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Research Article

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Comparing Connectivity Patterns in Prehistoric Germany by Means of Network Analysis, Artefact and Site Distribution and a Reassessment of Human Mobility (^{87}Sr/^{86}Sr)

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Abstract: Recent advances in the natural sciences, bioarchaeology and spatial analytical techniques have significantly improved our ability to reconstruct prehistoric human connectivity. However, traditional mapping approaches can often fail to integrate isotopic evidence with landscape modeling and artifact distribution comprehensively. This study addresses this gap by combining Least-Cost Path (LCP) analysis, spatial distribution of key archaeological artifacts (jade axes and hilted swords), and ^{87}Sr/^{86}Sr isotopic data from previous research to investigate movement corridors in the Late Neolithic (ca. 3,800–2,800 BCE) and Bronze Age (ca. 2,300/2,200–800 BCE) landscapes of central and southern Germany. Our objective is to model how prehistoric populations navigated and exploited natural landscape features for mobility and trade, assessing how these corridors influenced the spatial distribution of important trade commodities. By integrating isotopic data with modeled movement corridors, our study confirms through independent isotopic and spatial evidence, that mobility networks intensified and stabilized during the Bronze Age. This approach highlights a methodological advance rather than reiterating a well-known trend, as the broader variability of ^{87}Sr/^{86}Sr ratios directly corresponds with the establishment of sustained long-distance connections.

Keywords: archaeology; isotopes; network; Bronze Age; Neolithic

1 Introduction

Human mobility has played a central role in shaping prehistoric social landscapes. In Europe, evidence of long-distance exchange networks extends to at least the early 6th millennium BCE (Pétrequin et al. 2013, Vianello 2015). Such networks are embedded within the landscape and can be reconstructed by integrating archaeological and scientific datasets. Advances in natural sciences, including isotope geochemistry and spatial analysis, now allow detailed investigations of connectivity and movement patterns in prehistory (Aldred 2021, Bataille et al. 2021, Ensor 2021, Howey 2011, Kristiansen 2014).

Despite extensive archaeological research into trade and exchange, reconstructing prehistoric movement pathways remains methodologically challenging (Anthony 1990, Furholt 2018, Furholt 2021, Kintigh et al. 2014,

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Suchowska-Ducke 2015). Conventional distribution mapping often emphasizes isolated findspots over continuous spatial trajectories, limiting interpretations of dynamic mobility processes (Aldred 2021). Consequently, human and object mobility have often been analyzed independently, since the movement of artifacts does not necessarily mirror the movement or identity of the people associated with them, even though artifact transport ultimately depends on human agency (Braudrick and Grant 2000, Figliozzi and Jennings 2020).

To address these limitations, this study integrates archaeological and isotopic evidence with spatial modeling to delineate prehistoric movement corridors. We focus on two culturally significant artifact categories: Neolithic Alpine jade axes and Bronze Age hilted swords. These objects serve as proxies for social and economic networks and have well-documented typological and spatial distributions (Kaul 2022, Kristiansen 2014, Ling et al. 2014, Pétrequin et al. 2013, Pétrequin et al. 2015, Rassmann 2013, Suchowska-Ducke 2015).

This study examines long-distance mobility and connectivity in Neolithic and Bronze Age Central Europe by modelling the movement of two object groups with widespread distributions: Alpine jade axes (c. 5,300–3,700 cal BCE) and hilted swords (c. 2,200–1,600 cal BCE). Although these artifacts are separated by a chronological gap of over a millennium, their inclusion is deliberate. Each represents a distinct episode of intensified supra-regional movement, embedded in different technological and sociopolitical contexts. Rather than tracing a continuous trajectory, this study focuses on two peaks in large-scale connectivity, using them as comparative anchors to assess changing patterns of mobility and landscape use over time.

Alpine jade axes, sourced from Italian Alpine deposits circulated widely during the Neolithic, spanning from the Atlantic to the Black Sea (D'amico 2005, Pétrequin et al. 2013, Pétrequin et al. 2015). Their distribution reflects direct exchange networks rather than down-the-line trade and indicates socio-cultural importance beyond functional use, as evidenced by reshaping and re-polishing practices (Pétrequin et al. 2013).

