Anthropogenic landscapes? Modelling the role of hunter-gatherers in interglacial ecosystems in Europe

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CHAPTER 1

INTRODUCTION

1.1 Background

Throughout human history, relationships between people and their environments have been one of the fundamental drivers of changes in various systems including biological, techno-cultural, socio-economic, ecological, and digital. While the human-environment interactions span over millennia, the question when and how people started active changes of their environment is still highly debated especially in the light of the pressing environmental challenges confronting humanity.

As an attempt to emphasize the role of humans in environmental changes and to define the starting point of these processes the term "Anthropocene" was coined for the current human-dominated geological epoch (Crutzen, 2002; Crutzen & Stoermer, 2000). Since then, the beginning of this period, its geological relevance and which type of evidence should be used to define Anthropocene's starting point have been debated with suggestions varying from 13,800 BP when megafauna extinctions occurred, to the mid-twentieth century with the introduction of plastics and concrete production (Lewis & Maslin, 2015; Ruddiman, 2013; Waters et al., 2016; Zalasiewicz et al., 2015). These discussions also extend to whether the Anthropocene should be classified as an epoch or an event (Bauer et al., 2021; Gibbard et al., 2022).

The Anthropocene Working Group chose to identify the stratigraphic signal of the Anthropocene using the global distribution of primary artificial radionuclides from mid-twentieth-century atomic bomb explosions, and sediments from Crawford Lake near Toronto (Canada) as the Anthropocene's "golden spike" (global boundary stratotype section) (Anthropocene Working Group, 2019; McCarthy et al., 2023; Zalasiewicz et al., 2015). The proposal to recognize the Anthropocene as an official geological epoch was presented to the international Subcommission on Quaternary Stratigraphy which voted against it (Adam, 2024; Boivin et al., 2024). This decision to not formalize the Anthropocene as a geological epoch offers opportunities to study in depth the complex dynamics of human-environment relationships (Boivin et al., 2024). The questions about when and how humans began to shape the global earth system, including how human subsistence and land use strategies affected land cover, ecosystems and other aspects of their environments, were identified as priorities for research in archaeology and paleoecology (Ellis et al., 2021; Kintigh et al., 2014; Seddon et al., 2014).

Humans have a rich history of niche construction, defined as "the process whereby organisms, through their metabolism, their activities and their choices, modify their own and/or other species niches" (Odling-Smee et al., 2013). In accordance with this definition, agricultural practices and foraging lifestyles qualify as forms of human niche construction. It is widely recognized that the emergence of agriculture substantially intensified human impact on the environment compared to those of foraging societies (Delcourt, 1987; Kirch, 2005; Roberts et al., 2018; Ruddiman, 2013) defined as populations which mainly depend on food collection or foraging of wild resources (Ember, 2020).

Ethnographic observations show that hunter-gatherers influence their environment in several ways including modification of vegetation communities via burning (Nikulina et al., 2022; Rowley-Conwy & Layton, 2011; Scherjon et al., 2015; Smith, 2011). Besides ethnographic data, evidence from archaeological contexts show that fire use was an important part of the technological repertoire of the *Homo* lineage since at least the second half of the Middle Pleistocene (Gowlett & Wrangham, 2013; Roebroeks & Villa, 2011; Sorensen et al., 2018). Human-induced vegetation burning during the Late Pleistocene has been proposed as a potential factor for landscape changes in several case studies spanning various continents (Hunt et al., 2012; Pinter et al., 2011; Summerhayes et al., 2010; Thompson et al., 2021). Notably, the earliest evidence of human-induced vegetation burning was found at the Neumark-Nord site in Germany, dating back to the Last Interglacial period (LIG, ~130,000–116,000 before present; all dates are given in years before present (BP), where "present" is defined as 1950 CE) (Roebroeks et al., 2021). In addition, foragers using fire were suggested as main contributors to vegetation changes in Europe during the Last Glacial Maximum, potentially representing some of the earliest extensive anthropogenic alterations of Earth's systems (Kaplan et al., 2016).

