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Exploring Uncertainty and Significance

Analysing Human Response to Environmental Risk with Computational Archaeology

Kailin Hatlestad
Abstract

As humanity confronts the escalating challenges posed by rapid climate change, it becomes increasingly urgent to understand the complex dynamics of human-environment interactions to mitigate its multifaceted impacts. Archaeology, with its long-term perspective, offers the opportunity to examine past societal responses to environmental risks across diverse locations in Northwestern Europe and temporal scales.

This dissertation aims to contribute to this critical endeavour by exploring the socio-environmental dynamics and adaptive strategies of past societies, to inform effective responses to climate change challenges in both the present and future. Utilizing computational archaeology, which integrates digital technologies and computational methods to analyse big data, the dissertation employs probabilistic approaches, including Bayesian modelling like summed probability distributions of radiocarbon (\(^{14}\)C) data, to confront uncertainties inherent in reconstructing past human-environmental dynamics from interdisciplinary datasets. Additionally, quantitative methods, such as correlation tests and null hypothesis testing of \(^{14}\)C data, are employed to identify significant shifts in these dynamics, translating insights into quantitative terms for enhanced integration with policy-making processes.

The primary objective of the dissertation is to illustrate how the integration of archaeological and environmental big data can enrich the understanding of human responses to environmental challenges. The papers in this thesis demonstrate how computational methods can be applied to big data to understand spatiotemporal changes in human-environmental variables, uncovering risk management strategies and societal vulnerabilities. The papers highlight cases where human communities experienced mitigated adverse effects from severe environmental shifts due to diverse socioeconomic strategies. Simultaneously, the results emphasize regional variations in the impacts of climate change, crucial for understanding the effectiveness of human responses. Moreover, the thesis exhibits how big data analytics both complement and challenge existing archaeological interpretations, contributing to the development of new theories. Importantly, it underscores the significance of diverse socioeconomic strategies in mitigating risks, especially in the face of abrupt environmental events.

Keywords: computational archaeology, big data, risk, human-environment dynamics, spatiotemporal analysis, radiocarbon dating, climate change, land use, historical ecology, Scandinavia, Rhine-Meuse, Oder, Europe, Holocene

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For Dad
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


IV. **Hatlestad, K.** (2024). Anthracological and other Macrobotanical Approaches to Holocene Human-Vegetation Dynamics in Sweden, *Manuscript*.

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Throughout history, humans have continually modified their surroundings to enhance survival, mitigate risk, and navigate extreme climate and environmental conditions. The successful, and unsuccessful, navigation of these challenges offers a wealth of lessons on adaptive social behaviors, risk management strategies, and vulnerabilities. As we confront the escalating threat of rapid climate change, as highlighted by the Intergovernmental Panel on Climate Change (IPCC), understanding and leveraging historical lessons becomes increasingly critical. The IPCC's latest report, "Climate Change 2022: Impacts, Adaptation and Vulnerability," underscores that despite current attempts to mitigate human caused climate change, billions of lives worldwide will still be severely affected (IPCC, 2023).

Against this backdrop, there is an urgency to comprehend the complexities and interdependencies between human societies and their environments. Archaeology, with its focus on understanding past human behaviors and societies, is uniquely equipped for this task. Through its study of spatiotemporal patterns, archaeology illuminates the complexities of human-environment interactions over time, aiding our understanding of climate extremes and their impacts. The repercussions of climate extremes on society, including changes to the physical environment, impacts on the economy, health, demographic trends, cultural transformations, and food crises or conflicts, highlight the necessity for a comprehensive understanding of historical precedence and adaptive responses (Ljungqvist et al., 2021). The exploration of past sudden changes and disasters in archaeology gained momentum with the book *Volcanic Activity and Human Ecology* by Grayson & Sheets (1979). This book aligns such research with contemporary concerns regarding extreme climate events by offering insight into how past societies navigated environmental challenges, adapted to changing circumstances, and mitigated risks. These insights provide invaluable guidance for contemporary climate adaptation and mitigation efforts. The dissertation presented here seeks to contribute to this critical endeavor by exploring the adaptive strategies and socio-environmental dynamics of past societies, aiming to inform effective responses to the complex challenges posed by rapid climate change in the present and future.

Recognizing the formidable challenges inherent in exploring the complexities between land use practices, environmental dynamics, and societal shifts, this dissertation leverages computational archaeology methods and big data to
uncover historical trends within these factors. Despite the uncertainties surrounding historical reconstructions, including the imbalanced availability of records as well as their potential biases, innovative methodologies offer promising avenues for overcoming these obstacles. By adopting probabilistic approaches and utilizing computational tools, researchers aim to identify the timing and intensity of demographic and land use changes, as well as their spatial variations.

Computational archaeology, also known as ‘archaeoinformatics’ since its coinage in 2005 by Christian Albrecht University in Kiel, is a specialized field within archaeology that utilizes digital technologies and computational methods for analysing big data. The term ‘big data’ is challenging to define precisely. It is a shifting concept, that refers to the sheer volume of data as well as the methods of handling, analysing, and storing it (Mittelstadt & Floridi, 2016). However, this thesis adopts the definitions provided by Hampton et al. (2013), who describes it as “massive amounts of data not readily handled by usual tools”, and by Gattiglia (2015), who summarizes it as “high volume, high velocity, and/or high variety data.”

Computational methods offer indispensable tools for synchronizing large-scale datasets across archaeology and the natural sciences, particularly in climate change research. By building a paired chronological perspective on the relationship between climate and society, these methods expose socioeconomic transformations and can inform modern climate change response strategies. As such, the overarching aim of the dissertation is to demonstrate the ways in which paired archaeological and environmental big data can inform human responses to environmental risks. To achieve this aim, the following questions guide the thesis:

- How can computational methods be applied to big data in archaeology to analyse human-environmental relationships, particularly in understanding the timing and spatial variations of changes in population intensity and land use?

- How does the spatiotemporal analysis of integrated archaeological and environmental data contribute to the identification of societal vulnerabilities and risk management strategies, especially in response to rapid climate events and across varied environments?

- How can big data analytics enhance and challenge our understanding of prevailing archaeological interpretations, which often focus on distinct spatiotemporal contexts, and contribute to the construction of new theories?
By addressing these objectives, through the integration of computational methods and large-scale archaeological data, this dissertation seeks to contribute to a deeper understanding of human responses to environmental risk. It also strives to bridge disciplinary boundaries and explore the implications of the findings for sustainable land use and environmental management practices.

The scope of this thesis and its targeted research have been motivated by the European Union's Marie Curie Innovative Training Network project, TerraNova. TerraNova is an interdisciplinary European Landscape Learning Initiative that aims to map past environments, reassess human-environment interaction, and develop novel tools for land management (TerraNova, 2023). One aspect of the project involved modeling the settlement and land-use history of Northwest European landscapes, focusing on the long-term impact of human land use on fluvial systems located in Northwest Europe, specifically the Dalälven in Sweden, the Oder that borders Germany and Poland, and the Rhine-Meuse in the Netherlands. Additionally, the project aimed to identify influences in regional human-environmental interactions and develop a spatial database for archaeological and historical landscape data.

Considering the scale of this task, the dissertation adopted a data-driven approach, utilizing big data analytics to explore spatiotemporal patterns between archaeological radiocarbon data and environmental data. Data mining is an essential methodological approach TerraNova employs to analyse spatiotemporal aspects of socioecological data to design better land management systems. The digital age has made data more accessible, with growing interest in the open-source sharing of records and software and constantly evolving techniques and tools for analysis. Even so, the task of data mining is no small feat, given the vastly differing standards within and between disciplines and regions for organizing and recording human-environmental data. Addressing data variability remains an ongoing challenge, and this thesis aims to contribute to that effort.

Thesis structure

The dissertation builds its case through the following sections:

First, the section Current Trends – Big data, archaeology and environmental risk presents a broader contextual background for the case studies discussed in the thesis. It draws upon recent developments in synthetic studies of archaeology and environmental science, which examine the connections between humans and environmental variability. This section also discusses the use of quantitative analysis in integrating large-scale archaeological and palaeoenvironmental data. Moreover, it explores the ethical considerations that arise from synthesizing big data.
Next, Study regions provides an explanation for the Northwest European geographical focus of the papers of this dissertation and brief examples of previous research in these regions regarding human response to environmental risk.

Following this, the Method section outlines the computational methods and statistical analyses employed in the case studies, including those applied to large sets of radiocarbon dates and methods for correlating environmental data with archaeological findings. Additionally, it addresses the availability and access to archaeological radiocarbon samples and palaeoenvironmental data, highlighting challenges related to data quality and accessibility, which are being addressed through open-access initiatives and open-source software.

In the fourth section, Theory, key theoretical frameworks are discussed, including historical ecology, resilience, human niche construction, and risk, which underpin the investigations of human responses to environmental risk in this thesis. The interconnectedness of these concepts. Collectively, these concepts contribute to a nuanced understanding of human-environment interactions in the context of risk and uncertainty.

The fifth part of the dissertation, Paper summaries, provides synopses of the papers included in this collection, which share theoretical and methodological approaches to investigating human responses to environmental risks, across Northwest Europe. The complete articles are included as appendices (I-IV). Paper I explores how human niche construction serves as risk management by analysing spatial land-use patterns over time along the Dalälven river in Dalarna county, Sweden, using $^{14}$C archaeological records and QGIS. The study reveals how past land-use activities diversified and intensified, shaping the Boreal Forest environment into a more predictable landscape (Hatlestad et al., 2021; Appendix I). Paper II examines how societies in four Scandinavian regions responded to the 536/540 AD volcanic event, which triggered severe global cooling. The analysis investigates demographic and land use shifts before, during, and after the cooling period. By integrating climate simulations and radiocarbon data from archaeological contexts, Paper II provides insights into the demographic chronology and land-use practices of Scandinavian societies during this climate anomaly, emphasizing regional diversity in societal responses and the amplification of ongoing social changes (Arthur et al., 2024; Appendix II). Paper III applies computational statistical methods to analyse archaeological and environmental $^{14}$C datasets, investigating regional effects of significant climatic events, identifying links between environmental changes and cultural shifts, and underlining the value of integrating open science resources for comprehending regional complexities (Hatlestad, 2024, in review; Appendix III). Paper IV employs quantitative approaches to analyse anthracological and other macrobotanical remains from two Swedish regions, investigating wood species distribution and plant remains linked to agricultural practices within a radiocarbon dataset. The study uncovers shifts in farming intensity and resource preferences and emphasizes the value of integrating
methods to refine human-environment research techniques (Hatlestad, 2024, *manuscript*; Appendix IV).