Late Bronze Age hilted swords, particularly the Naue II type, trace back to the Eastern Alps and appear widely across Central Europe (Ling et al. 2014, Ling et al. 2019, Melheim et al. 2018, Rassmann 2013). Metallurgical and isotopic data suggest complex production and exchange systems involving multiple ore sources, reflecting extensive social and economic networks (Frei et al. 2019, Ling et al. 2014, Nørgaard 2018). Although primarily prestige objects, use-wear and evidence for interpersonal violence indicate swords also served practical combat functions (Horn and Kristiansen 2018, Kristiansen 2002).

We hypothesize that the spatial distribution of these artifacts aligns with ancient movement corridors shaped by topography, such as river valleys and mountain passes (PabSt 2013, Suchowska-Ducke 2015). We acknowledge that many artifact deposits, including swords and jade axes, were deliberate and often associated with ritual or symbolic contexts (Ballmer 2010, Ballmer et al. 2024, Brück and Fontijn 2013, Fontijn 2002, Ritchie 2000). Our approach therefore does not treat their distribution as direct evidence of movement but as a proxy for broader spatial patterns of connectivity, often structured by natural corridors such as river valleys and passes. Using Least-Cost Path modeling and published ^{87}Sr/^{86}Sr human isotope data, we examine whether these corridors correspond with isotopically inferred mobility patterns and how such patterns changed between the Neolithic and Bronze Age.

1.1 Previous Research

Prestige goods in prehistoric archaeology are defined as objects exchanged over long distances that often lack immediate utilitarian function but hold significant societal or ritual value (Pétrequin et al. 2013, Pétrequin et al. 2015, Renfrew 1969). Early conceptualizations by Malinowski (1920) highlighted such goods as markers of social transactions rather than practical use. A well-known example from the Neolithic is the distribution of spondylus shell bracelets throughout Europe despite the shells' natural occurrence only in subtropical and tropical seas (Dimitrijević and Tripković 2006). The circulation of such items is widely interpreted as a form of social exchange reinforcing status and networks (Chapman et al. 2011). However, the term 'prestige good' has sometimes become overgeneralized, encompassing any rich or emblematic grave goods rather than specifically denoting non-utilitarian long-distance exchange objects (Renfrew 1969).

Neolithic Alpine jade axes, dated to the 5th and 4th millennia BCE, represent a key category of prestige goods in Europe, and these axes are found widely distributed from Atlantic Europe to the Black Sea (D'Amico 2005; Pétrequin et al. 2013; Pétrequin et al. 2015). The jade material is sourced from Alpine quarries and sources from the Ligurian Apennines, primarily around Mount Viso and Mount Beigua (Pétrequin et al. 2013). The exchange of these axes is interpreted as occurring predominantly through direct contact networks rather than gradual down-the-line diffusion. Furthermore, evidence of reshaping and re-polishing indicates the axes' shifting symbolic and social roles beyond mere utilitarian function (Pétrequin et al. 2013). The spatial distribution of jade axes appears complementary to that of copper and gold artifacts in southwestern Europe, suggesting material and cultural boundaries within prehistoric exchange systems (Pétrequin et al. 2013).

Bronze Age hilted swords, particularly those of the Naue II type, likely originated in the eastern Alps and were distributed through networks linking Italy, the western Adriatic, the Carpathian Basin, and the Black Sea (Ling et al. 2014; Ling et al. 2019). Metallurgical studies show that the production of these swords involved sourcing copper and tin ores from diverse European regions, reflecting complex economic and social exchange networks (Jung et al. 2011, Ling et al. 2019, Melheim et al. 2018). Recent Scandinavian research reveals temporal fluctuations in ore sourcing strategies and corresponding human mobility patterns, highlighting dynamic social interactions connected to metal production and exchange (Frei et al. 2019, Nørgaard 2018, Reiter and Frei 2019).

The functional role of Bronze Age swords has been debated. Initial interpretations emphasized ritual use (Kristiansen 2002), but use-wear analyses and increased evidence of interpersonal violence in the 12th and 11th centuries BCE demonstrate their practical use in combat (Horn and Kristiansen 2018; Kristiansen 2002; Rassmann 2013; Suchowska-Ducke 2015). The swords are also understood as symbols of elite status and social alliances, circulating through exchange networks and elite "guest-friendship" practices (Frei et al. 2019, Kaul 2022).

