeit with much higher values, around 23.24 p/km^2 in the Neolithic and 20.72 p/km^2 during the Bronze Age. The very high estimates for this region are due to the fact that the region is relatively small and therefore 'empty areas' are not included as in other regions.

In south-eastern Scania the carrying capacity in the EN I has a very low median value of approximately 1.69 p/km^2 (Figure 56). During the following EN I/II – MN II period, a substantial increase to 13.78 p/km^2 is observed, representing the regional peak. During the MN III – V, the median carrying capacity decreases to 10.94 p/km^2. Later on, during the LN, the median is estimated to 10.24 p/km^2 and it further declines during the EBA, to a value of 6.19 p/km^2. However, the maximum estimate is recorded in this latter time frame, at *ca.* 40 p/km^2.

Western Scania exhibits a similar pattern (Figure 56), which is not surprising considering the proximity and similarity of the two regions. During the EN I the carrying capacity has a median value of *ca.* 1.48 p/km^2, followed by a substantial increase to 15.45 p/km^2. During the MN III – V the carrying capacity decreases to 11.28 p/km^2, mostly connected to a reduction in site density. During the LN the median carrying capacity slightly increases to a value of 12.48 p/km^2, but it is followed by a marked decline during the EBA (3.34 p/km^2). This sharp decline reflects the low number of EBA artefacts, as the cluster-based carrying capacity is at its highest during this period (39.16 p/km^2). As in most Swedish case-studies,



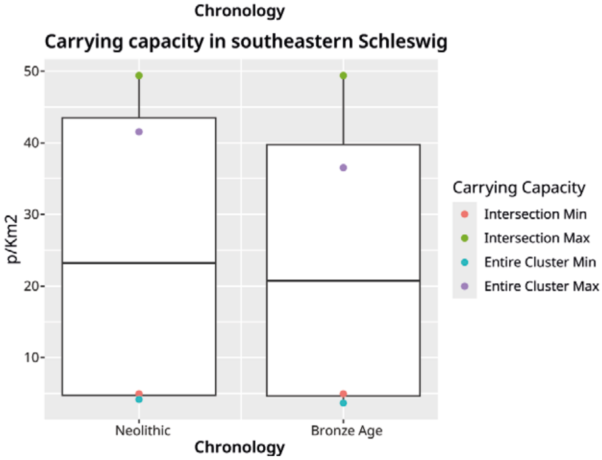


Figure 55. Carrying capacity estimation for the study regions. The results are derived from three different estimates, each with a minimum/maximum value: the extent of the cluster, the extent of the model, and the intersection between the two models.

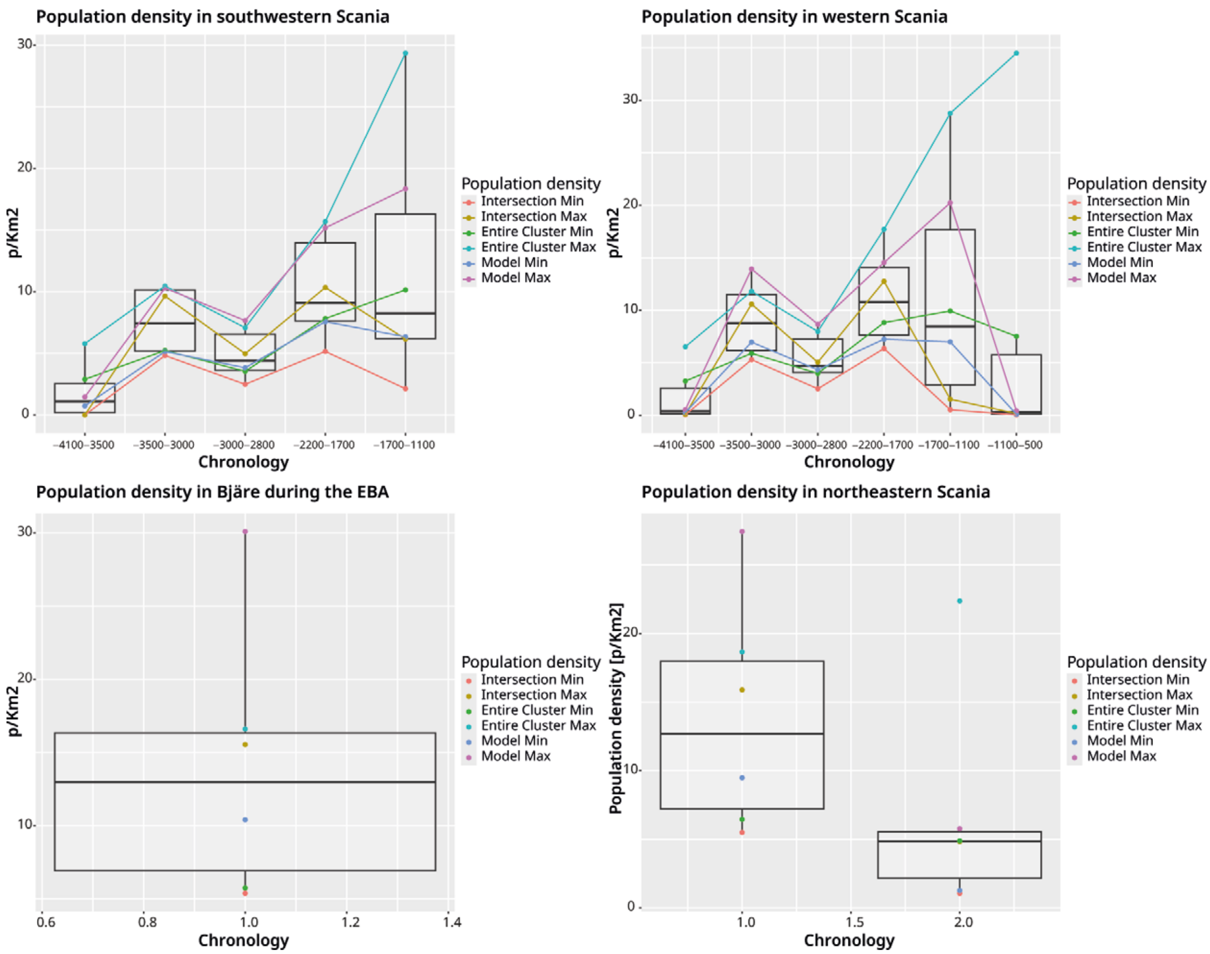


Figure 56. Carrying capacity estimation for the study regions. The results are derived from three different estimates, each with a minimum/maximum value: the extent of the cluster, the extent of the model, and the intersection between the two models.

the LBA is problematic in the reconstructions due to the very low number of sites, deeply affecting the results.

The information available for north-western Scania and the Bjäre peninsula is limited. In both cases, only the EBA estimate may have some value. In Bjäre, the median carrying capacity estimation is around 12.63 p/km^2, with a fairly large range of variation between 2.12 and 40.98 p/km^2 (Figure 56). The estimate and the approximate range of values are similar in north-eastern Scania, with a median carrying capacity of about 12.69 p/km^2. During the LBA this value drops to *ca.* 4 p/km^2, with the highest estimate around 22 p/km^2 (Figure 56).

6.4.2 Absolute estimates

This paragraph describes the results of the absolute demographic estimates derived from integrating the results presented in this chapter with the population density values reconstructed in Chapter 4. The largest impact in variation is determined by house size variation and settlement density. The ranges of values discussed here correspond to the median and the 2nd and 3rd quartiles.

In Bornholm (Figure 57), the median population density at the onset of the Neolithic is 1.64 p/km^2 (interquartile range of 1.29-2.83 p/km^2). During the following 600 years (3900-3300 BCE), it gradually increases to values around 3 p/km^2. A significant surge in density is observed at the passage to the MN (3300-3100 BCE), with a median of 6.25 p/km^2 (4.92-7.50 p/km^2). The rest of the MN stabilises to lower values (around 4 p/km^2) and there is a major decline to *ca.* 1 p/km^2 during the YN. The population density increases again in the LN, from 1.71 to 5.30 p/km² by 2100-1900 BCE (4.60-8.21 p/km²). The situation at the beginning of the Bronze Age shows a population density of 5.70 p/km², which increases during the rest of the EBA, reaching the peak 7.40 by Period III (6.99-9.13 p/km²). In the final centuries of the Bronze Age, the population density slightly decreases, with values ranging between 6.76 and 5.71 p/km².