In the *Discussion* section, the results of the papers are related and linked to the guiding questions of the dissertation, demonstrating how computational methods clarify human-environment relationships. Furthermore, the discussion highlights the spatiotemporal dimensions inherent in risk and vulnerability, and underscores the importance of integrating quantitative assessments with qualitative insights to foster the development of new theories and perspectives on human-environment interactions.

The *Conclusion* section provides a summary of the key findings of the research.
The intersection of big data, archaeology, and environmental history is instrumental in enhancing our understanding of human responses to environmental risks. Historical perspectives hold significant value in informing present-day responses to climate change. However, to achieve comprehensive analysis, data from diverse sources must be synthesized. Evolving computational methodologies and tools offer researchers the means to integrate and analyse vast amounts of information. These resources, increasingly accessible through various research infrastructure initiatives, ultimately foster a deeper understanding of the complexities inherent in socio-environmental systems.

Risky business

Archaeology plays a pivotal role in understanding past societies' responses to climate change by recording shifts in human behavior over time. By examining these changes in relation to environmental shifts, archaeology reveals actions that were more or less effective in different environments and in the face of various climate or weather extremes. The archaeology of disaster is especially interested in researching these moments of natural extremes and the societal responses that follow, particularly considering additional elements such as the nature of the disruption—whether it was human-caused or natural—and whether it occurred abruptly or gradually, and what the societal structure was like before the (Halstead & O’Shea, 1989; Bawden & Reycraft, 2000; Torrence & Grattan, 2003; Birkmann et al., 2010; Guttmann-Bond, 2010; Cooper & Sheets, 2012; Riede, 2017b; Martin, 2020; van Bavel et al., 2020). This dissertation takes a related approach and considers the social context before, during, and after the event. Such an approach is crucial as it provides valuable insights necessary for understanding and addressing contemporary environmental challenges effectively (Egan, 2019; Mjema, 2022).

There has been a notable surge in synthetic studies – those that amalgamate social and environmental sciences to deepen our understanding of past human-environment interactions – particularly on broader regional scales, since the first IPCC report came out in 1990 (see Carleton & Collard, 2020 for a review of the literature). These studies span two crucial dimensions: dissecting the
impact of human activity on landscapes and unraveling how environments have shaped human behaviors and societies (Butzer, 1982; Hardesty, 2007; Redman, 1999; Barton et al., 2011; van der Leeuw et al., 2011; van der Leeuw, 2014; Crumley, 2017; Burke et al., 2021; Riede, 2023). In a recent review article by Weiberg & Finné (2022), which examined human-environment interaction in the Mediterranean region, they identified 280 articles published between 2016 and 2021 dedicated to this topic. Similarly, a review focusing on historical time periods by Ljungqvist et al., (2021) analysed 165 studies published between 2000 and 2019 that explore the connection between humans and climate variability. At the core of much of the reviewed research is the effort to learn about and define how humans alter landscapes for their benefit and to examine societal responses to extreme climate events in the hopes that identifying these dynamics will motivate cross-disciplinary collaboration and inform today’s environmental issues (van der Leeuw et al., 2000; Van der Leeuw & Redman, 2002; Redman & Kinzig, 2003; Fisher et al., 2009; Barton et al., 2013; Erlandson & Braje, 2013; Petty et al., 2015; Barton, 2016; Boivin et al., 2016; Erlandson et al., 2016; Stephens et al., 2019; Boivin & Crowther, 2021). According to Carleton & Collard (2020) in their review paper, the themes of climate change and human impact primarily revolve around the utilization of proxy data to confirm and interpret change, while the theme of human-environment dynamics concentrates on abrupt climate events or regional differences. Other reviewers such as Ljungqvist et al. (2021) and Degroot (2021) confirm these research trends, noting a bias towards studying specifically climatic cooling events. Overall, these synthetic studies, ‘palaeo-environmental humanities (pEH)’ or ‘history of climate and society’ (HCS) studies, as they may be alternatively related and labeled, tend to incorporate quantitative approaches to comparing humans and the environment, with a focus on moments of environmental volatility or natural disasters (Riede, 2017; Degroot et al., 2021).

The Collaborative Research Center (CRC) 1266 ‘Scales of Transformation’ project, based at Christian Albrechts University in Kiel stands as an excellent example of synthetic studies that utilize a combination of archaeological and environmental big data, offering various regional examples. In particular, its project cluster F1 focuses on abrupt climate change or socio-environmental crises and their correlation with transformations evident in the archaeological record. However, despite the valuable research on human responses to environmental risk contained in the papers produced by CRC 1266 and individual researchers, their perspectives are often overlooked or not fully integrated into the current climate discourse (Braje & Erlandson, 2013; Petty et al., 2015; Rockman & Hritz, 2020; Boivin & Crowther, 2021). Additionally, historic human-climate studies struggle to engage with the IPCC in asking new questions and to communicate their applicability in the contact with local and regional policy. In a societal debate where the idea and cause of
climate change in general are questioned, incorporating lessons from history can become even more challenging.

In their 2020 paper, Kohler & Rockman address this issue and propose strategies to enhance engagement and overcome the barrier to informing the climate change discourse. First, they note the historical absence of archaeologists on the IPCC writing team and emphasize the need for closer collaboration between archaeologists and paleoclimatologists to recognize and elevate archaeological contributions within the predominantly climate science-focused report. Additionally, they advocate for a shift in research framing towards exploring the impacts of climate change on society. Appropriately, there are several current initiatives aiming to enhance our understanding of the impacts of rapid environmental change on human societies. For instance, CONVERGE, located at the Natural Hazard Center in Boulder, Colorado, is dedicated to investigating the effects of natural hazards and has a dedicated research network regarding Social Science Extreme Events Research (SSEER). In Aarhus, the Laboratory for Past Disaster Science (LaPaDis), led by Felix Riede, focuses on understanding the social response to past abrupt climate events. Another example is, the Center of Natural Hazard and Disaster Science (CNDS), established by the Swedish government in 2010, which integrates expertise from Uppsala University, Swedish Defence University, and Karlstad University to address the complexities of natural disasters and their societal implications, advancing our understanding of disaster resilience and response strategies.

Kohler & Rockman (2020) highlight the IPCC's keen interest in attribution studies, which assess the relative contributions of multiple causal factors to a change or event with confidence (IPCC, 2022), which underscores the necessity for increased engagement with quantitative analysis. However, this interest brings us to second significant obstacle: the uncertainty surrounding the interpretation and integration of information from the deep past (Riede et al., 2016; Hussain & Riede, 2020). Advancements in computational methods are enhancing our capacity to address this uncertainty (Barton et al., 2011, 2012, 2013; Anichini et al., 2012; Bevan & Lake, 2013; Isern et al., 2014; Gattiglia, 2015; Barton, 2016; Brown, 2017; Crema et al., 2017; Huggett, 2018; Riede et al., 2020). These computational tools facilitate the interrogation and integration of vast datasets across disciplines, including archaeology and environmental science. Moreover, statistical probabilistic methods enable researchers to quantify uncertainty in their analyses, providing probabilities for different outcomes and offering a more nuanced understanding of past human-environment interactions (see Methods for a more detailed discussion). Traditional humanities interpretation and understanding remain crucial, especially when integrated with results from computational approaches, as multimethod corroboration enhances and strengthens our interpretations, making them more resilient and robust in addressing uncertain factors.
Quantitative analysis

The integration of statistical analysis into archaeology has been longstanding, as the field inherently seeks to investigate relationships and distributions of materials in time and space. This use ranges from simply describing the frequency of material phenomena at sites to making inferences from representative samples. However, the utilization of statistics in archaeology comes with its own set of challenges, notably due to the characteristic uncertainty and subjectivity involved in interpreting archaeological data. In his book, *Quantitative Archaeology*, Shennan reflects on the persistent difficulties archaeologists encounter when attempting to incorporate quantitative methodologies, how often the instruction in statistics is not properly related to archaeological analysis and can be ‘boring’ (Shennan, 1988). Four decades ago, Thomas critiqued misuse of such methods in archaeology, claiming few uses were ‘good’, but most uses being ‘bad’ and ‘ugly’ (Thomas, 1978); the main critique being that archaeologists must develop knowledge of basic statistics in order to properly use its methods.

The technological revolution has helped to advance archaeological research and enabled the exploration of previously inaccessible dynamics. From remote sensing techniques to Geographic Information Systems (GIS), the use of digital tools in archaeological excavation and research is now commonplace; these tools have enabled the systematic recording of larger volumes of data with greater accuracy. Furthermore, researchers are increasingly applying sophisticated analytical techniques in their work, such as Bayesian analysis, spatial statistics and machine learning. This shift in the use of analytical technique can be attributed to several factors, including advancements in technology, a growing inclination towards interdisciplinary data analysis, and the exponential growth of data requiring innovative interrogation methods. This transition not only builds upon existing understandings but also enriches and challenges them, fostering a greater comprehension of past human-environment interactions.