While these Pleistocene cases are still debated, vegetation burning by hunter-gatherers during the Early–Middle Holocene (~11,700–6000 BP) is generally accepted (Davies et al., 2005; Dietze et al., 2018; Mason, 2000; Zvelebil, 1994), even though the quality of the data is not necessarily that different from the Palaeolithic evidence (Nikulina et al., 2022). There are more Early–Middle Holocene case studies than from Pleistocene contexts, with most of the evidence for the Early–Middle Holocene coming from Europe (Bos & Urz, 2003; Caseldine & Hatton, 1993; Gumiński & Michniewicz, 2003; Heidgen et al., 2022; Hjelle & Lødøen, 2017; Hörnberg et al., 2006; Innes et al., 2013; Kaal et al., 2013; Mellars & Dark, 1998; Milner et al., 2018; Sevink et al., 2023; Woldring et al., 2012). In addition, evidence suggests that humans had already altered natural fire regimes in Australia as early as 11,000 years ago (Bird et al., 2024).

Despite numerous case studies suggesting anthropogenic burning (intentional or not) by prehistoric hunter-gatherers, it remains challenging to establish whether these local-scale activities led to changes on regional and/or (sub-)continental scales (Nikulina et al., 2022). In addition, assessing the potential impact of past hunter-gatherers on their environments to some extent requires knowledge of "human-free" or "natural" ecosystems, which arguably points to the concept of a "natural palaeoenvironment". In the same vein, restoration for biodiversity conservation often requires a reference ecosystem or baseline (Burge et al., 2023) which is often referred to as a historical state before large-scale human exploitation of resources (Hildong-Rydevik et al., 2017). The search for such baselines is challenging due to the complexities of past environmental processes (Schreve, 2019). Thus, studying the impact of early human activities on their environment is crucial not only for archaeology and related fields but also for informing ecosystem restoration projects aimed at a sustainable future. By examining past human-environment interactions, we can better understand the landscape dynamics.

Landscapes are complex systems where heterogeneous components interact to impact ecological processes and might demonstrate non-linear dynamics and emergence (Newman et al., 2019). Modelling approaches offer excellent opportunities to explore how specific components of complex systems might interact, particularly when real-time experiments are not feasible.

Agent-based modelling (ABM) is often used to simulate real-world processes over time, to explore complex systems where multiple factors intertwine, and to suggest possible scenarios of system functioning (Romanowska et al., 2021). Importantly, the outcomes of ABM exercises can be compared to empirical data such as pollen-based vegetation reconstructions. The ABM approach has been applied in various contexts to examine past human-environment interactions and changes in land use and land cover caused by ancient societies (Boogers & Daems, 2022; Lake, 2000; Reynolds et al., 2006; Riris, 2018; Rogers et al., 2012; Santos et al., 2015; Saqalli et al., 2014; Scherjon, 2019; Verhagen et al., 2021; Vidal-Cordasco & Nuevo-López, 2021; Wren & Burke, 2019). In ABMs designed to study foragers, the role of fire used by hunter-gatherers to modify their habitats and its consequences is often overlooked (except for brief mentions in some studies such as Ch'ng and Gaffney (2013) and Snitker (2018)).

While acknowledging the potential for other modelling techniques, spatially explicit ABM is employed to address the unique challenges of this study, including the quantification of the potential impact of past hunter-gatherers within a dynamic environment where various processes influence human decisions to initiate vegetation changes. ABM allows to discern the earliest anthropogenic signals in landscape dynamics, moving beyond mere correlation between several proxy-based evidence. Additionally, it becomes possible to examine the interplay between scales, as we can observe how decisions at a local level influence broader landscape dynamics.

This study presents a spatially explicit ABM HUMan impact on LANDcapes (HUMLAND) with a primary emphasis on vegetation burning by hunter-gatherers.

This model explores key factors in continental-level interglacial vegetation changes during the LIG and the Early Holocene (~11,700–8000 BP, i.e., the period before the widespread adoption of agriculture in Europe). An important element of this study is assessment of differences between pollen-based reconstruction (inferred vegetation created by various processes including anthropogenic and natural fires, climatic fluctuations, megafauna presence, etc.) and dynamic vegetation model output (climate-based vegetation cover i.e., potential natural vegetation cover driven by climatic forces only).