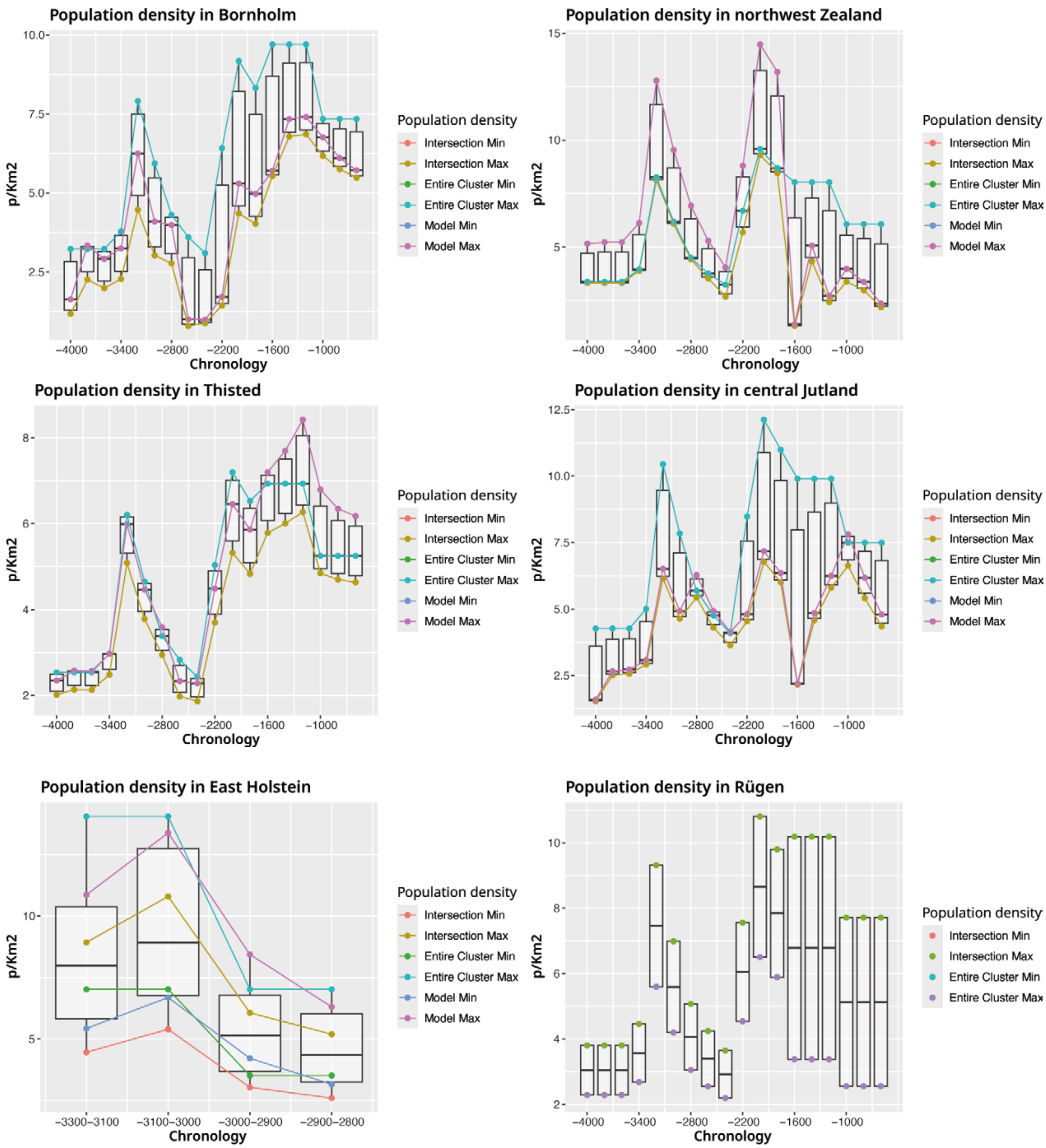
In north-western Zealand, the population pattern is very similar, exhibiting stability between 4100 and 3300 BCE, with values ranging from 3.37 to 3.76 p/km², an increase at the beginning of the MN to values of 8.26 p/km² (8.16-11.65 p/km²) and then a steady decline, with a density at a local minimum of 3.23 p/km² (2.82-3.84 p/km²) during the YN (Figure 57). After this period, population density increases and reaches the peak between 2100 and 1900 BCE, at 9.58 p/km² (9.37-13.25 p/km²). A dramatic drop to 1.40 p/km² is observed at the onset of the EBA, which is the lowest estimation for the region. The rest of the Bronze Age shows a wavy pattern, with values oscillating between 5.07 p/km² (Period II) and 2.35 p/km² (Period VI).

In Thy (Figure 57), a gradual increase in population density is observed between 4100-3300 BCE, from 2.35 to 2.82 p/km². A peak is reached at 5.99 p/km² (5.31-6.15 p/km²) between 3300 and 3100 BCE, followed by a dip to 4.46-3.38 p/km² during the rest of the MN, leading to the minimum of 2.28 p/km² (1.97-2.40 p/km²) during 2500-2300 BCE. Starting in the Late Neolithic the population density seems to increase again, reaching a peak during the EBA. The median of the entire EBA is stable at 6.93 p/km², although it is possible to see an increase in the upper values from Period I to Period III. The population density during the LBA decreases to 5.25 p/km².

In Central Jutland (Figure 57), the initial density is of 1.59 p/km² (1.55-3.60 p/km²). By 3500-3300 BCE, it rises to 3.08 p/km² (2.96-4.53 p/km²) and then to 6.51 p/km² (6.24-9.46 p/km²) by 3300-3100 BCE. The population then declines, reaching a median value of 4.10 p/km² (3.75-4.13 p/km²) between 2300-2100 BCE. This YN dip is followed by an increase to 7.17 p/km² (6.87-10.89 p/km²) between 2100-1900 BCE. A significant drop to 2.20 p/km² is observed at the onset of the EBA, although it has to be observed that the upper range of values remains unchanged. The median for the EBA I is possibly an outlier, as the values in the following periods are around or above 5 p/km². The median peak is observed during the LBA IV, at a value of 7.49 p/km² (6.84-7.73 p/km²). However, considering the quartiles distribution a higher population density was observed between 2100-1100 BCE. The population density decreases in the last two periods of the Bronze Age, reaching 4.80 p/km² (4.46-6.82 p/km²) by 700-500 BCE.

In East Holstein (Figure 57), the population density during the MN I has a median of 7.98 p/km² (5.83-10.38 p/km²). It then experiences a slight increase to 8.91 p/km², with a general rise in both maximum and minimum ranges (6.78-12.74 p/km²). This is followed by a decrease during the MN III/IV and during the MN V, when the minimum is reached at 4.35 p/km² (3.25-6.04 (6.78-12.74 p/km²)).