An important technological advancement in the field was the development of statistical and mapping software, following established platforms such as SAS (Statistical Analysis System) and SPSS (Statistical Package for the Social Sciences), and ESRI’s ArcGIS, which revolutionized geographic information systems. Subsequently, the emergence of open-source applications like R and QGIS further democratized access to advanced analytical tools (R Core Team, 2023; QGIS Development Team, 2024). The increased accessibility in archaeology has led to a prolific integration of methodologies and approaches from the natural and environmental sciences. Scholars, including Malmer and Butzer, among others have played crucial roles in paving the way for such interdisciplinary collaboration (Hodder & Orton, 1976; Clarke, 1977; Straus & Clark, 1978; Malmer, 1981; Butzer, 1982). Their contributions exemplify early efforts in spatial analysis within archaeology, such as borrowing
from geographic methods to map artifact densities against environmental conditions (Malmer, 1981).

Nowadays, there is an abundance of instructive texts available to guide interested archaeologists in the utilization of spatial software and statistical methods. Notable examples include *Quantitative Methods in Archaeology Using R* by Carlson (2017) and *Computational Approaches to Archaeological Spaces* by Bevan & Lake (2013), among others (Conolly & Lake, 2006; Gillings et al., 2020). Such texts both discuss and provide instruction in computational methods like statistical software analysis, data visualization, data mining, and database organization, all of which play a crucial role in effectively handling large datasets (Mazzocchi, 2015; Cooper & Green, 2016).

The renewed emphasis on quantitative analysis rekindles concerns about simplistic dualistic interpretations of environmental determinism, particularly when researchers investigate social and environmental factors concurrently, potentially leading to the assumption that all human actions are mere responses to the environment (Hulme, 2013; Arponen et al., 2019). Recent debate has revolved around the impact of a ‘third revolution’ in archaeology, which risks pushing the field too far toward quantification and excessive reliance on statistical methods, potentially overlooking the intricate interplay between socioeconomics and environmental factors (Kristiansen, 2014; Larsson, 2014; Niklasson, 2014; Ribeiro, 2019; Degroot et al., 2021; Ljungqvist et al., 2021). Quantitative approaches pose a risk of oversimplifying the nuanced qualitative aspects of the archaeological record, promoting the assumption of a one-size-fits-all solution to climate issues. However, the papers in this thesis underscore the importance of prioritizing critical approaches, examining both environmental and social factors simultaneously, and emphasizing the need for comprehensive data collection at both regional synthesis and local levels to gain a deeper understanding of changes.

**Ethical considerations**

There are numerous tensions surrounding big data, encompassing diverse perspectives on the ethical considerations that must be taken into account; it is quite a beehive of an issue. These range from the sustainability of big data sets, including the environmental impact of storing vast amounts of data and the pressure of maintaining digital archives, to issues of fairness in the distribution of data. Questions of ownership regarding who is permitted to share the data, and considerations about the subjects or entities that the data pertains to (privacy and security), are also posed, including the context in which it may be shared (Mittelstadt & Floridi, 2016; Lucivero, 2020). These concerns are closely linked with the question of equal access to digital technologies and the internet (Hampton et al., 2013; Gattiglia, 2015; Gupta et al., 2020). Furthermore, considerations regarding the quality and potential biases of the data are
paramount. It is essential to remember that data is not synonymous with truth; instead, it forms the foundation for analysis (Gattiglia, 2015). Despite its quantifiable nature, data inherently possesses qualitative aspects influenced by factors such as the methods of selection and sampling. To clarify and ensure transparency, both the factors influencing data interpretation and the decisions made based on this interpretation need thorough explanation.

The concept of FAIR data principles – Findability, Accessibility, Interoperability, and Reuse – serves as a guiding framework in managing these complex issues in big data and open science (Wilkinson et al., 2016; Derudas, 2023). However, it is important to acknowledge that implementing these principles can be more challenging than anticipated, and their application may not always be straightforward (Mons et al., 2017). Interpretations and implementations of FAIR practices differ across local or national institutions and organizations, as there is no requirement for their adoption (Doorn & Ronzino, 2022). Moreover, local or national laws interact with FAIR principles. For example, in Europe, the General Data Protection Regulation (GDPR) protects “special categories of personal data”, including genetic data, which archaeological data can encompass (EU FRA, 2019). These issues are closely tied to concerns regarding data ownership, security, and access.

In addition, there are ethical considerations in the study of human-environmental disaster research and climate change studies. Scholars like Riede and others assert that archaeologists have a responsibility to engage in policy and public conversations about environmental disasters and their impacts with the public (Riede et al., 2016; Shaw, 2016; Riede, 2017a). This engagement helps to raise awareness about the various possibilities and outcomes associated with such events (Birkmann et al., 2010).

While there may be no singular solution to the multitude of ethical challenges posed by big data in human-environmental research, prioritizing ethical awareness and responsibility, including transparency in research practices, serves as a foundational step towards addressing these concerns and upholding ethical standards in research practices.

The papers in this thesis capitalize on open science practices and remarkable data accessibility within the studied field lab areas. Nevertheless, there is an imbalance in data availability across Europe, stemming from factors such as funding disparities, research focus and limited digital infrastructure support. Papers I-IV uphold FAIR principles by sharing data and code used within the papers, thereby promoting transparency and accessibility in research practices. Importantly, these files are compatible with open-source software such as R and QGIS, ensuring interoperability in line with FAIR principles.
Study regions

The focus on Northwest European Landscapes stems from TerraNova's ambitious project objectives to develop a comprehensive digital atlas of human and environmental distribution throughout the Holocene period. This initiative aims to provide researchers and policymakers interested in human-environment interaction and climate change with access to layers of pertinent social and environmental information essential for refining current land management strategies.

In this project, a number of ‘field labs’ were selected in Northwest Europe (see Figure 1). In practical terms, the selection of field labs was guided by two primary criteria: first, to offer a diverse representation of European environments, and second, to prioritize areas where expert support was readily available. The geographical area encompassed in this thesis consists of three geographically distinct field labs, each typically centred around a major river system: the Dalälven in Sweden, the Rhine-Meuse in the Netherlands, and the Oder between Germany and Poland. These field labs serve as focal points for conducting detailed investigations into the dynamics of human-environment interaction within specific geographic contexts. The understanding of landscape evolution in distinct regions has the potential to inform targeted interventions for sustainable land management practices.

The compilation papers of this dissertation offer detailed insights into the geographical and cultural backgrounds of the field labs, each presenting unique environmental and cultural evolutions. Despite sharing geographical proximity in Northwest Europe, the field labs differ significantly in their historical and environmental trajectories.

Sweden, characterized by its boreal environment, was the last of the three regions to be populated following the last glaciation and has experienced dramatic land transformations due to isostatic uplift (Knutsson & Knutsson, 2012; Larsson, 1999; Stroeven et al., 2016). The Dalälven watershed, encompassing a diverse range of landscapes from mountains to coastlines, reflects the multifaceted nature of this region's environmental dynamics.

Previous Scandinavian focused research has explored societal responses to extreme climate events. Riede (2017b) proposed the 'Laacher See hypothesis,' suggesting a volcanic eruption triggered demographic and cultural changes in the Bromme culture during the Late Glacial period. Bunbury et al. (2023) found evidence of farming practices adoption during the Holocene Thermal
Maximum (HTM) and societal resilience to cooling periods through intensified trade networks, leading to economic growth and larger house sizes. The 'fimbulwinter' in Scandinavia, linked to the 536/540 AD volcanic events, spurred social transformations and shifts in settlement patterns, documented in various studies.

The Oder, situated at the southern end of the Baltic Sea, has similarly experienced substantial changes throughout the Holocene. Influenced by the shifting shape of the Baltic and isostatic uplift, albeit to a lesser extent than Sweden, this region boasts a blend of continental and maritime environments (Harff et al., 2020; Sydor & Uścinowicz, 2022). Positioned at the crossroads of East and West, the Oder holds significant historical and ecological significance (Kleijne et al., 2020; Bunbury et al., 2023). Burdikiewicz's (2011) research on societal responses to the Younger Dryas also highlights the Oder River area as a transition zone for late glacial societies. It suggests that changes in lithic technology, particularly a reduction in size, or migration, this case northward to follow reindeer subsistence, were common responses to the cooling climate event. Other studies in this region explore technological changes, architecture, settlement patterns, burial practices, mobility, and increasing regional exchange as responses to various extreme climate events of the Holocene (Borzenkova et al., 2015; Pokutta, 2013; Kneisel et al., 2019; Dörfler et al., 2023).

The Rhine-Meuse region, influenced by frequent transgressions of the North Sea throughout the Holocene, has long been subject to human manipulation due to its strategic geographic location (Hijma & Cohen, 2019; Nienhuis, 2008). This landscape exemplifies the intricate relationship between humans and their surroundings. Similar to other field lab areas, societal responses to climatic events in the Rhine-Meuse region varied depending on the specific event, such as the 8.2k, 4.2k and 3.2k BP events. These responses included technological transitions, cultural changes, and migrations (Kleijne & Huisman, 2023; Louwe Kooijmans et al., 2005; Robinson et al., 2013; van Dinter & van Zijverden, 2010).
Figure 1. Map displaying the field lab locations, including Dalälven in Sweden, Rhine-Meuse in the Netherlands, and the Oder Delta spanning Germany and Poland. Other regions investigated are depicted in grey. Numerals indicate the corresponding paper (I, II, III, or IV) that analysed each area.
Method

Given the computational advancements and resources now available for archaeological analysis, the methods of the papers included in this compilation thesis primarily focus on the statistical analysis of large sets of radiocarbon dates. This approach aligns with a broader trend in archaeology, as discussed in the *Current Trends – Big data, archaeology and environmental risk* section, where many researchers have embraced the concept of “dates as data,” and employ statistical analysis, often summed probability distributions (SPDs), on radiocarbon-dated archaeological samples to model patterns of human activity and their interactions with the environment over time (Rick, 1987; Crema et al., 2017). Consequently, archaeologists are no longer confined to a narrow spatiotemporal focus but can adopt a broader perspective, revealing the intricate dynamics between space, time, humans, and nature from a regional and multitemporal standpoint.