Strontium isotope ($^{87}Sr/^{86}Sr$) provenancing has provided critical evidence for understanding mobility and exchange in this context. Isotopic analyses of human remains associated with Bronze Age elite burials reveal the potential presence of non-local individuals, supporting interpretations of long-distance mobility linked to socio-political networks (Frei et al. 2019, Reiter and Frei 2015). These isotopic data, combined with archaeological and metallurgical evidence, offer a multi-disciplinary framework for investigating the circulation of prestige goods and the mobility of people within Neolithic and Bronze Age Europe.

2 Materials and Methods

2.1 Research Area

The study area encompasses the entirety of Germany, which presents a varied landscape spanning from the lowlands of northern plains to the uplands and mountainous regions of central and southern Germany. This geographical diversity includes major natural features such as the Central Uplands (*Mittelgebirge*), extensive forested regions, fertile loess soils, and major river valleys including those of the Rhine, Danube, and Elbe (Dix et al. 2005, Kamleitner et al. 2023). These features have shaped human occupation and mobility since the Paleolithic, creating a complex mosaic of environmental zones that influenced settlement choices and patterns of interaction (Hofmann et al. 2013, Whittle and Bickle 2013).

The rich archaeological record of what is today Germany reflects its role as a cultural crossroads in prehistoric Europe, especially during the Neolithic and Bronze Age. The region is characterized by dense distributions of settlements, burial sites, and material culture indicative of long-distance exchange and population movements (Bickle et al., 2011; Peeters et al. 2015). Extensive research has highlighted the importance of both local adaptation to diverse environments and broader supra-regional connectivity across these landscapes (Hofmann et al. 2013; Kamleitner et al. 2023). Environmental and topographic variability directly affected prehistoric mobility, with uplands and forested areas potentially acting as natural barriers, while fertile valleys and plains facilitated movement and settlement (Dix et al. 2005, Kamleitner et al. 2023). However, human mobility was also influenced by socio-cultural factors such as territorial boundaries, social networks, and economic interactions, which do not always align with physical geography alone (Hofmann et al. 2013, Peeters et al. 2015).

Contemporary anthropogenic changes, including agriculture, urban expansion, and infrastructural development, have heavily modified the archaeological landscape, affecting site preservation and visibility (Bilotti et al. 2024, Kempf 2019, Kempf 2020). This introduces bias in the archaeological record that must be critically acknowledged in any spatial or mobility analysis.

Overall, the research area offers a robust and well-documented setting to investigate prehistoric mobility and connectivity. The diverse environmental contexts and well-studied archaeological data provide a foundation for integrating multiple methodological approaches, including isotopic provenance and spatial modeling, to reconstruct past human movement across Germany (Figures 1 and 2).