The population density in Rügen and south-eastern Schleswig is based on fewer estimates, as only data from the monuments was used for the analyses (Figure 57). The data has been divided into 200-year windows to account for variations in house size and settlement density over time. Nevertheless, the confidence in these estimates is reduced due to their reliance on fewer factors. In Rügen, the density during the EN I and part of EN II is around 3.05 p/km², with an interval between 2.29 and 2.81 p/km². There is a slight increase to 3.40 p/km² at the end of the EN, before reaching a median of 7.46 p/km² (5.60-9.31 p/km²). From 3100 to 2900 BCE, the density declines to 5.59 p/km². This reduction continues over the next few centuries, reaching 4.07 p/km² by the beginning of the YN and reaching a minimum of 2.92 p/km² at the end of the period (and an interval of 2.20-3.65 p/km²). The estimated population density increases again during the



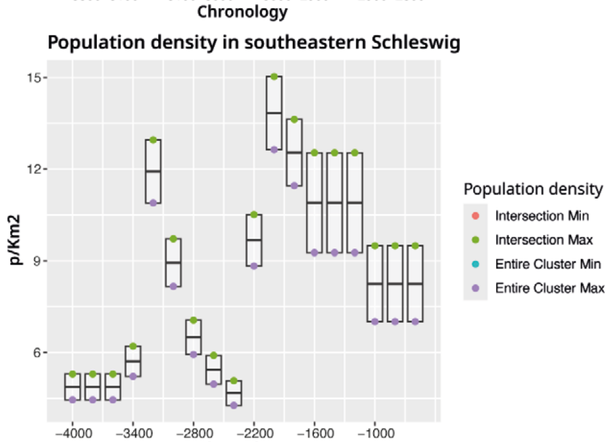


Figure 57. Population density estimation for the study regions. The results are derived from three different estimates, each with a minimum/maximum value: the extent of the cluster, the extent of the model, and the intersection between the two models.

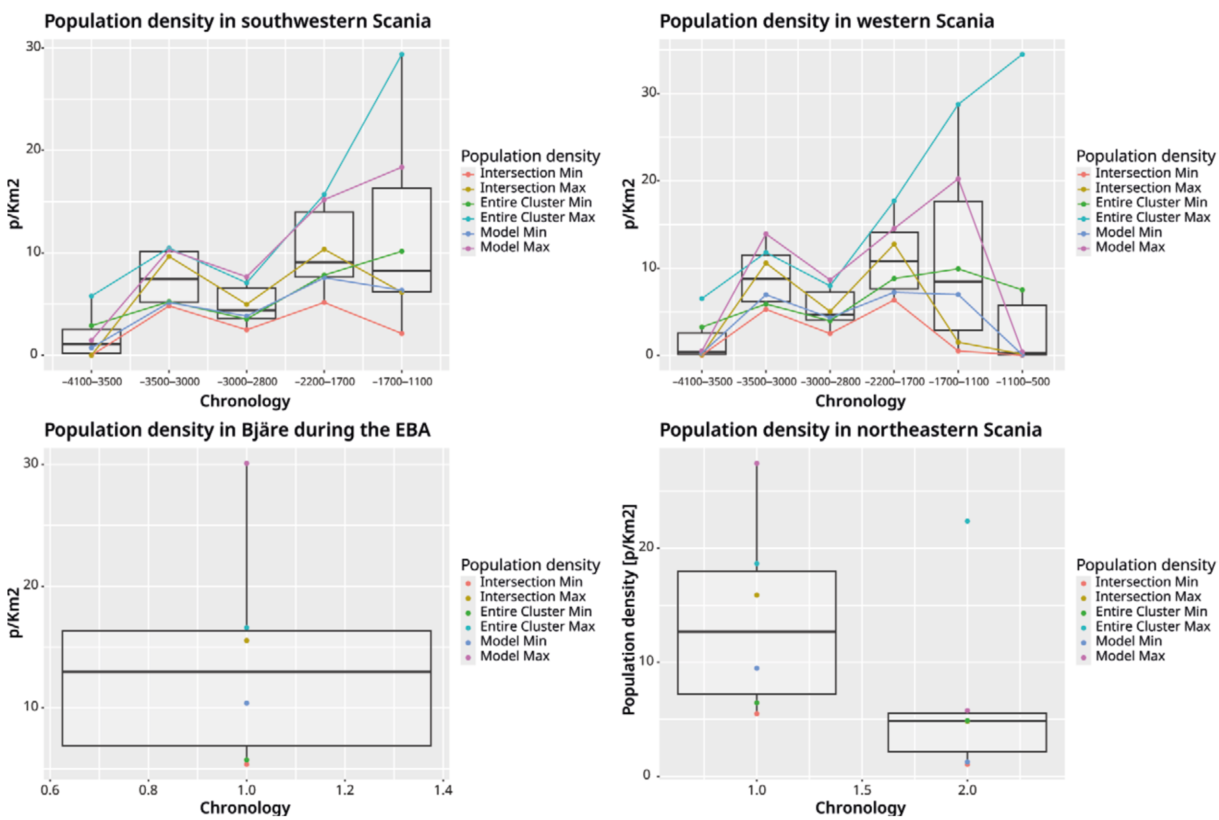


Figure 58. Population density estimation for the study regions. The results are derived from three different estimates, each with a minimum/maximum value: the extent of the cluster, the extent of the model, and the intersection between the two models.

LN period with a value of 8.65 p/km² (6.50-10.80 p/km²) between 2100-1900 BCE. During the Bronze Age median values are lower than this peak (6.78 p/km² in the EBA and 5.14 p/km² in the LBA) but the range is rather wide, with the EBA ranges largely overlapping with the LN period (3.40-10.19 p/km²).

In south-eastern Schleswig, the population density remains at values around 4.87 p/km² (4.45-5.30 p/km²) from 4100 BCE to 3500 BCE. After a slight increase, there is a peak to 11.92 p/km² (10.89-12.96 p/km²) between 3300 and 3100 BCE. However, the density gradually declines to 8.25 p/km² in the following period and the lowest values are reached at the end of the YN, around 4.67 p/km². A new increase is observed during the LN, until a peak of 13.84 p/km² (12.64-15.03 p/km²) is reached between 2100 and 1900 BCE. The population density decreases at each subsequent time frame, with an initial decline before the EBA, followed by a decrease during the EBA (9.27-12.54 p/km²) and a final decline during the LBA (7.01-9.49 p/km²).

The population density trends in south-western Scania show significant variability across the different periods (Figure 58). The population density during the EN I is 1.09 p/km² (0.18-2.53 p/km²). During the EN I/II – MN II there is a substantial increase, with a median reaching 7.40 p/km² and an interquartile range from 5.09 to 10.14 p/km². A decrease to a median of 4.40 p/km² (3.61-6.55 p/km²) is observed during the following MN III – V. As already mentioned, the YN is problematic in the region and the values are not displayed. However, a significant reduction in population is likely, as observed in other regions. A dramatic increase occurs during the LN, with the median rising to 9.09 p/km² (7.63-13.98 p/km²). During the EBA, the median remains high, at 8.25 p/km². However, the range of values is very broad, between 6.21 and 16.31 p/km². The data for the LBA is scarce and cannot be appropriately described.

The demographic pattern in western Scania is relatively similar to what has been described for the neighbouring SW part of the region (Figure 58). The observed density during the EN I is around 0.40 p/km² (0.14-2.58 p/km²). The EN I/II – MN II shows a remarkable increase in population density with a median of 8.73 p/km² and a range from 6.07 to 11.51 p/km². A slight decline in population density is observed during the MN III – V, with a median of 4.69 p/km² (4.08-7.25 p/km²). A significant increase in population density is evident during the LN with a median of 10.80 p/km², and the interquartile range between 7.65-14.10 p/km². As in the previous case study, the median density lowers during the EBA (8.46 p/km²), yet the interquartile range is wider, making the interpretation more uncertain (2.90-17.66 p/km²). A stark decrease is observed during the LBA, with a median of 0.30 p/km² and a range from 0.11 to 5.75 p/km², which may be partly attributed to the underrepresentation of LBA sites in the region.

In Bjäre, population density estimates during the Bronze Age present a median of 12.97 p/km², with a range between 6.90 and 16.33 p/km² (Figure 58). These figures are consistent with trends observed in the north-eastern and south-western parts of Scania. The density is comparable, albeit marginally higher, than what is seen in western Scania. Similarly, north-western Scania during the EBA exhibits a population density of 12.69 p/km² (7.20-17.97 p/km²). A notable decrease in population density is observed during the LBA, with a median of 4.85 p/km² and a range between 2.15 and 5.44 p/km² (Figure 58).

7. Discussion

This chapter provides a discussion of the findings presented in the previous chapter, contextualising them within the framework of current knowledge in the study region and evaluating their implications. Firstly, the results are examined in relation to the initial research questions, highlighting both the limitations and potential of the adopted approaches. Secondly, the chapter assesses the impact of these results on the current understanding of human-environmental relationships and palaeodemography.