Data availability

The quality of and access to the growing amount of data pose challenges to proper analysis. An increasing number of archaeological datasets are being made available by individual researchers, often provided as supplemental information accompanying peer-reviewed papers and increasingly on GitHub repositories, or through dataset projects like EUROEVOL and PAECA (Shennan & Steele, 2008; Weninger et al., 2009; d'Errico et al., 2011; Hinz et al., 2012, 2016; Vermeersch, 2020). Subsequently, other researchers are working to amalgamate these datasets into a larger, centralized source. Examples of such efforts include the p3k14c synthetic database and, more recently, the Xronos open repository, which help to align archaeological data offerings with those in palaeoenvironmental science (Bird et al., 2022; Hinz & Roe, 2022). For example, NASA’s Paleoclimatology repository allows users to search for specific datasets across their own collections and those of other data publishers, such as Neotoma and Pangaea (Williams et al., 2018). Open data repository efforts aim to enhance data accessibility, though similar to archaeological data, biases in coverage and availability exist in palaeoclimatological datasets. Some regions or time periods may be overrepresented due to easier access or historical interest, while others may lack sufficient data.
The creation of R packages by some of these databases (i.e. Xronos, Neotoma) facilitates data integration with computerized statistical analysis, though the standardization process of combining large amounts of data can sometimes result in a loss of detailed information. However, this standardization is necessary to ensure comparability across disparate datasets. Indeed, when working with datasets there is a trade-off between having access to broader, but potentially less detailed information, versus seeking out or creating more locally specific datasets that offer richer relational context for the $^{14}$C samples.

In this compilation thesis, the accessibility and quality of archaeological data are significantly influenced by geographical location. In the Oder case study region in Germany, access to site records is not often digitized. This means that researchers still need to contact individual state or Bundesländer Offices for Culture (Landesarchäologie) to access these records. Depending on the infrastructure of these offices, researchers may be required to physically search through records to retrieve $^{14}$C dates and detailed information related to them. Alternatively, there may be access to a data-reduced geoportal, as for example in Brandenburg, although accessing $^{14}$C data through this portal may be limited to onsite use via their intranet and data retrieval can be a time-consuming process due to the need for manual text searches within the portal (Land Brandenburg, 2024).

On the opposite side of the river, Poland's National Heritage Institute (Narodowy Instytut Dziedzictwa) has developed a geoportal where users can search for site information (NID, 2023). However, the completeness and level of access to the information vary, and searching for individual $^{14}$C data can again be a time-consuming process.

In the Rhine-Meuse study region in the Netherlands, data access is facilitated through their DANS Data Station Archaeology, however, extracting $^{14}$C information from this platform can be a challenging data mining task (DANS, 2024). Recently, the Netherlands has undertaken the aggregation of $^{14}$C records from archaeological contexts into a centralized database, promising enhanced accessibility in the future.

As for the Swedish study region, this thesis has benefited from extensive initiatives by county museums and independent researchers aimed at creating $^{14}$C databases and promoting data sharing. These efforts have facilitated fine-grained categorization and analysis, enhancing the depth of research in the region. Efforts are presently ongoing to provide researchers with access to these extensive repositories of radiocarbon data through the Swedigarch infrastructure (Swedigarch, 2024).
Uncertainty and significance

The papers of this thesis each extensively utilize computational techniques, leveraging database software, alongside QGIS and various R packages for data curation, analysis, and visualization. These methodologies are specifically aimed at testing radiocarbon-dated samples to identify temporal synchronicities between human and environmental variables in an effort to discern human responses to ecological changes. The progression of this method of human-environmental study was sparked by, as mentioned prior, the ‘dates as data’ approach and comparative $^{14}$C analyses in the natural and social sciences (Deacon, 1974; Geyh, 1980; Rick, 1987, Carleton & Groucutt, 2021).

Radiocarbon dating and analysis techniques

The papers in this compilation thesis predominantly employ summed probability distributions (SPDs) or kernel density estimates (KDEs) of calibrated radiocarbon dates to visualize population trends over time. By aggregating the probabilities of calibrated dates falling within specific time intervals, these methods facilitate the identification of periods of population growth or decline, shifts in settlement patterns, and changes in economic or social activities (see Figure 2 for a graphical example; Shennan et al., 2013; Brown, 2017; Crema et al., 2017). Researchers utilize these time series visualizations to make inferences about past human behavior and societal organization. One common method involves analyzing the shape of the probability distribution curve at certain time periods to discern changes in human activity. Additionally, researchers often compare the curve to environmental variables to explore the relationship between humans and their environment. While this visual analysis, often referred to as ‘eyeballing,’ serves as an initial step for further investigation, it does not provide a rigorous assessment of the significance of observed changes.

Figure 2. Example of an SPD (dark grey) and a KDE (light grey) created in the OxCal v4.4.4 program. Coloured bars represent periods of analytical interest investigated in Paper I.
Concerns about the accuracy of radiocarbon samples in representing archaeological site chronology have led to criticism of radiocarbon dating methods used as proxies for population dynamics (Crema, 2012; Williams, 2012; Brown, 2017; Carleton & Groucutt, 2021; Crema, 2022). Notably, challenges arise regarding the interpretation of ¹⁴C samples. The ‘dates as data’ approach suggests that an abundance of samples falling into one time period implies increased population. However, these samples are vulnerable to selection bias resulting from factors like research focus and funding priorities, while taphonomic processes can influence the preservation and composition of the archaeological record, ultimately affecting sample size. Overcoming these challenges often involves obtaining a greater number of dates and specifying what the dates represent, adopting a categorical or behavioral process approach that extends beyond population dynamics. Additionally, utilizing statistical methods can help mitigate biases, although these measures do not completely eliminate them.

Furthermore, the calibration techniques applied to radiocarbon dates introduce additional complexities. Calibration curves, such as IntCal20, the reference curve used in the analysis of the papers in this thesis, which form the foundation of the calibration process for radiocarbon dates, are constructed from samples with known calendar ages to correct for fluctuations in atmospheric carbon-14 levels over time (Reimer et al., 2020). However, uncertainties inherent in this process necessitate the use of statistical methods to refine the curve (Bronk Ramsey, 2009). Interpolation and simulation techniques are commonly employed to bridge gaps between measured data points and account for uncertainty in the calibration curve (Reimer et al., 2020). To address this uncertainty, widely used radiocarbon calibration programs, such as OxCal, utilize Bayesian statistical methods to calibrate radiocarbon dates and offer calibrated date ranges rather than precise calendar dates for the timing of archaeological events or phases (Bronk Ramsey, 2009; Reimer et al., 2020).

Given the intricate process involved in reconciling the uncertainties of radiocarbon dating with the probabilistic nature of calibrated dates, it is important to recognize that summing the probabilities could potentially amplify biases. To address this concern, the papers of this thesis employ the SPD methods from the rcarbon package in R, which allows for steps to minimize biases, for instance, binning or thinning (Crema & Bevan, 2021). If one site or time period is overrepresented, samples that are close to each other in time are grouped into the same ‘bin’ (e.g., group), facilitating a comparison of the frequency of events in each bin and thereby reducing the potential impact of overrepresentation on the analysis. However, binning is subject to the choice of the parameter (e.g., 50 or 200 years), and these different parameters must be tested to determine their impact through sensitivity analyses (Crema, 2022). Alternatively, thinning allows for the selection of a specific number of dates to reduce biases introduced by the sampling process, offering another avenue for improving the integrity of the data analysis.
Kernel density estimation (KDE) does something similar to binning, but rather than dividing data into bins, kernel density analysis uses a smoothing function, or a kernel function, to estimate the density of events at each point in time and this helps correct for biases in the distribution of data, such as overrepresentation of certain sites or time periods, cutting through the noise and providing a more accurate representation of the underlying trends (Brown, 2015, 2017; Crema & Bevan, 2021). Rcarbon also provides a function to produce composite kernel densities (CKDE), meaning that dates are randomly sampled to create a KDE and the process is iterated many times (Monte Carlo Method) to produce an envelope of KDEs (Crema & Bevan, 2021).

Null hypothesis testing and p-values
To deepen the understanding of patterns generated by SPDs and KDEs beyond visual inspection, Papers II-IV employ null hypothesis significance testing to identify significant periods of change and categorize SPDs, illustrating how behavioral processes reflect specific human activities. Null hypothesis significance testing involves comparing the outcomes of observed SPDs to various growth models to assess whether the observed patterns are statistically significant (Crema & Bevan, 2021). For instance, if the trend observed in an SPD significantly deviates from the expected distribution under a specific growth model, it may suggest a departure from the null hypothesis and provide insights into the underlying dynamics of human occupation or activity (see Figure 3). It is worth noting that one issue with growth models in this context is the uncertainty regarding the applicable model of growth for that time period. Generally, it can be assumed that growth occurred rather than remained uniform, so exponential and logistic models are commonly employed models. The rcarbon package offers the modelTest() function specifically designed for this purpose; it allows testing against a choice of models: exponential, logistical, uniform, or custom created models (Crema & Bevan, 2021).

Significance, as measured by p-values, serves as a tool in the scientific method for evaluating the likelihood that an observed variable is non-random and aids in deciding whether to reject the null hypothesis (Nuzzo, 2014). P-values essentially measure uncertainty, with lower values as stronger evidence against the null hypothesis, however rather than greater certainty in the observed effect. For instance, p-values help identify genuine signals, such as deviations from an exponential growth model that assumes a consistent rate of growth in observations over time. If observed $^{14}$C dates exceed a growth model, it suggests an increase in human activity, which prompts questions about the drivers of such changes, such whether natural, environmental factors or socioeconomic shifts, including the adoption of different land use practices, might be the reason for the change. Additionally, rcarbon’s method of null hypothesis significance testing establishes a critical envelope indicating the
upper and lower bounds of the growth model. Giving attention to uncertainty helps refine the analysis and offers a more nuanced understanding of the data.