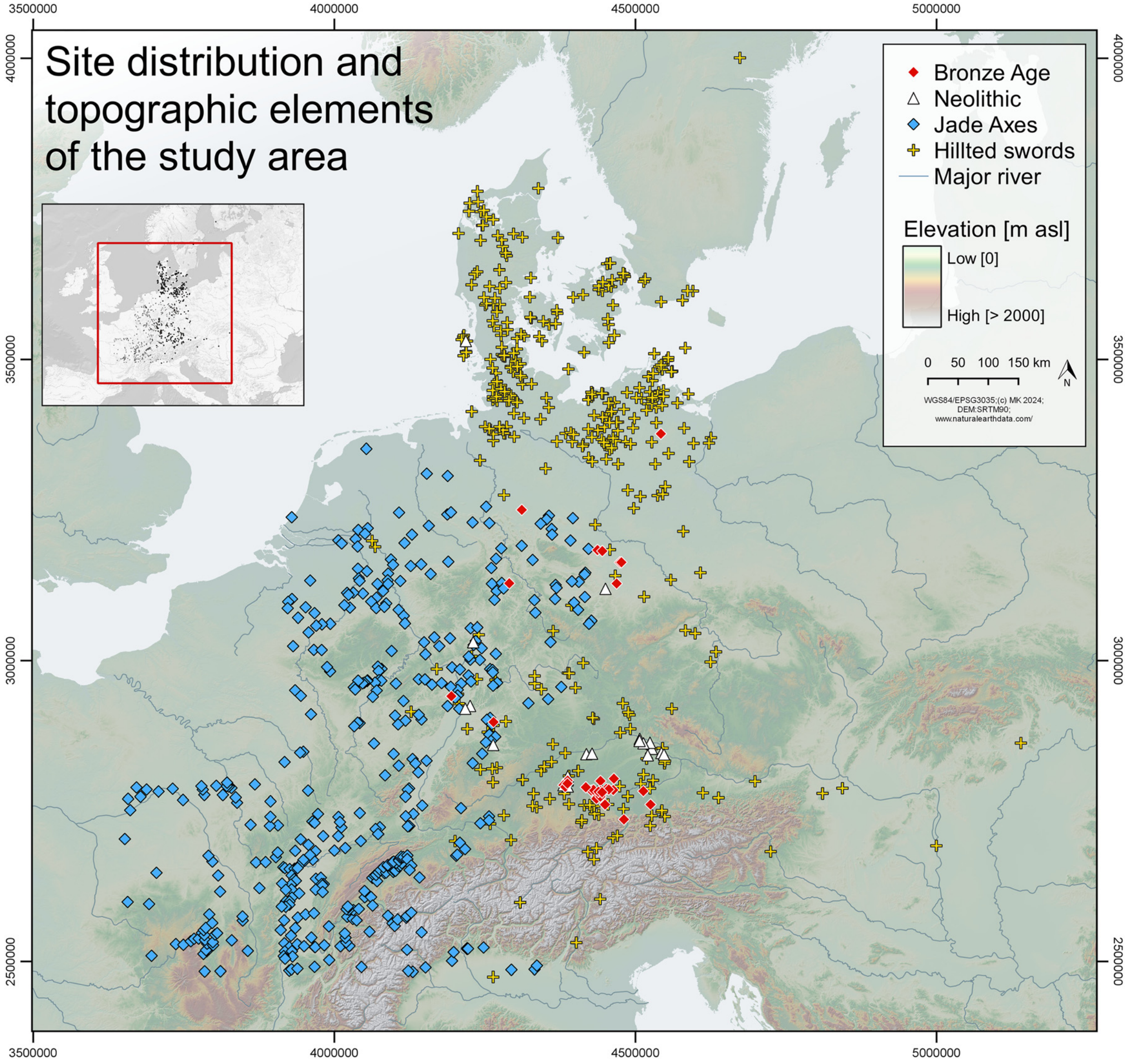

Figure 1: Neolithic and Bronze Age site distribution compared to Jade Axes and Hilted sword finds across Central Europe (the map was produced using QGIS. Basemap: SRTM90 from CIAT-CSI SRTM website (http://srtm.csi.cgiar.org), last accessed 25th of July 2024 (Jarvis et al. 2008b, Reuter et al. 2007). Source data: Kristiansen (2002), Pétrequin et al. (2013), Pétrequin et al. (2015), Rassmann (2013), Suchowska-Ducke (2015). Map by MK.