7.1 How many?

The central research question of this thesis was to estimate the population size in the study area and its fluctuations over time. However, the nature of the data and the need to analyse the area through smaller case studies enabled comparisons between different regions, increasing the possibilities to understand local and global changes.

One significant finding is that, according to the reconstructions presented here, none of the regions ever reached their environmental carrying capacity. This implies that it was not a constraining factor during the period under study. Consequently, it may undermine the frequently cited hypothesis in the literature, which links population fluctuations to climatic events. A possible concern, however, is the wide and relatively constant confidence interval in these estimations, potentially diminishing their usefulness. Despite this, a degree of consistency in farming technology across the study region during the period considered is well-known, particularly for the Neolithic period after 3500 BCE, when a transition from horticulture to agriculture occurred with the introduction of the plough. This is mostly due to the later arrival of agriculture in the study region, where advancements such as animal traction, the wheel, ploughing, manuring, and dairy consumption were already established (Gron et al., 2015, 2016, 2017; Gron and Rowley-Conwy, 2017; Gron and Sørensen, 2018). The carrying capacity estimates are based on the total potential land available near prehistoric monuments, explaining the relatively stable outcomes over time and why actual population figures did not exceed these estimates. An exception is western Scania during the Late Bronze Age, where both the median carrying capacity and total estimates are low, likely due to research biases and a lack of data for this period.

The case studies from south-eastern Schleswig and Rügen require some general considerations. Here, reconstructions were based on limited data due to accessibility issues. A more complete assessment of the available data would have been very time-consuming and could not be carried out at this stage. In these cases, most of the observed variation has to be connected with settlement density from other regions and house size variation, as they are the only high-resolution time-related variables.

Despite differences in local densities and temporal shifts, certain global population trends are evident across sub-regions. Generally, all case studies indicate a demographic increase during the Early Neolithic, peaking in the first part of the Middle Neolithic. Subsequently, the rest of the Middle Neolithic and Younger Neolithic periods generally show lower population densities. From the Late Neolithic onwards, variability increases, with widespread demographic growth peaking either in the central-final Late Neolithic (I/II or II) or during the Early Bronze Age. Specific patterns in different regions, such as Bornholm and Thy peaking during the Early Bronze Age, align with archaeological findings (Kristiansen, 2018). Post-Late Neolithic trends vary, with Scania and northern Germany showing slight reductions in median density, indicating a smooth transition, as supported by the available literature (Andersson, 2004; Artursson, 2009; Brink, 2009a). In Central Jutland, however, there is a different pattern, with a drop in median population density during the Early Bronze Age I, followed by a rapid recovery until a peak in median population density during Period IV. On the other hand, north-western Zealand has a very specific trend, with a significant decline in population density throughout the Bronze Age, with median values generally below 5 p/km^2, comparable to the Younger Neolithic estimates. This reduction might be due to several factors. Examining the model's output reveals significant variations in site patterns, notably a preference for coastal areas while most inland regions appear abandoned. This observation, however, might be influenced by a research bias. In fact, the region underwent an extensive study focusing on the Neolithic period around the mid-20th century, whose outcomes may have led to a skewed perception of the total number of sites (Mathiassen, 1959). Despite more than fifty years having passed since this study, the region remains sparsely populated, with its largest modern town having fewer than 30,000 inhabitants, and it is situated away from the region's primary communication routes, located more to the south. This certainly had an impact on the number and intensity of archaeological investigations over the past decades. Looking at the current state of knowledge in Zealand, it is assumed that during the Late Bronze Age the island became a hub for metal production and network centrality. However, the findings are mostly found in the region's north-east (Kristiansen, 2018, 2022a; Nørgaard, 2017). This situation could suggest either an underrepresentation of north-west Zealand in the archaeological record or its actual marginal role during the Bronze Age. Considering its geographical location and the trends in global connections, the latter seems plausible, with eastern Zealand being well-integrated and centrally located for maritime routes. These, were most likely aimed to connect the Danish Isles to Scania, controlling north – south transit, and possibly bypassing eastern Jutland and the northern and western shores of Zealand, via routes through Fehmarn and Lolland. Nonetheless, only future research in the region can determine whether this assumption represents reality or not.

The disparity in population density across various case studies may stem from multiple factors. The most obvious is the distinct nature and size of each case study. In certain cases, some areas, such as the western coast of Thy, central Bornholm, or inner Zealand, might have been peripheral in one or more time frames, evidenced by a consistently lower number of sites during specific (or all) time frames. This would result in a reduced overall density, particularly in comparison to areas or periods where site distribution was more uniform. Conversely, in south-eastern Schleswig, a smaller area with high site density was considered, returning generally higher population densities. Nonetheless, the availability of multi-proxy estimates, linked to house size and settlement density variations, appears to mitigate this bias. This is demonstrated by the fact that the final estimates do not vary significantly in terms of total ranges, seldom exceeding 15 people per km^2.

Various studies have attempted to correlate demographic fluctuations with technological advancements and climate change. These dynamics often implicitly relate to Malthusian or Boserupian theories of population dynamics. In northern Europe, one common method to assess human impact involves analysing pollen diagrams, particularly focusing on landscape openness. The patterns, more thoroughly described in Chapter 2, will be summarised here to facilitate comparison with the demographic trends (Figure 59). The pollen diagrams show minimal signs of high-intensity human activity during the Late Mesolithic period, with a noticeable decline in forest cover and a rise in human-related proxies beginning around 4000 BCE (Feeser et al., 2012; Rasmussen, 2005; Sørensen, 2014). However, a more stable open landscape emerges later, peaking around 3500-3300 BCE (Feeser and Dörfler, 2015). This pattern aligns with the demographic trends observed here, marked by a gradual increase from the start of the Neolithic to a peak in the early Middle Neolithic. However, after this period, pollen diagrams indicate an increase in mixed oak forest taxa and a decrease in non-arboreal species, reversing around the start of the 3rd millennium BCE (Feeser and Dörfler, 2015). This phase is interpreted as a population or land-use contraction followed by renewed growth (Feeser et al., 2019). However, it might not have been as widespread as previously thought, potentially reflecting climatic changes rather than population dynamics. Indeed, this study's results suggest the bust phase was more protracted, ending only at the close of the Younger Neolithic. Contrary to starting around 3300 BCE, it appears to have begun a few centuries later, with timing varying by region. The higher spatial and chronological resolution of pollen diagrams from northern Germany, compared to other regions, might not represent the broader western Baltic trends, potentially causing this divergence. In fact, even within that region there are noticeable differences between eastern Holstein and Mecklenburg, with the former region showing a short phase of increase of human activity related proxies at the end of the MN I (Feeser and Dörfler, 2015). However, eastern Holstein's demographic estimates only show a peak during the MN II, with a decline observed only post-3000 BCE. Closer examination of pollen diagrams reveals that despite a 'woodland regeneration' phase, agricultural indicators do not significantly decrease in absolute terms (Feeser et al., 2012). This suggests a change driven by external factors rather than human population dynamics, especially given that the carrying capacity seems not to have been reached during this period. A more visible decline in farming activity (*Plantago lanceolata*) is visible only during the MN II, and more so during the MN's latter part and the Younger Neolithic, aligning with the study's findings of a population decrease in this period. Northern Germany's pollen diagrams appear stable for the remainder of the YN, with a possible further decrease in human impact following a volcanic eruption in Iceland around 2438 BCE, leading to climatic deterioration (Feeser et al., 2012). This aligns with most regional reconstructions, showing the lowest point of the bust during this phase. A significant regional increase in human activity becomes evident during the Late Neolithic, particularly after 2100 BCE (Feeser et al., 2012).