**Figure 3.** Example of a null hypothesis significance test result for Inland Sweden radiocarbon dates using a logistical growth model created in the `rcarbon` package. Grey area represents the 95% confidence envelope of the fitted logistical growth model. Black line represents the observed SPD with red areas showing periods exceeding the expected growth and blue areas showing periods below the expected growth. The dashed red line represents the 536/540 AD event as investigated in Paper II.

Continuing on the topic of methods used to test for significance, correlation tests play a pivotal role in understanding relationships between environmental variables. Additionally, the Mann-Kendall test, employed alongside correlation tests, helps assess trends and changes over time in environmental variables, enhancing our understanding of temporal dynamics. While some researchers have employed trigger or coincidence analyses to infer causality based on the timing of events, the papers of this thesis focus on correlation approaches to acknowledge the intricate nature of the examined system, where multiple factors interact, and recognize the inherent uncertainties in radiocarbon timing analyses (Kintigh & Ingram, 2018; Heitz et al., 2021; Kim et al., 2021). Spearman's correlation, employed and detailed in Paper III, holds the power to quantify the strength and direction of the relationship between variables such as demographic proxies and environmental proxies. It determines whether a robust positive or negative relationship exists, signifying whether changes in one variable correspond with changes in the other. Furthermore, the consistency of observed patterns over time can indicate the significance and stability of the relationship between humans and their environment. Conversely, alterations in the relationship over time suggest the presence of other influencing factors, highlighting the dynamic nature of socio-ecological relationships and underscoring the importance of considering temporal changes in data analysis and interpretation.

A limiting factor is the resolution and frequency of data, as already discussed. Even in areas where the resolution of archaeological data is high, as
the field labs of focus in this thesis do, there might not be enough environmental data, or vice versa. One positive example is Palmisano et al. (2021). Their study provides a comprehensive illustration of integrating SPDs, KDEs, and correlation tests in their research. Focusing on Italy, their study examines regional demographic trends correlated with climate fluctuations from the late Mesolithic to the Early Iron Age. Palmisano et al. (2021) examine human behavioral variations and their correlation with climate change across different time periods and regions utilizing diverse local climate proxies, including cave, lake, and marine records, and employing analytical tools from the `rcarbon` package as well as the Pearson correlation coefficient. The study’s multifaceted approach yields a nuanced understanding of the intricate interplay between human societies and their environments over time. Notably, their findings reveal demographic fluctuations across regions, where a 'boom' in demographics in one area often corresponds to a 'bust' in other areas. Furthermore, these fluctuations appear independent of changes in the hydroclimatic proxies studied.
Theory

Several significant and pertinent theoretical concepts intersect within the papers of this thesis, collectively providing insights into the interpretation of patterns evident in the archaeological $^{14}$C data and environmental proxies studied in the articles. These concepts encompass ideas found within historical ecology, risk management, resilience and human niche construction. At the core of these frameworks and theories lies the fundamental concept of complex systems' response and adaptation to natural hazards. Diverse case studies in various volumes and compilations exploring human responses to environmental risks, drawing on these concepts to understand human-environment interactions and address contemporary climate challenges, highlighting their utility (Halstead & O'Shea, 1989; Cooper & Sheets, 2012; McIntosh et al., 2013; van Bavel et al., 2020).

First, the argument that exploratory analysis of big data does not require advanced theory, as theory might hinder problem-solving must be problematized. Exploratory analysis of large datasets may enable an objective examination of relationships between patterns and trends without the constraints of pre-existing theories, challenging the assumption that advanced theoretical frameworks are always necessary for data analysis (Mazzocchi, 2015; Coveney et al., 2016).

Research design

Some argue that exploratory analysis of big data does not require advanced theory, as theory might hinder problem-solving. Anderson (2008) suggests that not having a theory in advance allows for an objective observation of patterns, essentially advocating for letting the numbers speak for themselves (Anderson, 2008; Mazzocchi, 2015). However, Gattaglia (2015) asserts that working with big data is a method of high-level analysis rather than simply dealing with 'high volume, high velocity, and/or high variety data'. Thus, substantial discernment judgment is also needed (Coveney et al., 2016). While big data analyses may not be constrained by specific methods, they are still grounded in theoretical principles and guided by hypotheses derived from theory.
Exploring data using computational methods is intriguing and acknowledges the wealth of available data, yet it must be integrated effectively to address questions about human-environment relationships. In the context of this thesis, the integration of concepts and theory is especially important. Identifying risks and analyzing human responses to these risks necessitates the application of theoretical frameworks. These frameworks have guided the methodology, determining how data is structured and which tests are employed, ensuring rigor and relevance to the research questions at hand. Consequently, the papers in this thesis draw upon theories and frameworks related to complex socioecological systems to inform their research design, such as historical ecology, risk management, human niche construction, and resilience.

Key concepts
As stated above, several concepts work together to build an understanding of human response to environmental risk. Historical ecology integrates social and natural records offering a temporal perspective essential for revealing correlations and consequences of social actions, serving as a pivotal framework for the concepts of resilience, risk, and niche construction. Resilience, or the ability to adapt in a changing environment, minimizes the likelihood and severity of negative outcomes associated with risk. Additionally, human niche construction theory explains how humans actively shape their environments to mitigate risk and enhance resource stability, primarily through land use activities. Finally, risk management theory addresses the way human populations manage resource risk amidst ecological uncertainty, especially in response to unpredictable environmental events.

Historical ecology
Carol Crumley (1987), a pioneer of the historical ecological approach through her work in Burgundy, France, among other regions, describes historical ecology as an incorporation of humans as integral components of ecosystems, offering an “evidence-validated, open-ended narrative” of how human activities and environments have evolved and changed (Crumley, 2021). The historical ecology framework serves as a foundation for understanding the dynamic relationships between humans and their environments due to its openness to various methods and theories that aid in comprehending these interactions over extended periods and across diverse geographical contexts (Balée, 2006; Isendahl & Stump, 2019).

Furthermore, historical ecology's spatiotemporal scope enhances this understanding; it demands an analysis of the causes and consequences of change over time and space, aligning closely with this thesis’ aim to understand human response to environmental risk. This necessitates investigating the
periods before, during, and after an event to identify a change in the relationship between the environment and humans, and if there are changes in human action can they be considered independent of environmental factors or a response to them (Sinclair et al., 2020). As such, the papers of the thesis adopt the long-term perspective of historical ecology to observe enduring effects of rapid changes or natural disasters, as well as more gradual transformations.

**Resilience**

Resilience theory remains an important framework for discussing risk. Resilience refers to the capacity of social and environmental systems to incorporate small scale changes to withstand large scale negative change (Gunderson et al., 2002; Walker et al., 2004; Adger, 2006).

Resilience theory involves tracking a system over time to study its response to change, including extreme events, and assessing whether the system maintains its integrity or undergoes significant transformation. This parallels historical ecology's emphasis on the temporal dimension, as both heavily emphasize the importance of time in understanding ecological dynamics and human-environment interactions. By analysing societal structures before and after such negative disturbances, resilience theory facilitates the evaluation of societal vulnerabilities to environmental change (Adger, 2006; Pfister, 2010; Nelson et al., 2016; Connolly & Lane, 2018; Riede & Jackson, 2020; van Bavel et al., 2020; Arthur et al., 2024). Additionally, the papers of this thesis inspect how the societal structures that exist before extreme events can affect the magnitude of the natural hazard’s consequences, aiming to identify vulnerabilities within society. For instance, Paper II suggests that regions overly reliant on one type of land use, such as agriculture, makes them more susceptible to extreme climate change, and this dependency on agriculture alone can result in societal decline or a total restructuring of society.

Defining and measuring resilience poses a significant challenge. While qualitative approaches are common, such as Weiberg & Finné’s (2018) identification of resilience in the Late Bronze Age Peloponnese using political structure as a proxy (Degroot, 2021), Riris offers a quantitative approach, positioning their study as a step toward comparative and quantifiable resilience. Motivated by the interpretative view's limitations on meaningful cross-regional comparisons, Riris sought to define resilience as a measurable property in socioecological systems, drawing from ecological methods. This involved quantifying $^{14}$C population frequencies in relation to a known climate event, the Medieval Climate Anomaly (MCA), revealing regional disparities in resilience.
Human niche construction

Human niche construction examines how human activities, particularly through land use practices, shape landscapes, influencing ecological systems over time and subsequently impacting future activities and choices (Laland & O'Brien, 2011; Eriksson, et al., 2021). However, as implied by the ecological term 'niche construction,' this process is not unidirectional. Species other than humans also shape niches that overlap with human niches. Simultaneously, these niche constructions also shape long-lived physical memories (Riede, 2011; Collard et al., 2011; Smith & Zeder, 2013; Erlandson et al., 2016; Ellis et al., 2018).

As noted by Gould (1989), who suggests that 'historical contingency' plays a pivotal role in evolutionary processes, this notion resonates with human niche construction. For instance, in Scandinavia, the first agricultural clearings altered ecological dynamics, creating new biodiverse spaces in the meeting of pasture and forest, as examined by Eriksson (2017) during the Neolithic to Bronze Age shift in central and Northwest Europe. Though farming can deplete soil quality and vegetation structure, these changes allow for novel responses that were not previously required. Moreover, the concept of human niche construction aligns with the spatiality of historical ecology, which focuses on connections and behaviors at a landscape level rather than individual sites.

As critical evaluation and debate are integral components of the scientific process, theories are routinely challenged. One common argument against human niche construction is the perception that the definition of a 'niche' can be quite ambiguous, encompassing all human actions and thereby providing limited heuristic value (Spengler, 2021). However, proponents argue that the all-encompassing aspect of human niche construction allows for interesting and fresh perspectives on data and interpretations (Laland & Sterelny, 2006). Critics also argue that human niche construction sometimes repackages or overlooks feedback concepts, which proponents claim makes it unique. The case studies in this thesis find human niche construction to be a valuable concept when considering the construction of risk management strategies and how historical contingencies affect opportunities to respond to environmental risk.