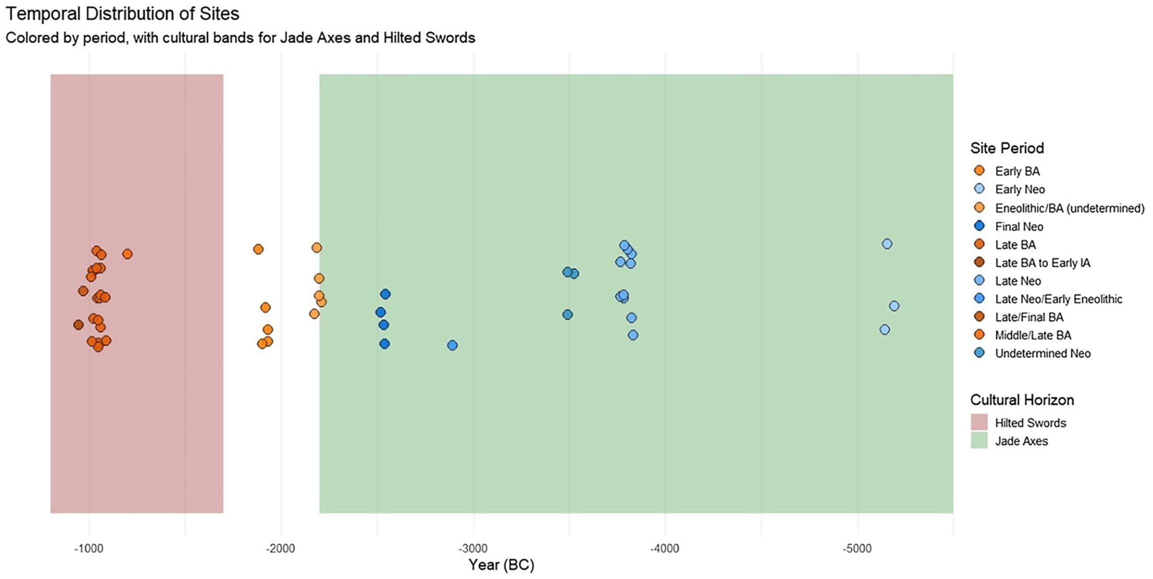

Figure 2: Temporal distribution of sites containing jade axes and hilted swords. The *x*-axis represents years (BC). Points are vertically offset for visual clarity and do not indicate quantitative values.

2.2 Material Culture

The archaeological collection of Alpine jade axes was sourced from Supplementary Materials associated with comprehensive studies by Pétrequin et al. (2013, 2015). This dataset comprises approximately 1800 large polished Alpine jade axe heads that were in circulation c. 5,300–3,700 cal BC (c. 7,250–5,650 cal BP), representing several typological variants (types A–D) documented through the extensive fieldwork of the JADE and JADE 2 projects conducted between 2006 and 2010 (Pétrequin et al. 2013). For this study, a subset of 414 datapoints from this dataset was selected to focus specifically on finds within and around present-day Germany.

The Bronze Age hilted sword dataset was compiled from multiple rigorous sources, including Rassmann's doctoral research (2013), comprehensive collections documented by Kristiansen and Earle (2022), and analytical work by Suchowska-Ducke (2015). Together, these sources provided a detailed corpus of 389 sword finds across central and southern Germany. Crucially, the dataset encompasses the Naue II sword type, which holds particular significance for Late Bronze Age socio-political dynamics.

Naue II swords, a well-defined category of hilted swords, date to approximately 1,350–1,100 cal BC (ca. 3,300–3050 BP) and are widely recognized as emblematic of elite warrior status and extensive social networks during the Late Bronze Age (Kristiansen and Larsson 2005, Rassmann 2013, Ling et al. 2019, Horn and Kristiansen 2018). The overall temporal range of the hilted swords included spans from roughly 1,350 to 750 cal BC, covering the Late Bronze Age's primary phases of socio-political change (Kristiansen and Larsson 2005, Ling et al. 2019, Rassmann 2013).

All geographical coordinates associated with the jade axes and sword finds were standardized to the WGS84 coordinate system (EPSG:4,326), ensuring compatibility with contemporary geospatial analysis tools. This allowed for precise mapping and integration of these datasets with Least Cost Path (LCP) models aimed at reconstructing potential prehistoric movement corridors.

2.3 Sites

The primary archaeological sites included in this study derive from the Big Interdisciplinary Archaeological Database (BIAD), a central element of the ERC-funded COREX project. BIAD aggregates extensive archaeological datasets, including graves, individual human remains, radiocarbon (^{14}C) dates, genetic data, and isotopic signatures such as ^{87}Sr/^{86}Sr ratios.

After rigorous data cleaning and removal of duplicates, the dataset incorporates 22 Neolithic sites and 34 Bronze Age sites distributed throughout Germany, spanning the Early to Final Bronze Age (see Tables 1 and 2). These sites include both settlement and funerary contexts and represent all registered German sites within BIAD as of May 2025.

The study purposefully does not differentiate site types in the LCP analysis, instead focusing on modeling landscape-based mobility potential informed by topography and environmental cost surfaces. This approach allows for a broad characterization of how the physical landscape, including factors such as terrain ruggedness and resource distribution, may have structured movement and connectivity across prehistoric Germany. It is as far as is possible based on the available data to be unbiased in our assumptions of where the activity areas of different kinds may have affected the mobility patterns of prehistoric individuals.