Pollen diagram trends show significant similarities with other study areas. For instance, in Dallund Sø in Funen, a stronger human impact is noted after 3500 BCE (Rasmussen, 2005), a pattern also evident in different parts of Scania (Friman and Lagerås, 2023; Lagerås and Fredh, 2020). However, in Funen, the diagrams indicate a high human impact between 3300 and 2800 BCE, characterised by the rise of secondary forest indicators at the expense of primary forests, alongside an increase in grazed-land indicators (Rasmussen, 2005). During the subsequent Younger Neolithic, anthropogenic-associated proxies diminish, though this pattern is delayed compared to Jutland. Reforestation continued past 2400 BCE, mirroring the demographic curves shown here. Towards the Late Neolithic's end, Dallund Sø's diagrams indicate a minimum in tree cover, signifying increased forest clearance and correlating with higher populations in most Danish case studies. This pattern persists into the Early

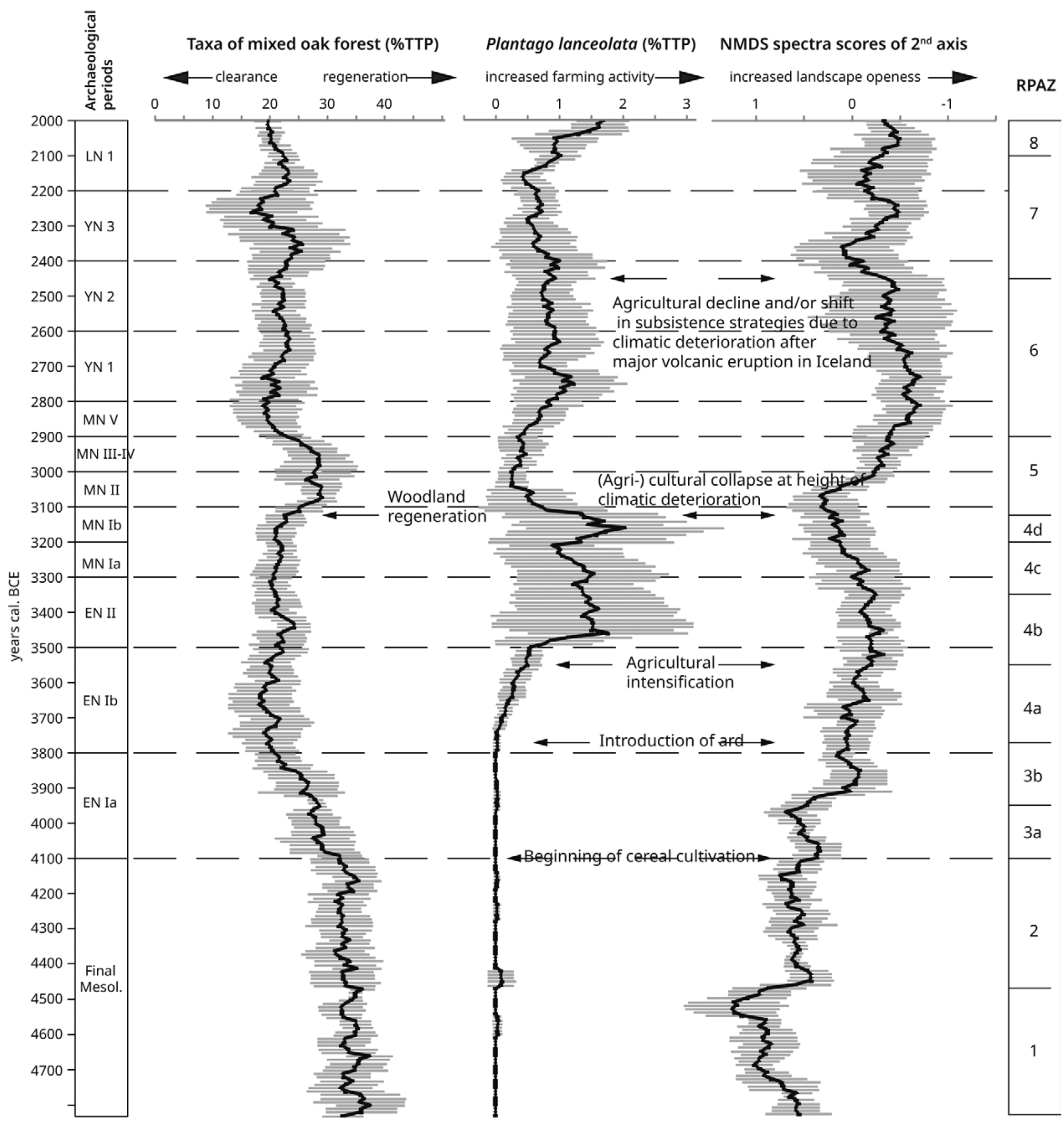


Figure 59. Comparison of regional pollen assemblage zones (RPAZ) in Schleswig-Holstein as shown by Feeser et al. (2012). Oak forests are generally considered to be inversely related to human activity, whereas Plantago lanceolata and landscape openness are believed to be directly related to human activities. Image reproduced with permission of the authors.

Bronze Age, but landscape openness spikes and reaches high levels in the later part of the Bronze Age, with tree pollen decreasing from approximately 82% to 44% (Rasmussen, 2005). Calibration and dating errors in ^{14}C prevent precise timing of a subsequent decrease in tree cover, which may date to either the Early Iron Age or the very end of the Bronze Age (Rasmussen, 2005). In Scania, a similar pattern is observed, with a marked increase in land openness after 1000 BCE. However, the case study's resolution, especially for the LBA, precludes a closer demographic comparison. On Zealand, the situation is only partially visible, with slightly higher population levels during the LBA compared to the EBA. The lack of correlation between the pollen diagrams of Scania and the Danish Isles with those of Thy and Central Jutland may suggest different trajectories, as suggested by Kristiansen (2022a). Pollen diagrams from Thy indicate that openness peaked at the end of the EBA, potentially contributing to the area's decline in centrality (Bech, 2018c; Kristiansen, 2018). If this decline is not attributed to farming-related carrying capacity, it might instead be driven by a scarcity of construction materials and fuel for heating and cooking, as the available studies suggest, and as evidenced by the decline in population density detailed here.

The results presented here, along with their discussion, suggest that pollen diagrams can be useful for studying population dynamics. However, their application should be limited to very small regions, and the number of diagrams used should be as high as possible. When compared to archaeological estimates derived from their catchment areas, pollen diagrams can offer valuable insights. Their visual correlations might indeed reflect actual patterns, as demonstrated in the case of Thy. Nonetheless, even when based on data from multiple core samples, pollen diagrams are not reliable for precisely delineating local or specific historical trajectories. This is exemplified by the notable discrepancy between the pollen diagrams from northern Germany and the demographic patterns observed during the Middle and Younger Neolithic periods. This inconsistency could be due to the fact that changes in land cover and species distribution are not always attributable to human activity. Furthermore, even when human influence is evident, its representation in the diagrams is not always directly quantifiable or straightforward. A better solution might be to integrate pollen diagrams and palaeoenvironmental reconstructions in the study of first-order effects, rather than using them as an explanatory variable for population dynamics.

7.2 Comparison

Apart from a few well-documented areas, a structured comparison between the existing literature and specific case studies is not possible. This is possible in areas like Thy during the Bronze Age, as well as in western and south-western Scania. In other instances, only broad regional patterns are available, requiring a discussion based on general results. Specifically, I compare the findings of this study with several other research works that focused on relative demographic variations, generally based on the use of SPDs, as done by Hinz et al. (2012), Shennan et al. (2013) and Feeser et al. (2019). However, for certain periods, absolute reconstructions are available and have been used in discussing the results presented here (Kristiansen, 2022a; Müller and Diachenko, 2019).

While it is possible to combine the results from each sub-region to obtain a global trend of population density variation, this is not desirable. Firstly, it would conceal regional differences, which are a significant aspect of this study, especially when compared to existing literature. Secondly, it would erroneously suggest that all unexamined regions had densities similar to the ones calculated for the case studies. These areas, typically characterised by exceptional site density, likely reflect a mix of research bias and historical population dynamics. Consequently, simple extrapolation is not possible. The only viable way to extend the results to the entire region involves using predictive models to identify areas with probable high site intensity. Despite these limitations, there are discernible common trends across different regions that can be used for broader comparisons and interpretations of the results.