Risk

Risk management is closely linked to human niche construction since strategies to mitigate risk frequently lead to the creation of new niches, examples are the development of the iron industry for trade. Risk management prioritizes adaptive strategies against various risks, including altering land use patterns, or in the words of Smith (2013), a society's inability to effectively adapt to different environmental or socially constructed challenges in a sustainable manner signifies a lack of effective risk management. Risk management
strategies, such as adaptation, mitigation, trade, buffering, and migration, represent human responses to socioenvironmental (White, 1974; Winterhalder, 1986; Halstead & O’Shea, 1989; Winterhalder & Goland, 1997; Winterhalder et al., 1999; Fitzhugh, 2001; Riede, 2017a; Martin, 2020; Hatlestad et al., 2021; Arthur et al, 2024). For example, exchange and migration offer ways to buffer against adverse conditions or adapt to new environments. These strategies are discussed in Paper I as example of possible strategies when living in marginal agricultural environments (Hatlestad et al., 2021). Migration often emerges as a prevalent response to inhospitable environmental conditions, prompting communities to relocate to more favorable areas. An archaeological example of this is the risk response strategy is explored by Heitz et al. (2021) in two contexts related to the Alpine Neolithic period. Their research discusses the local farming communities' adoption of a “quasi-seasonal” settlement pattern, characterized by alternating between lakeshore and hinterland sites and examines how the decline in lakeshore settlements coincides with a significant cooling period around 3400 BCE.

Many researchers apply a combination of these concepts when investigating disasters and analyzing responses to risk and uncertainty evidenced by several volumes and compilations featuring numerous and varied case studies exploring human responses to environmental risks, (Torrence & Grattan, 2003; Cooper & Sheets, 2012; van Bavel, 2020). These rich compilations, along with their multitude of examples, draw on the concepts of historical ecology, resilience theory, human niche construction, and risk management, among others, highlighting the convergence of these concepts and their crucial role in comprehending the intricate interactions between humans and the environment.
Paper summaries

As mentioned in the introduction, the papers summarized here share theoretical and methodological approaches to investigating human responses to environmental risks, whether rapid climate events or uncertain ecological environments, across Northwest Europe. Despite focusing on diverse locations and time periods, these papers share a common emphasis on deep-time series analysis with a spatial component and utilize big data from an interdisciplinary perspective. Incorporating environmental proxy data and various statistical methods, such as kernel density estimates and trend analysis, they provide insights into long-term trends and patterns in human-environment interactions. Moreover, many of the case studies conduct null hypothesis significance testing of radiocarbon data and make regional and categorical comparisons of human land use, revealing regionally specific vulnerabilities, as well as commonalities. Overall, these case studies contribute to a comprehensive understanding of the co-evolution of nature and society over extended periods.

Paper I: Coping with Risk. A Deep-Time Perspective on Societal Responses to Ecological Uncertainty in the River Dalälven Catchment Area in Sweden

This first paper examines how past societies have coped with risk and ecological uncertainty. The chosen study site, Dalarna county in Sweden, offers a distinctive opportunity to investigate how human niche construction, demonstrated through land use practices, responds to resource risk in an agriculturally marginal boreal forest setting. Additionally, research in this area holds significance as it provides alternative narratives of livelihood and resilience pathways outside of the typical focus on agriculture and urban centers, underscoring the importance of conducting studies in more remote or "outland" areas (Hennius, 2021).

The paper adopts an empirical, quantitative approach to analysis, utilizing 14C-samples from archaeological contexts compiled by Joakim Wehlin of Dalarna Museum as the foundation for this study. The 1039 radiocarbon records span approximately 11,000 years of Dalarna’s history. These records were gathered from years of reports on archaeological excavations conducted by the museum, representing a significant databasing and organizational effort.
that yields a wealth of spatial and temporal information about Sweden’s history. Such labor-intensive efforts are crucial for facilitating comparative analysis in archaeological research.

The methods employed for analysis establish a framework and methodology for analysing radiocarbon data within a paired Geographic Information System (GIS) and statistical context, which is adaptable and replicable across diverse landscapes. This entails providing a land use classification system for radiocarbon sample information (assuming other records offer comparable detail), and visualizing the temporal kernel density estimates (KDE) of this data within a GIS environment (see Figure 4). Through this approach, we gain insights into the spatial significance of areas for specific land use practices at different points in time. This approach refines the historical ecology of the region, which integrates social and natural records to uncover correlations and consequences of social actions.

![Figure 4. KDE map showing spatiality of land use during different time periods investigated in Paper I.](image)

The results indicate that during certain periods, communities were motivated to diversify their land uses in order to reduce their reliance on agricultural practices, particularly given the limited support for cultivation agriculture in the boreal environment. This result highlights the role of diversified land use as a strategy for managing risk. Additionally, the findings underscore the
importance of considering unintended consequences or downstream effects when formulating land use policies; specifically, a beneficial consequence is suggested to arise from the shieling agriculture niche in the area: increased biodiversity resulting from the creation of pastures. The convergence of pastures and forest can generate a positive 'edge effect', contributing to habitat heterogeneity. Furthermore, the results suggest that periods of settlement expansion serve as a niche strategy aimed at exploiting valuable trade resources. Trade serves as a means of mitigating resource risk, allowing for the exchange of goods between areas with differing resource availabilities. These findings offer a nuanced perspective by in turn supporting, challenging, and enhancing previous theories on human-environment interaction in the region, thereby contributing to the refinement of our understanding and ideas in this field.

These insights can inform approaches to policy creation for land management practices. This can be achieved by demonstrating the depth of time associated with past practices, emphasizing the need to consider potential unintended consequences, and highlighting the value of diversity, and consequently redundancy, in mitigating unknown risks. Additionally, it can illuminate areas where exploitation may have supported rather than undermined ecological integrity.

Paper II: The Impact of Volcanism on Scandinavian Climate and Human Societies during the Holocene: Insights into the Fimbulwinter eruptions (536/540 AD)

Paper II investigates how societies in four Scandinavian regions responded to extreme climate variability triggered by volcanic events during 536/540 AD. It explores demographic shifts and changes in land use intensity before, during, and after the abrupt climate cooling caused by these volcanic eruptions. Climate simulations using the iLOVECLIM model revealed pronounced cooling and precipitation reduction following the volcanic event. Integrating these findings with radiocarbon dates from archaeological sites unveiled significant regional diversity in societal responses to this environmental disruption. This offers valuable insights into the demographic chronology and land-use practices of Scandinavia during this period. Additionally, the research suggests that the abrupt climate anomaly amplified pre-existing social change rather than triggered it, highlighting the interconnectedness of environmental and societal dynamics.

In the study, we used the iLOVECLIM model, a downscaled global climate model that enhances spatial resolution for temperature and precipitation. This is crucial as although it is commonly accepted that 536/540 AD was an event of cooling, it has been unclear how this affected local climates and rainfall. Conducting ensemble experiments with volcanic forcings allowed us to assess
the specific impact of volcanism on regional climate conditions during the 536/540 AD period. Ensemble experiments, commonly used in climate modeling, involve running multiple simulations with varied initial conditions, including different volcanic forcings, to assess potential outcomes and address uncertainties. Statistical analysis using a student t-test confirmed significant cooling in Southern Sweden and substantial cooling in Norway and Dalarna, indicating the influence of volcanic forcings on regional temperatures during this period. While a decrease in temperature following the 536 and 540 eruptions affected all study areas, the effect on agriculture is likely to have varied regionally. Analysing changes in simulated growing degree days (GDD0) helped to reveal regional agricultural vulnerability (see Figure 5). Dalarna and Inland Norway experienced similar, sizable reductions in length of the growing season (~30%) after the eruption, while Southern Sweden had a 20% reduction in growing degree days. Coastal Norway exhibited the most significant reduction during the event, with a drop of almost 500°C-days.

The climate findings were compared with the timing of changes revealed through the analysis of archaeological 14C samples. Significant changes in 14C were determined using null hypothesis testing methods implemented with the rcarbon package in R. Specifically, a null permutation test was run on the 14C samples to examine the regional variations in population trends. Notably, regional shifts close to the event were observed, and intriguingly, not all trends were negative or indicative of decreases in population density. Swedish regions exhibited positive trends, while Norwegian areas displayed negative trends. A spatial permutation test was conducted to examine the spatial distribution of population growth or decline, revealing clusters of intensified activity within each region. Additionally, permutation tests were employed to analyse various categories of land use within each area during this period, providing insights into the level of economic diversification. The findings indicated increased land use across all categories in Dalarna, while the coastal regions of Norway exhibited declines across all categories.

As a next step, permutation tests were employed to analyse different categories of land use within each area during this period, providing insights into the level of economic diversification. The findings indicated increased land use across all categories in Dalarna, while the coastal regions of Norway exhibited declines across all land use categories. These results suggest that inland Sweden adapted to abrupt environmental risk through trade and diversified land use practices. Conversely, populations in other areas may have experienced decline due to migration as a response to environmental challenges. However, it is noteworthy that the decline trends in some regions, possibly indicating migration, and the increasing trends in other regions appear to have begun prior to the climatic event. This implies that the abrupt climate anomaly amplified pre-existing social changes.
Figure 5. Example map of regional climate conditions for Europe during the 536/540 AD volcanic event investigated in Paper II. Showing (a) Ensemble mean precipitation simulated without volcanic eruption, averaged from 1 to 1000 AD as reference period; (b) Ensemble mean precipitation change during the volcanic eruption (536–541 AD) (c) Growing Degree Days index (GDD0) simulated without volcanic eruption, averaged from 1 to 600 AD and (d) Growing Degree Days index change during the eruption period (536–541 AD) relative to the GDD0 without volcanic eruption expressed as °C-days.