1.2 Research questions

The primary research question addressed in this study is whether–and to which degree–hunter-gatherer activities could have impacted vegetation cover in Europe during the LIG and the Early Holocene. To address this question, six objectives have been set:

1) to review the currently available proxy-based evidence for past hunter-gatherer impact on interglacial environment in Europe (Chapter 2);
2) to evaluate the differences between potential natural vegetation as established via the CARbon Assimilation In the Biosphere (CARAIB) model and pollen-based vegetation obtained via Regional Estimates of VEgetation Abundance from Large Sites (REVEALS) for the study periods (Chapters 3 and 4);
3) to develop an ABM which is capable of tracking and quantifying different types of impact on vegetation (Chapter 3);
4) to identify the most influential parameters which define the intensity of human-induced vegetation changes (Chapter 3);
5) to generate potential scenarios of vegetation transformations due to megafauna plant consumption, anthropogenic and natural burning during the study periods (Chapter 4);
6) to track and to quantify the potential impact of Neanderthals and Mesolithic humans on vegetation for the most frequently generated scenarios (Chapter 4).

1.3 Datasets and research methodology

The research presented in this dissertation is multifaceted, positioned at the intersection between several disciplines including archaeology, ecology, and computer science. As a result, this study integrates various datasets developed within the broader research framework (Arthur et al., 2023, 2025; Davoli et al., 2023;

Pearce et al., 2023; Serge et al., 2023; Zapolska et al., 2023a, 2023b) to address the complexity of the main research question and objectives. Due to that, collaboration with other researchers on certain aspects was naturally involved. However, all work presented in this dissertation–including conceptualization, methodology, model development, validation, formal analysis, investigation, data curation, writing, visualization, project administration, and the open-access publication of all outputs–was carried out by the author. This is supported by the author's role as the first author on all relevant publications (Nikulina et al., 2022, 2024b, in press) and published models (Nikulina et al., 2023, 2024a). Contributions from co-authors are explicitly acknowledged in the statements of the respective publications, where permissible under journal guidelines.

1.3.1 Literature review of proxy-based evidence for hunter-gatherer impact on European environment

To meet the first objective of this study, the literature review was conducted (Nikulina et al., 2022). Firstly, hunter-gatherer niche construction activities were described based on ethnographic observations (Rowley-Conwy & Layton, 2011; Smith, 2011). Afterwards, proxies for each category of niche construction activity were listed and evaluated in relation to proxies' spatial resolution and availability for the LIG and Early Holocene contexts (Nikulina et al., 2022). Finally, the use of proxies within LIG and Mesolithic contexts was illustrated and compared between the two time periods (Bos & Urz, 2003; Innes & Blackford, 2003, 2017; Pop & Bakels, 2015; Roebroeks et al., 2021). Based on this, the validity of current understanding of Neanderthal and Mesolithic hunter-gatherer impact on interglacial landscapes was discussed (Nikulina et al., 2022).

1.3.2 CARAIB-REVEALS comparison and their integration into HUMLAND ABM

There is no accepted protocol for comparing the CARAIB and REVEALS models and for integrating them into a single ABM. The similarity between the two datasets is that they both produce quantitative output: CARAIB generates distributions of fractions for 26 plant functional types (PFTs), and REVEALS provides proportions for individual taxa. To meet the second objective, the approach was developed to compare CARAIB and REVEALS outputs, to include them into HUMLAND, and to compare ABM output with REVEALS estimates (Henrot et al., 2017; Nikulina et al., 2024b; Popova et al., 2013; Zapolska et al., 2023a). In accordance with this approach, CARAIB and REVEALS outputs were reclassified (i.e., transformed in accordance with the developed classification scheme) to compare them in terms of the distribution of dominant PFTs and vegetation openness. Because CARAIB and REVEALS assess vegetation openness differently, we use the term "vegetation openness" broadly, referring to vegetation density and its influence on visibility and activities of hunter-gatherers, such as movement. After reclassification, the datasets were compared per time window: two LIG (mesocratic I and mesocratic II) and seven 500-year-long Early Holocene (11,700–8200 BP) time windows (Nikulina et al., in press).

1.3.3 HUMLAND ABM

In this study a novel spatially explicit ABM HUMLAND was developed to track and to quantify different types of impact on vegetation in accordance with the third objective of this research (Nikulina et al., 2024b, in press). This ABM explores the impact on vegetation from different sources and operates at a temporal resolution of one year and a spatial resolution of 10 km × 10 km, with each simulation run consisting of 1000 steps. The primary observations made during simulation runs include the distribution of the dominant PFTs (percentage of grid cells covered by each of four PFTs: herbs, shrubs, needleleaf and broadleaf trees) and mean vegetation openness in percentage. These observations are collected only for grid cells that have both CARAIB and REVEALS values.