7.2.1 Relative demographic reconstructions

This section compares the results presented here with the most relevant studies available for the region, particularly these by Shennan et al. (2013) and Feeser et al. (2019). A primary limitation is that most summed probability distributions are restricted to the Neolithic period. This is largely because in southern and central Europe the Bronze Age starts a few centuries earlier and during the 1st millennium BCE calibration issues affect the results, limiting most studies to earlier periods. Another

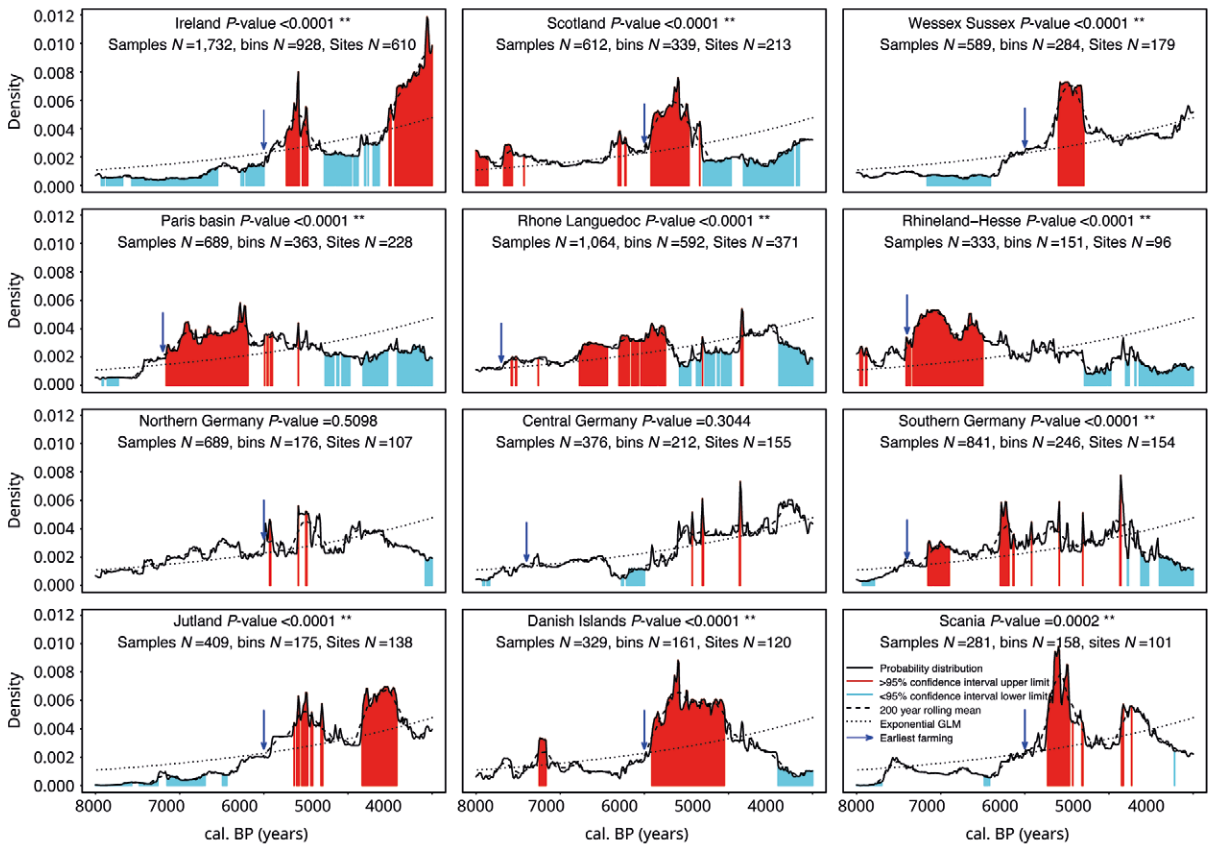


Figure 60. Population density changes inferred from SCDPD between 8000 and 4000 cal. BP for each sub-region are presented. Deviations from the null model that are statistically significant (refer to Methods) are highlighted in red and blue. Figure from Shennan et al. (2013) available under a CC BY-NC-SA 3.0 licence.

significant concern is that some of the SPDs are based on a relatively limited number of radiocarbon samples (Hinz et al., 2012; Shennan et al., 2013). While it is now possible to replicate their methodology with an expanded dataset, the radiocarbon curves in this study have been used to simulate the dating of relatively dated sites and houses. Consequently, employing them for direct comparison would pose methodological issues.

The results of Shennan et al. (2013) are shown in Figure 60. For northern Germany they are mostly within the confidence interval, with only a positive fluctuation at the onset of farming during the 4th millennium BCE, which is in line with the results of the present study. For Jutland, the results display a considerable degree of overlap with this study, with a peak starting from the mid-4th millennium BCE, followed by a reversion to the prevailing trend and a new surge at the start of the 3rd millennium. This latter peak is only indicated as a 'tail' effect of the Early Neolithic II – early Middle Neolithic growth in our estimates and is not observed by Feeser et al. (2019). The boom noted in the Danish Isles' curve aligns perfectly with the results for Bornholm and north-western Zealand, both in intensity and duration. This boom reverts to the main trend with a subsequent decline after the onset of the 3rd millennium BCE (Shennan et al., 2013). A very similar pattern is evident in the Scanian case studies, with an increase around the middle of the 4th millennium, followed by a decline (or a return to trend in the SPDs). The second increase at the start of the 3rd millennium, however, cannot be discerned in the models due to the limits of the available chronological resolution.

In their study, Feeser et al. (2019) identify five distinct phases of population growth between the Neolithic and Bronze Age, specifically around 4000-3500, 3000-2900, 2200-2100, 1450-1300, and 1000-750 BCE. They also note four periods of decline, or busts, around 3400-3100, 2400-2300, 1650-1500, and 1250-1100 BCE. These phases are determined through analyses of pollen records, soil erosion patterns, and

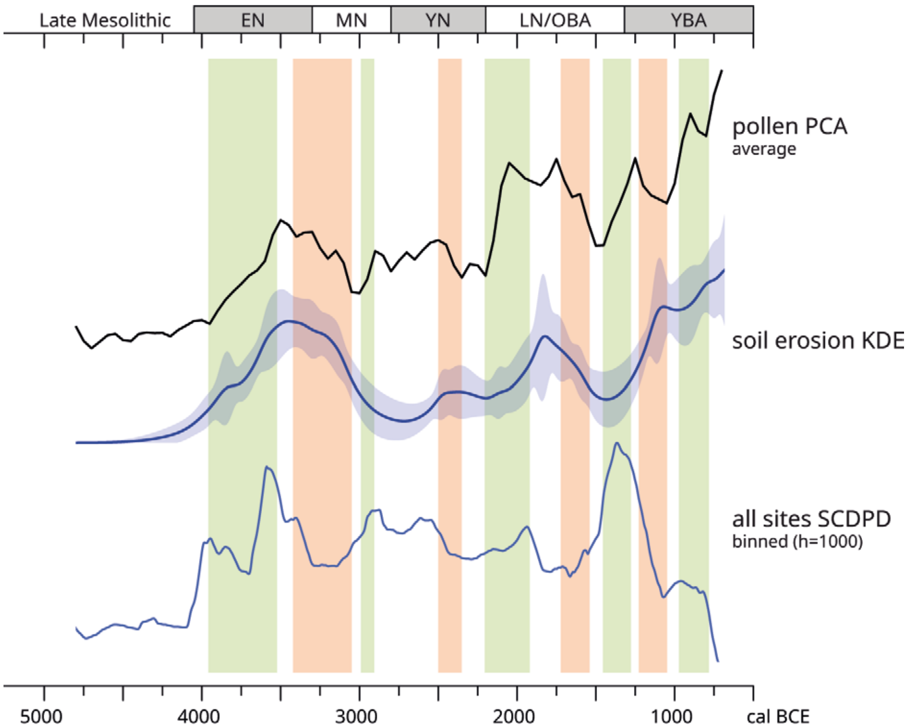


Figure 61. Population dynamics in southern Jutland and northern Germany after Feeser et al. (2019) available under a CC BY-NC 4.0 licence.