Table 1: Sites and period divisions for the Bronze Age. Eneolithic and Bronze Age sites in Germany with approximate dates: Eneolithic/BA (undetermined) 2,800–1600 BC (4,750–3550 BP); Early BA 2200–1600 BC (4,150–3550 BP); Middle/Late BA 1600–800 BC (3,550–2750 BP); Late BA 1300–800 BC (3,250–2750 BP); Late/Final BA 1100–800 BC (3,050–2750 BP); Late BA to Early IA 1300–600 BC (3,250–2550 BP). Period divisions follow the conventional Central European (southern German) archaeological chronology (Coles and Harding 2014, Harding 2000, Krause et al. 1988, Reiter et al. 2024).

Latitude	Longitude	Country	Period
51.75	11.68	Germany	Eneolithic/BA (undetermined)
51.264	9.563	Germany	Late BA to Early IA
49.191	9.223	Germany	Late/Final BA
48.317	10.891	Germany	Early BA
48.318	10.89	Germany	Early BA
48.314	10.895	Germany	Early BA
48.246	10.801	Germany	Early BA
48.264	10.887	Germany	Early BA
53.45	13.33	Germany	Middle/Late BA
48.16	11.42	Germany	Late BA
48.3	11.63	Germany	Late BA
48.15	11.63	Germany	Late BA
47.95	11.72	Germany	Late BA
48.17	11.47	Germany	Late BA
47.93	12.73	Germany	Late BA
47.72	12.13	Germany	Late BA
48.16	11.91	Germany	Late BA
48.04	11.53	Germany	Late BA
48.22	10.84	Germany	Late BA
48.21	11.3	Germany	Late BA
48.07	11.62	Germany	Late BA
48.33	11.93	Germany	Late BA
48.13	12.58	Germany	Late BA
48.18	11.76	Germany	Late BA
48.14	11.58	Germany	Late BA
48.17	11.81	Germany	Late BA
48.13	11.66	Germany	Late BA
48.27	10.89	Germany	Late BA
51.733	11.795	Germany	Eneolithic/BA (undetermined)
51.242	12.116	Germany	Eneolithic/BA (undetermined)
51.557	12.209	Germany	Eneolithic/BA (undetermined)
51.557	12.245	Germany	Eneolithic/BA (undetermined)

Table 2: Site locations in Germany with assigned Neolithic phases and corresponding approximate date ranges. Early Neolithic sites date to ca. 5,500–4800 BC (7,450–6750 BP), Late Neolithic to ca. 4,800–2800 BC (6,750–4750 BP), Late Neolithic/Early Eneolithic represents the transitional phase ca. 3,000–2800 BC (4,950–4750 BP), and Final Neolithic dates to ca. 2,800–2200 BC (4,750–4150 BP). Sites labeled "Undetermined Neo" have unresolved Neolithic period assignment. Period divisions follow the conventional Central European (southern German) archaeological chronology (Coles and Harding 2014, Harding 2000, Krause et al. 1988, Reiter et al. 2024).

Latitude	Longitude	Country	Period
49.428	8.683	Germany	Late Neo
50.381	8.729	Germany	Undetermined Neo
51.168	11.848	Germany	Early Neo
48.331	10.899	Germany	Late Neo
48.317	10.891	Germany	Late Neo
48.318	10.89	Germany	Late Neo
48.246	10.801	Germany	Late Neo
48.226	10.896	Germany	Late Neo
48.759	12.803	Germany	Undetermined Neo
48.849	9.221	Germany	Undetermined Neo
54.872	8.401	Germany	Late Neo/Early Eneolithic
48.377	10.899	Germany	Late Nep
48.85	12.767	Germany	Late Neo
48.663	12.707	Germany	Final Neo
48.691	13.016	Germany	Final Neo
48.913	12.539	Germany	Late Neo
48.706	11.325	Germany	Final Neo
48.845	12.619	Germany	Early Neo
49.385	8.573	Germany	Early Neo
48.883	12.533	Germany	Late Neo
48.667	13.073	Germany	Late Neo
48.711	11.453	Germany	Final Neo