HUMLAND includes four types of impact on vegetation: climatic impact, human-induced and natural fires, and megafauna plant consumption. These types of impact on vegetation are considered among the most influential, widespread, and potentially visible on regional-(sub-)continental scales (Bond & van Wilgen, 1996; Nikulina et al., 2024b; Pringle et al., 2023; Whelan, 1995). HUMLAND has adjustable parameters for various impact types; these parameters can be modified during simulation runs (Nikulina et al., 2024b).

This model incorporates several datasets (Nikulina et al., 2024b) including potential maximal megafauna plant consumption (Davoli et al., 2023), digital elevation model (Danielson & Gesch, 2011; Gesch et al., 1999; https://www.usgs.gov/), Water Information System for Europe (WISE) (https://water.europa.eu/). While all datasets are integral to the development of the HUMLAND ABM, the outputs of the CARAIB and REVEALS models play an important role (Serge et al., 2023; Zapolska et al., 2023a, 2023b). CARAIB results serve as the starting point for all simulation runs, providing initial environmental settings. In contrast, the REVEALS model outputs used to compare HUMLAND outputs with observed vegetation cover. Specifically, the success of generated scenarios (Nikulina et al., in press) is measured by its ability to produce output similar to the REVEALS data.

1.3.4 Genetic algorithm

To meet the fifth objective, the genetic algorithm optimization technique was used to enable systematic and computationally efficient exploration of parameter space for generation of scenarios (Nikulina et al., in press). Each of them is represented by a different combinations of parameter values within the HUMLAND model.

The genetic algorithm is widely recognized as a useful approach for ABM optimization (Olsen et al., 2018; White et al., 2022), though application in archaeological research has been relatively limited (Scherjon, 2019). Optimization includes testing different designs and adjusting model elements (e.g., agent behaviours and parameter values) to obtain a desired output of a model (Turgut & Bozdag, 2023). In the current study, this output is a simulated vegetation cover that is similar to the past vegetation patterns represented by the REVEALS dataset.

Since CARAIB and REVEALS are compared in terms of the PFT distribution and vegetation openness, there two goals for the genetic algorithm runs: 1) to minimize differences in mean percentages of grid cells dominated by trees and 2) to minimize the differences in the mean vegetation openness between HUMLAND output and pollen-based (i.e., REVEALS) results. For each genetic algorithm goal, we assessed the feasibility of generating scenarios with and without human-induced fires. In all experiments humans influence the intensity of megafauna plant consumption via hunting pressure.

1.3.5 Quantification of Neanderthal and Mesolithic impacts on vegetation

To meet the last objective, parameter values with the highest frequency in HUMLAND scenarios where the output aligned with REVEALS reconstructions were selected. HUMLAND was run with the selected combinations of parameter values to quantify the number of modifications made by Neanderthals, Mesolithic groups, megafauna, natural fires, and climate (Nikulina et al., 2024b).

1.4 Thesis structure

The dissertation consists of a collection of three articles, accompanied by introductory and discussion chapters. Two papers have already been published in peer-reviewed journals, and one paper is currently in press. The findings of this research have been presented at various international conferences and workshops, leading to the publication of different aspects of this work in conference proceedings.

Chapter 2 presents the literature review of palaeoenvironmental proxies and combinations of these for understanding hunter-gatherer niche construction activities in Europe. LIG and Early Holocene case studies are discussed. The results of this review show that published evidence for Mesolithic manipulation of landscapes is based on the interpretation of data qualitatively comparable to those available for the LIG (Nikulina et al., 2022).

In the following chapter (3) the HUMLAND ABM is presented. This chapter includes the sensitivity analysis of the model and its first application. The results of this work support the hypothesis that European ecosystems were strongly shaped by human activities already in the Early Holocene (Nikulina et al., 2024b).

Chapter 4 shows HUMLAND ABM application to two LIG and several Early Holocene time windows. In this work the developed model was combined with a genetic algorithm to explore possible scenarios for the past interglacial ecosystems functioning. The obtained results indicated that climate and megafaunal activities were not the only factors shaping European landscapes, with hunter-gatherers being important for interglacial ecosystems through both direct (via vegetation burning) and indirect (via hunting herbivores) pathways already in the LIG (Nikulina et al., in press).