radiocarbon dating (Figure 61). Their study primarily covers southern Denmark and northern Germany, thus can only serve as a partial reference for some regions in this research. Since the radiocarbon dates used to simulate site chronology for Bornholm and north-western Zealand include southern Jutland, these two case studies can be considered part of this study region. In both cases, which is largely true for all case studies included here, the first boom is not observed before 3500 BCE (MN II), peaking between 3300 and 3100 BCE (MN I). While some growth is noted from the onset of the Neolithic, it is often minor compared to the later period. This finding contrasts with Feeser et al. (2019) and is supported by the previously mentioned study by Shennan et al. (2013), the archaeological record (*e.g.* Sørensen, 2014) and, for the relevant sub-regions by Hinz et al. (2012). In all the mentioned cases the findings are in line with the results presented here. The differences might be attributable to varying patterns within the considered region, which may be either smoothed over or overshadowed by the dominant pattern (the region with more ^{14}C data). Furthermore, the use of large binning (1000 years) in their study could have contributed to these discrepancies. However, their KDE plot of the ^{14}C data suggests that population growth does not commence before 3750 BCE, which also influences the timing of the first decline phase and subsequent boom (Feeser et al., 2019: 5). Generally, the bust phases identified in Feeser et al. (2019) are not evident in Shennan et al. (2013) for most of the period in the south-western Baltic region. A lower activity level is noted for northern Germany and southern Jutland between 3300 and 3100 BCE by Hinz et al. (2012). The limited number of ^{14}C dates in the latter study and the lack of testing for significance make it difficult to evaluate its relevance and correlation with other studies. The bust phase at the end of the Younger Neolithic (2400-2300 BCE) is also observed in this study, alongside subsequent growth in the Late Neolithic. The bust phase at the start of the Early Bronze Age (1650-1500 BCE) is not observed in Bornholm, but is well-represented in north-western Zealand and south-eastern Schleswig. A similar trend is observed in central Jutland, just north of the study area. The following population increase aligns roughly with the second period of the Bronze Age and is strongly evident in most of the Danish case studies, particularly on Bornholm and central

Jutland. However, the later decline phase and the Late Bronze Age boom have not been detected in any of the case studies.

Local cumulative probability density functions (cPDF) based solely on ^{14}C data from Late Neolithic to Bronze Age longhouses have been produced for some Danish regions (Olsen and Kanstrup, 2018). These curves highlight not only the incompleteness of radiocarbon databases, which often lack access to data collected by contract archaeology research, but also facilitate a comparison with the demographic estimations presented in this study. The curves from Thy align closely with the region's pollen data, exhibiting a peak during Periods III and IV, followed by a decline in the Late Bronze Age (Bech, 2018c; Olsen and Kanstrup, 2018). This pattern corresponds with the demographic estimates from central Jutland and Thy, indicating a gradual increase in population until the end of the Early Bronze Age (continuing until LBA IV in central Jutland) before a subsequent decrease in population density. A similar pattern is observed for southern Jutland, with a curve comparable to Thy's but shifted 100-200 years earlier (Bech, 2018c; Olsen and Kanstrup, 2018). This pattern is clearly observable in the results from Bornholm. However, this pattern does not apply to Zealand, which likely follows a distinct trajectory, as the archaeological and palynological evidence in the region suggests (Kristiansen, 2022a; Rasmussen, 2005).

7.2.2 Absolute demographic reconstructions

The most significant studies focusing on absolute demographic reconstructions within the study region have already been outlined in Chapter 2. Regrettably, no comprehensive absolute estimates are available that cover the entire region and the full time frame under study. In addition to regional estimates for Thy, there are additional ones for specific areas, such as those for Ystad in southern Scania (M Larsson, 1992). However, these often reflect very local patterns or they were carried out in areas with issues in terms of research biases.

One of the most complete accounts of population estimates comes from Müller and Diachenko (2019; Figure 62). Unfortunately, their study region combines southern Scandinavia and central Europe, making it challenging to discern more specific regional patterns. Moreover, their results are presented in 500-year intervals, complicating direct comparisons with the estimates obtained in this study. Their model indicates a population decline between 4000 and 3500 BCE, a period coinciding with the introduction of farming in the south-western Baltic, which contrasts with findings from other studies focusing on that region. The subsequent rise in population partially coincides with the peak generally observed during the Middle Neolithic, but their pattern shows a sharp decline between 2000 and 1500 BCE, which is not observed in the study region. However, in earlier research focusing on southern Scandinavia and central Europe, Müller proposed a slightly different pattern, suggesting a more uniform growth, a bust between 2500 and 2000 BCE, and an increase in the subsequent 500 years (Müller, 2015, 2017b). These studies, centring on continental and macro-regional patterns, are challenging to compare with the outcomes of this research. Additionally, it is probable that the population in southern Scandinavia was consistently lower than in central Europe for most of the time frames considered, implying that the patterns described in their study reflect central Europe's situation more than Scandinavia's. Finally, the inclusion of vast, potentially sparsely populated areas such as central Sweden, Norway, and parts of the Alps might explain the low population density calculated compared to the estimates obtained in this and other studies (< 3 p/km^2).

Conversely, Kristiansen (2022a) presents much higher density estimates for Denmark. His estimates, confined to the Early Bronze Age, are derived from data on individual sites and regional findings from Thy, with an estimated density of 10-15 p/km^2 (Bech et al., 2018; Kristiansen, 2022a). Compared to the EBA

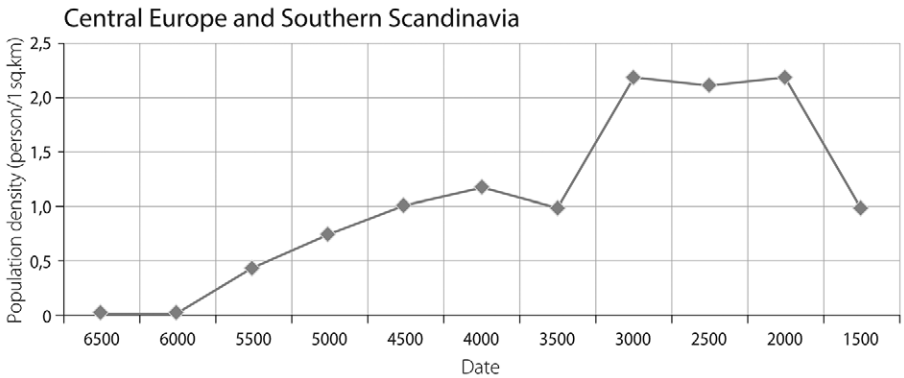


Figure 62. Population density in central Germany and southern Scandinavia. Figure from Müller and Diachenko (2019) available under the CC BY 4.0 DEED licence.

estimates in this study, ranging from 6.44 to 8.05 p/km², Kristiansen's figures are approximately double. However, these figures are closer to the upper end of the results for Bornholm (6.99 to 9.13 p/km² during Period III) and, to some extent, central Jutland (5.92 to 8.99 p/km² in Period III and 6.84 to 7.73 p/km² in Period IV). However, considering the overall density for Denmark, these estimates largely overlap, with Kristiansen's ranging from 5 to 7.5 p/km² and 6.7 to 10 p/km². Consequently, the observed differences might be attributed to the granularity of the estimates. In this study, I differentiate between higher and lower densities based on the predictive model, thereby identifying variations within a single region (see Chapter 6.2.1).

7.3 Modelling considerations

A key accomplishment of this study is the development of a fully reproducible, quantitative approach, capable of modelling historical population dynamics amidst challenges such as data fragmentation and spatial and temporal uncertainties. This research represents the first effort to integrate local data from individual settlements into their respective micro-regions, subsequently assimilating these small-scale analyses into a broader context through a computational and quantitative approach. Moreover, this is also the first time that a formal methodology has been employed for absolute demographic reconstructions in the region.