The insights gained from these regions’ responses to this abrupt climate provide guidance for addressing contemporary climate challenges. Trade and diversified land use are effective adaptations that can support societies in mitigating the impacts of sudden environmental disturbances which highlights the importance of integrating these strategies into local and regional climate discussions and planning efforts. Moreover, migration must be recognized as a common response to environmental disruptions. A realization that underscores the need for creating economies and infrastructures that can anticipate and accommodate such movements. By incorporating these lessons into our approach to contemporary climate challenges, we can better prepare and adapt to the uncertainties posed by changing environmental conditions (Chase & Scarborough, 2014).
Paper III: Diverging Deltas: An Integrative Study of Archaeology and Environmental Data Across Holocene Climate Events in the Rhine-Meuse and Oder Regions

This paper surveys the variations in Holocene climate, particularly focusing on the 8.2k, 4.2k, and 3.2k BP events, and their repercussions on human populations (see Figure 6). The study zeroes in on the Rhine-Meuse and Oder regions in Northwestern Europe, characterized by dynamic riverscapes that have undergone distinct socio-environmental changes over the Holocene. Building upon similar theories and methods employed in Papers I & II, Paper III investigates shifts in population density before, during, and after extreme climate changes. Notably, the paper introduces an examination of the utilization of open-source data and software tools to conduct this analysis. The local pollen data utilized in the analysis can be found and reused through the Neotoma Explorer geoportal. The pollen data is also interoperable with our research through the Neotoma 2 package. The population proxy data is sourced from the Xronos Database, which is available online and interoperable with R through the Xronos package. Moreover, the software tools used, including R and QGIS, are open-source, enabling the replication of these analyses without the need for proprietary software.

Paper III continues to repurpose summed probability distribution and null significance hypothesis testing methods, applying them to a distinct geographical area and a different C14 dataset. Additionally, the paper enhances its quantitative analysis by incorporating the Mann-Kendall test to identify trends within environmental data and the Spearman correlation test to compare environmental data with archaeological data.

The Mann-Kendall method revealed that certain climate proxies exhibited extreme trends during the study periods of 8.2k, 4.2k, and 3.2k BP. Importantly, they showed that the effects of these climate events varied between regions, both in terms of the magnitude of the change and the type of change. For instance, during the 3.2k BP event, while the Rhine-Meuse region experienced dryness, the Oder region saw a significant increase in precipitation. Similarly, the Spearman correlation test produced varying results depending on the region and the specific event period being examined. While considering the entire Holocene period, a consistent positive correlation between temperature and precipitation was observed in both the Rhine-Meuse and Oder regions. However, upon closer analysis of specific time periods, such as the 8.2k, 4.2k, and 3.2k BP events, this positive correlation between temperature and rainfall did not always hold true. There was a noticeable shift in the strength of these relationships, which is expected when considering different scales.
Figure 6. Time-series trends of archaeological radiocarbon dates and environmental proxies for the Oder region as investigated in Paper III.

This observation is significant because it offers insight into how human societies may have been impacted by climate events and adapted to changing environmental conditions, such as through migration and technological shifts. Comparing these quantitative changes to archaeological interpretations further illuminates the adaptive strategies employed by past societies. For example, transitions in technology and burial practices during the 4.2k BP event in the Rhine-Meuse region occurred amidst a cooler and drier climate. SPD data
indicates that the population was thriving before and during much of this cool-dry event, suggesting that the transition in technology and burial practices was likely influenced by social factors rather than solely as an adaptation to environmental risk. Moreover, archaeological research suggests that a large migration began prior to 4.2k BP, bringing with it diverse approaches, which could have contributed to the sustained population in the Rhine-Meuse area over this period.

Paper IV: Anthracological and other Macrobotanical Approaches to Holocene Human-Vegetation Dynamics in Sweden

Paper IV employs a comparative quantitative method to analyse radiocarbon-dated anthropological and macrobotanical remains, aiming to investigate the evolving patterns of human-vegetation dynamics and resource utilization within Swedish communities across the Holocene period. Specifically, it concentrates on Götaland and Svealand, regions representing Southern and Central Sweden, respectively. Through the examination of charcoal and macrobotanical remains found in archaeological contexts, the study offers insights into the preferred utilization of different wood species in relation to agricultural practices during specific periods.

This research builds upon the methodologies of previous papers, in this case analysing a comprehensive radiocarbon database meticulously compiled from archaeological excavation reports by wood analyst Ulf Strucke (Strucke, 2024). This dataset prioritizes $^{14}$C samples associated with identified wood or botanical species. Currently, the dataset comprises over 20,000 radiocarbon records spanning the Holocene and encompassing the entirety of Sweden. However, it must be acknowledged that not every record within the dataset is linked to a plant species, yet efforts are ongoing to expand and refine this database.

Similar to Paper I, Paper IV employs a combined GIS and statistical methodology to analyse different biogeographic regions of Sweden – the landsdelar of Götaland and Svealand. These two regions, Götaland in the south and Svealand to its north, are biogeographically distinct areas in Sweden, with Götaland characterized by a temperate climate and broadleaf forests, while Svealand represents a boreal forest environment. This regional distinction enables us to consider local preferences in resource utilization, which are compared to regional pollen records and assessed using statistical functions provided by the rcarbon package in R (see Figure 7). Additionally, multi-layered heatmaps were generated in QGIS to visualize changes and identify correlations and patterns, including expansion, contraction, or stability, in the distribution of wood species alongside agricultural macrobotanical remains.
The results of this comparative analysis of macrobotanical and anthracological remains demonstrate the effectiveness of adopting a multifaceted approach to understanding past human-vegetation dynamics. Additionally, they highlight the long-term impact of human resource utilization on vegetation dynamics. The permutation test results reveal a decline in the use of hazel species around 2,000 BP in both regions, coinciding with an increase in macrobotanical remains associated with agriculture shortly thereafter. This suggests a potential clearing of hazel in favor of expanding agriculture, possibly due to the more fertile soils found in hazel forests.

Moreover, the long-term perspective reveals periods of fluctuation wherein humans capitalized on opportunities arising from climate changes, such as the 6000 BP rapid climate warming (Warden et al., 2017). These periods potentially shaped agricultural landscapes based on resource preferences, coinciding with an increase in macrobotanical remains and the diversification of wood resources. When considered alongside pollen and climate change data, these patterns provide insights into human responses to both natural environmental shifts and those induced by human activity.

![Figure 7. Example of SPDs of anthracological and other macrobotanical species in Götaland as investigated in Paper IV.](image-url)
Discussion

In early April 2024, an earthquake with a magnitude of 7.4 struck Taiwan. Despite the potential devastation associated with such events, Taiwan's proactive measures, including retrofitting buildings following a 1999 earthquake that claimed nearly 2,500 lives, minimized casualties, with the current death toll standing at 12 (The Guardian, 2024). This recent natural disaster in modern society underscores the importance of learning from past experiences to mitigate environmental risks, aligning with the research discussed in this thesis.

The research presented in the papers of this thesis adopt the approach that lessons from the past are learned through the investigation of past human response to environmental risk (Van de Noort, 2013). Leveraging recent technological advancements and integrating increasingly available archaeological and environmental big datasets, the papers aim to uncover and comprehend adaptive social behaviors, risk management strategies, vulnerabilities and the environmental consequences of human activities (see Table 1 for an overview). The research was guided by three questions, as stated in the introduction, which will shape the discussion section here.
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<td>IV</td>
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Table 1. Overview of Papers I-IV; *all data are open access, however, the data varies in its level of ‘FAIR’
Analyzing human-environment relationships with computational methods

How can computational methods be applied to big data in archaeology to analyse human environmental relationships particularly in understanding the timing and spatial variations and changes in population intensity and land use?

All papers undertake the analysis of large and interdisciplinary datasets, aiming to uncover significant patterns, trends and correlations. Specifically, archaeological radiocarbon data were obtained from worldwide open data repositories (e.g., Xronos), as demonstrated in Paper III for the Rhine-Meuse and Oder river regions (Hinz & Roe, 2022). Papers I, II, and IV, on the other hand, relied on localized open access radiocarbon collections. Furthermore, environmental data, including those from global data repositories like the Neotoma Paleoecology Database as seen in Paper III, were utilized (Williams et al., 2018). Additionally, collaboration with climatological researchers in Paper II provided access to recent downscaled climate models (iLOVECLIM) for Europe, facilitating detailed examinations of climate histories in specific Scandinavian regions. The openly available iLOVECLIM model results were subsequently utilized and refocused on different European regions for Paper III (Arthur et al., 2022, 2023).

The expansive nature of these datasets offers a distinct advantage, providing researchers with a comprehensive perspective. This capability enables the recognition and comparison of environmental impacts and responses across different regions, a particularly relevant feature given the varying magnitudes of the current climate crisis across geographical areas.

In the presented papers, computational methods serve not only as crucial tools for managing the growing volume of archaeological and environmental data but also provide the opportunity to discover new dimensions in human-environmental relationships. This exploration is made possible by the volume and variety of available data, as well as the multitude of ways it can be categorized, queried, and tested, particularly with statistical or quantitative techniques.

The papers in this dissertation utilize various methods to analyse the timing and spatial variations in population intensity, land use, and the effects of extreme climate events. For instance, Papers I and IV utilize the spatial KDE techniques in QGIS on large radiocarbon datasets to illustrate changing land use and resource practices. Additionally, Papers II and III utilize summed probability distributions, permutation tests, and correlation tests within the open-source R programming environment to identify spatiotemporal changes.
in human activity and environmental variables in response to extreme climate events and abrupt climate changes (R Core Team, 2023). Paper IV expands upon these methodologies, applying both QGIS visualization techniques and statistical analysis functions from the rcarbon package to a radiocarbon dataset that contains archaeological and environmental elements. This allows for tracing human resource exploitation throughout the Holocene, utilizing identified wood and macrobotanical species as indicators (Bevan et al., 2017).