Yet, there remains substantial work ahead, as this study represents only an initial step. Specifically, the integration of more detailed data from thoroughly excavated regions was not possible, given the extensive literature review it would have required, particularly from excavation reports in Denmark and Sweden. Such integration, both feasible and essential for future research, would enhance the robustness of local population pattern assessments, which are critical for scaling the model's outputs. Enhanced resolution is particularly needed in Sweden and Germany. While this may be more straightforward in Sweden, the current availability and quality of data in Germany would require a more substantial effort. A crucial next step is to incorporate more radiocarbon data into the simulations, particularly from Denmark, where access limitations precluded their inclusion in this stage of the research.

On the computational side, the code is designed to be easily modifiable and updatable, facilitating the integration of higher-resolution variables or improved data. Additionally, the workflow established here is universally applicable to a variety of case studies, regardless of geographical and chronological boundaries, given the availability of suitable input data. Certainly, a more accurate identification of covariates is necessary to yield deeper insights into past land-use practices, vital for understanding demographic trends, settlement locations, and socio-economic factors. An even more comprehensive investigation of the first-order properties would be advantageous; integrating, for instance, mobility studies (as done in Bilotti et al., 2024b). While single variables can be modified or replaced depending on the specifics of each case study, this would result in a diminished automation. In this work, the latter aspect was preferred, sometimes at the expense of the specificity and precision of the single case study. This, and integration of better data, could help to narrow the current confidence bandwidth, especially in the calculation of the carrying capacity. Nevertheless, even at the present stage the model has successfully identified periods of population increase and decrease with distinct, non-overlapping bandwidths.

Comparing the model outputs with simpler ^{14}C curves, such as SPDs or CKDEs, provides some interesting insights. The radiocarbon-based models exhibit a bias during the 1st millennium BCE, a consequence of the well-documented issues with the calibration curve (the Hallstatt plateau). Although this bias is somewhat mitigated by the mandatory ^{14}C sampling during rescue excavations in Denmark and Sweden, the large ^{14}C database used in the computation of the radiocarbon curve does not integrate all these data. Despite this constraint, the model presented here does not indicate a sharp demographic decline during the Late Bronze Age, showing that this bias has been successfully mitigated. A decline during this period has indeed been identified in many regions, yet the magnitude of this decline is not as pronounced as that shown in the radiocarbon curves, which represents one of the key findings of the model presented here.

8. Conclusions

The aim of this study was to investigate population dynamics in the south-western Baltic region during the Neolithic and Bronze Age. The method adopted allowed an integration of different data sources and different scale of analysis, trying to overcome the issues related to data uncertainty and homogenisation issues commonly found in large-scale studies. Due to data constraints, the region was divided into smaller case studies, selected based on archaeological research intensity, kernel density estimation on site data, and literature review. In total, 11 regions were chosen.

Among the estimates proposed, two different types have been calculated: environmental carrying capacity and absolute demographic reconstructions. An important consideration is that the carrying capacity has not been reached in any of the study regions, challenging the hypothesis of a correlation between population dynamics and climatic disruption. However, this finding does not undermine the possibility that very short-term events such as famines or epidemics, as often recorded historically, may have had an impact in the demographic fluctuations. Furthermore, a narrower confidence interval is necessary to increase the validity of the presented results. However, the chronological resolution currently achievable in prehistory does not allow this possibility. Nevertheless, it seems that the carrying capacity as average estimates over longer periods was never reached and did not pose a threat to past populations.

Moreover, the study identified patterns of growth and decline in absolute terms in the demographic estimates provided. This pattern seems to be in line with the suggested boom and bust phases identified in the SPDs for many regions in Europe. However, a very important consideration is that each region experienced rather different patterns in terms of absolute change and in the timing of the peaks. Despite these differences, global population trends across sub-regions were identifiable, with a general demographic increase during the Early Neolithic, peaking in the Middle Neolithic, followed by a period of lower population densities during the Younger Neolithic. The pattern for the Late Neolithic and Bronze Age was more varied depending on the region, with some case studies, like Thy, peaking during the Early Bronze Age, and others, like Zealand, during the Late Neolithic.

A comparison with other studies shows that in general global trends were correctly defined, but some local or minor ones are either smoothed or mistakenly identified in large-scale studies. In particular, the notable discrepancies between pollen diagram data from northern Germany and observed demographic patterns suggest that changes in land cover and species distribution are not always directly attributable to human activity. Furthermore, differences in the timing and intensity of population fluctuations between this and other studies may be attributed to the relevance of local and micro-regional aspects that have been identified here thanks to the granularity of the estimates.

Due to the nature of this work, several aspects could not be fully integrated. Choices had to be taken and directions prioritised. However, it is important to be aware of what has been left behind, *in toto* or in part, and would need to be integrated in the future. Besides the outcome in terms of demographic estimates, this study also provided a quantitative and reproducible workflow that permits the integration of relatively dated archaeological data with radiocarbon data, allowing an increase in temporal resolution via chronological modelling and simulation. This aspect is certainly important and deserves more attention in the future.

Additionally, the results show that a better integration of the pollen records and the other proxies is essential, and cannot be limited to visual or qualitative comparisons. The use of tools such as REVEALS allows the quantitative reconstruction of past vegetation cover. Its use with a sufficient number of pollen diagrams may allow a more precise definition of plant distribution in regions with high-intensity research. This would, in turn, increase confidence in using such tools and including them as direct measurements of land use and, consequently, human impact. A simple pollen diagram is not sufficient for demographic reconstructions, and precise spatial modelling, even if only probabilistic, is necessary. In some regions, data are already available but a coherent and robust work in this direction is time-consuming and requires an interdisciplinary endeavour.

Another point that is worth developing is labour-requirement estimations. This partly concerns the construction of monuments, such as megaliths or burial mounds, which could aid in understanding the social organisation of the societies involved and the level of socio-economic integration necessary for such activities, especially now that absolute demographic reconstructions are available. Similarly, an analysis of daily activities, based on the available technology, can also be undertaken. This would help in refining the carrying capacity estimates and it would make possible to determine the amount of labour-surplus available in each household that could have been diverted for other activities.

A final aspect that deserves some attention is the use of point process models. In this work, their use has been functional to the demographic reconstructions, scaling the predicted areas in the models with the population density of some key regions and combining it with cluster analysis, used to identify site catchments. However, their potential as predictive models has not been fully investigated and they can be used to identify patterns of site preferences and their variation through time. Moreover, their combination with the chronological modelling presented here offers many possibilities that have been only marginally explored. Lastly, addressing second-order effects is crucial to better understand social organisation and demographic structures.

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POPULATION DYNAMICS AND LAND-USE PATTERNS

in the southwestern Baltic region during the Neolithic and the Bronze Age

This work aims to study population dynamics and land-use patterns in the South-Western Baltic region during the Neolithic and Bronze Age (4100 to 500 BCE). Understanding demography is essential for comprehending socio-cultural transformations, as demographic patterns have long been recognised as major drivers of social change and complex dynamics. Palaeodemography has gained momentum in archaeology and become a central aspect of the discipline thanks to recent methodological and computational advances. Despite that, the discipline faces several challenges due to the patchiness of archaeological data.

In order to overcome this issue, this study uses a multi-proxy and formal approach aiming to reduce chronological uncertainty and improve spatial resolution, thereby enhancing understanding of regional variations. This study produced two different estimates: labour-based carrying capacity and absolute demographic reconstructions. In none of the study regions the carrying capacity was reached, challenging the hypothesis of a correlation between population dynamics and reaching the full capacity of a region. The study also identified patterns of growth and decline in absolute demographic estimates. These patterns align with the boom and bust phases identified in the literature for many European regions.

However, each sub-area exhibited distinct patterns in terms of absolute change and the timing of peaks, which cannot be observed at regional or supra-regional scales. Despite these differences, global population trends across sub-regions were identifiable, with a general demographic increase during the Early Neolithic, peaking in the Middle Neolithic, followed by a period of lower population densities during the Younger Neolithic. The patterns for the Late Neolithic and Bronze Age varied depending on the region. Comparisons with other studies show that while global trends were identified, some are either smoothed out in large-scale studies or incorrectly identified and points towards the necessity of a more localised, yet formal and fully reproducible, approach to palaeodemography.

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