However, these techniques are criticized because they involve drawing conclusions or making predictions about past human actions and environmental conditions using a limited sample or indirect data, which introduces uncertainty into the analysis. Statistical techniques used in these papers, such as summed probability distributions and null hypothesis testing, attempt to account for this uncertainty. Additionally, these papers address the criticism that reducing the archaeological record into numerical representations may not capture the full richness and complexity of the data, potentially leading to oversimplified conclusions, by emphasizing the importance of juxtaposing quantitative findings with existing archaeological interpretations.

While it is true that uncertainty poses challenges to quantitative interpretations, it's important to recognize that uncertainty is inherent in any interpretation of the past, whether in archaeology or environmental sciences. Despite their limitations and the acknowledgment that they are not absolute truths, quantitative methods play a crucial role in enhancing our interpretations of human-environment dynamics by providing systematic frameworks for analysing complex data.

Spatiotemporal dynamics of risk and vulnerability

*How does the spatiotemporal analysis of integrated archaeological and environmental data contribute to the identification of societal vulnerabilities and risk management strategies, especially in response to rapid climate events and across varied environments?*

The spatiotemporal analyses used in Papers I, II and III have effectively uncovered adaptive social behaviors and risk management strategies in response to rapid climate events across different regions and time periods. Paper I's analysis uncovers geographically significant shifts in land use over time, demonstrating how societies in agriculturally marginal areas diversified their economic activities to reduce reliance on agriculture. Throughout the Holocene, communities initially exhibited risk-averse behavior by settling near areas with predictable resources, such as lakes and rivers. Notably, the
spatiotemporal analysis reveals a contraction in land use and an increase in hunting practices around the period of the 3.2kya BP climate event. Additionally, there was a notable intensification of diverse niche activities, such as hunting, agriculture, and metal production, during the early Vendel period, closely aligning with the occurrence of the 536/540 AD volcanic events. This suggests that the environment's capacity to sustain diversified niche activities may have contributed to its resilience against climate extremes (Gräslund & Price, 2012; Solheim & Iversen, 2019; Arthur et al., 2024). The primary focus of the paper was not to delve into the specifics of the influence of volatile climates on economic strategies, it lays the groundwork for further analysis on the relationship between changing land use activities and environmental events.

Similarly, the findings of Papers II and III also highlight the importance of diverse socioeconomic structures in mitigating risk, particularly in relation to the impacts of sudden environmental events. In exploring the impacts of the 536/540 AD volcanic events in the coastal and inland regions of Sweden and Norway, Paper II highlights the significance of understanding the regional magnitude of effects. It underscores the importance of residing in an environment where communities are compelled to adopt diverse economic strategies, as this appears to mitigate the impacts of rapid climate events. Paper III further illustrates these points, focusing on different regions in Europe, specifically the Rhine-Meuse and the Oder Delta, and examining slower-moving climate events characterized by extreme changes in precipitation and temperature. The paper underscores the regional variability of these climate changes and suggests that changes in cultural practices during the 4.2 event in the Rhine-Meuse area were not solely linked to the cooler and drier climate but occurred alongside increased activity, possibly associated with a large migration from the East. This migration may have introduced diverse land use and economic approaches or risk management strategies. These examples underscore the varying vulnerability of different regions to environmental changes.

Reshaping archaeological perspectives

How can big data analytics enhance and challenge our understanding of prevailing archaeological interpretations, often focused on distinct spatiotemporal contexts, and contribute to the construction of new theories?

The papers in this thesis frequently contextualize their quantitative analyses within existing interpretations of past human-environment interaction, validating both types of interpretations. For instance, in Paper IV, the suspected
relationship between hazel and agriculture is confirmed through permutation analyses and spatial visualization of resource intensities over time using QGIS (Bevan et al., 2017; Mjærum et al., 2022). Hazel appears prominently in the anthracological record of Sweden until around the turn of the millennium or 2,000 BP, coinciding with an increase in macrobotanical remains.

However, discrepancies between quantitative and qualitative interpretations can arise, challenging prevailing viewpoints. For example, as was hinted at in the preceding discussion, the 536/540 AD volcanic event is traditionally viewed as disastrous for Scandinavia, in addition to other areas of the world, leading to societal reorganization and population reductions (Gräslund & Price, 2012; Löwenborg, 2012). While such a narrative does hold true in certain contexts, this broad interpretation overlooks regional nuances, as highlighted briefly in the quantitative analyses of Paper I and explored in more depth in Paper II.

Paper III also challenges existing understandings about the societal effects of several extreme climate changes in the Holocene, including the 8.2k, 4.2k, and 3.2k events. The approach to the environmental data provides a nuanced examination of the diverse effects these climate events had on different regions, such as the Rhine-Meuse and Oder Delta. It underscores that the 8.2k event was the most extreme or impactful in both regions, with significant changes in both precipitation and temperature. However, the subsequent two events did not consistently exhibit paired changes in climate and precipitation for each area; instead, there were variations for each area. Moreover, the archaeological radiocarbon data does not always trend negatively around these extreme events, suggesting that societies were resilient or adapted to these changes. The findings of Paper III, which demonstrate societies' capability to adapt even in extreme climates, contribute to the ongoing debate surrounding environmental determinism in synthetic archaeological and environmental research. This field employs quantitative analysis to identify related patterns and often leans towards the concept of environmental determinism.
Conclusion

The aim of this thesis has been to investigate human responses to environmental risks using computational approaches, with a focus on significance testing and managing the inherent uncertainty in the archaeological record. Employing these techniques has not only revealed intriguing findings concerning risk management strategies and adaptive responses but has also illustrated the complex and interdisciplinary nature of archaeological research. It underscores the importance of embracing technological advancements and quantitative methodologies, while also highlighting the challenges involved in handling and analysing the growing volume of high-velocity, high-variety, and high-volume data available in archaeology and the environmental sciences. Additionally, it emphasizes the complexities of fostering collaboration between the natural sciences and social sciences.

Advancements in technology and statistical analysis of big data offer significant utility by enabling spatiotemporal comparisons and the discovery of patterns and correlations that go beyond traditional archaeological excavation and literature searches. Big data analysis is particularly vital for climate change adaptation research, given the need to comprehend diverse environmental effects and human responses. Furthermore, quantitative methods play a crucial role in validating qualitative archaeological interpretations and enhancing the relevance of findings for policy-making, as they assign a level of significance to the archaeological records.

In sum, key findings of this research are:

- Long-term spatiotemporal analysis illuminates the timing of the emergence of land uses and human niche constructions, highlighting regional differences and supporting the ability to refine research focus and ask different questions about possible interconnections between regions and environmental events.

- The papers consistently emphasize the significance of maintaining diverse socioeconomic structures in mitigating risk, especially in the face of sudden environmental events. Additionally, the intensification of exchange niches, such as iron production or the fur trade in Inland Scandinavia, highlights exchange as a useful risk
management strategy. The local-regional view afforded by this spatiotemporal research underscores the importance of migration as a response to environmental risks.

- Regional variations in environmental impacts, as observed in Scandinavia during the 536/540 AD event, resulted in the Norwegian coast, which was heavily reliant on agriculture, experiencing the most significant alteration in its growing season, a distinctive vulnerability. When coupled with pre-existing social structures, these locally disparate environmental effects give rise to unique regional vulnerabilities.

- This research challenges the notion of deterministic quantitative research in human-environmental studies, as seen in the 4.2k event in the Rhine-Meuse region. Despite facing cooler and drier conditions, radiocarbon data from archaeological sites indicates continuous occupation before and during much of this event, suggesting that transitions and technological advancements were likely influenced by social factors rather than solely by adaptation to environmental risk.

The findings have several implications for the field of archaeology and environmental studies, particularly within the framework of historical ecology. For instance, the utilization of computational methods on big data in archaeology offers a comprehensive and scalable perspective on human-environmental relationships. This enables the analysis of timing, spatial variations, and changes in population intensity and land use, providing researchers with a deeper understanding of past human societies and their interactions with the environment. Additionally, by integrating archaeological and environmental data and conducting spatiotemporal analysis, historical ecology reveals adaptive social behaviors in response to rapid climate events; research discussed here highlights the significance of diverse socioeconomic structures to mitigating risk, thus contributing to the development of effective risk management strategies.

Moreover, the contextualization of quantitative analyses within existing interpretations, not only enriches our understanding of past human-environment interactions but also prompts a reevaluation of established narratives and assumptions. When findings address discrepancies between quantitative and qualitative interpretations, they often stimulate the construction of new theories. Importantly, the implications of these findings reach beyond academic discourse, offering lessons into how societies have historically adapted to environmental risk and informing current initiatives aimed at tackling contemporary climate change.
Looking forward, several promising avenues emerge for further exploration in computational and big data methods within archaeology, particularly regarding understanding human responses to environmental risks. First, long-term spatiotemporal analysis reveals distinct regional variations in environmental impacts, urging a more focused exploration of the interconnectedness between regions and into localized dynamics. Such targeted approaches promise to provide concrete insights into how specific environmental factors influenced past societies in different geographical areas.

Additionally, integration between archaeology and environmental science disciplines is imperative. This includes cultivating opportunities to collaborate, as well as adopt more multivariate approaches that compare qualitative and quantitative analyses. Furthermore, efforts that successfully link research with policy not only improve decision-making processes but also help overcome the challenge of engaging policymakers. While qualitative assessments provide indispensable insights, there is a need to translate these insights into quantitative terms for effective integration with policy. Addressing these multifaceted challenges is a formidable task, demanding continued effort and a persistent exploration of opportunities to address them. However, it represents a promising path for advancing archaeological and environmental research and strengthens its relevance to contemporary societal issues.

In closing, I have aimed for this thesis to effectively communicate that utilizing computational archaeology to analyse big data from a perspective that considers environmental risks presents a unique opportunity to deepen our understanding of past human-environment interactions and to ‘learn from the past.’ Integrating historical perspectives, harnessing diverse datasets, and conducting synthetic research studies moves us towards more informed decision-making processes and sustainable resource management practices as we confront the escalating threat of rapid climate change.
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