2.3.1 Strontium

The sites and $^{87}Sr/^{86}Sr$ data used for the network analyses in this study were obtained from BIAD. A total of 56 sites were included, comprising 34 Bronze Age sites and 22 Neolithic sites with associated $^{87}Sr/^{86}Sr$ data. This would also be possible to investigate separately from the find data. These sites cover a broad temporal and spatial range, enabling an investigation of mobility patterns across the Neolithic to Bronze Age transition. Human $^{87}Sr/^{86}Sr$ isotopic data were derived from skeletal remains excavated at these locations, providing direct evidence of individual mobility across the study region. This study focuses on the variation in $^{87}Sr/^{86}Sr$ values between the Neolithic and Bronze Age periods, deliberately excluding isoscapes and baseline data to prioritize comparative analysis of individual isotopic values over time.

2.3.2 Least Cost Path

Least Cost Path (LCP) analysis is a computational method for identifying the most efficient routes between two or more points across a geographic space. In archaeology, LCPs have been widely applied to explore movement and connectivity (Howey 2011, Llobera 2011, Verhagen and Jeneson 2012, White and Barber 2012, Whitley and Hicks 2003). LCP models require two key inputs: the spatial coordinates of the origin and destination, and a cost surface representing travel friction, typically based on slope, elevation, or land cover. The output is a single optimal path (Herzog 2022, Llobera 2020).

A key limitation of LCPs in archaeology is the assumption that selected points were directly connected, a premise more defensible in historical contexts (van Lanen et al. 2015, Vletter and Van Lanen 2018), but harder to justify for prehistory. Even if two points were connected, other sites may have influenced route selection, and indirect connections are often overlooked. Additionally, given the incomplete nature of archaeological data due to both undiscovered and lost sites LCP results risk overinterpretation. Variables such as site size, catchment, and network centrality introduce further uncertainty. Nonetheless, researchers frequently assume dataset completeness or minimal impact from missing data.

Beyond these interpretative challenges, LCP analysis presents computational issues. These include the selection of cost models, algorithm choice, and Digital Elevation Model (DEM) resolution (Verhagen and Jeneson 2012, Herzog 2022). High-resolution DEMs do not necessarily improve performance (Herzog 2022) and may capture modern surface features, while smoothing can obscure relevant natural terrain (e.g., minor valleys), altering slope-derived travel costs.

To address some of these concerns, we adopt a modified version of the "From Everywhere to Everywhere" (FETE) approach (White and Barber 2012). Our variation integrates concepts from Circuit Theory (CT), which models the landscape as an electrical circuit where resistance (friction) regulates directional current flow (Crabtree et al. 2021, Howey 2011, McRae et al. 2008, McRae et al. 2009, McRae 2016). To avoid directional bias, we sampled a grid of points across an enlarged study area minimizing edge effects, such that each point acted as both origin and destination in turn. This landscape-based sampling removes the need to define actual or proven archaeological sites as start/end points and is computationally more efficient than standard FETE. Nevertheless, computational tests on smaller samples show that the main drawback of this simplification is the loss of localized patterns, patterns which are not a major concern within this study. It also allows for later comparison between modeled movement corridors and site distribution patterns.

The method is open-source and documented in detail in Bilotti et al. (2024), available at https://gitlab.com/bilottigiacomo/marfil. In brief, it uses GRASS GIS functions (r.walk, r. path) called through R via the rgrass package (Pebesma and Bivand 2023: GRASS Development Team 2023). A ~300 m resolution DEM (aggregated from SRTM-90; Jarvis et al. 2008b, Jarvis et al. 2008a) was used due to the extensive spatial extent (southern Alps to the North German Plain), balancing resolution and computational efficiency (Howey 2011).

The resulting paths were combined to create a kernel density surface using the density function from the spatstat package (Baddeley 2017; Baddeley et al. 2016; Baddeley and Turner 2025). These densities were aggregated, scaled, and clipped to the study area following Bilotti et al. (2024). Instead of visually comparing corridor structure to site locations, we employed statistical testing to evaluate whether archaeological sites were situated closer to high-mobility corridors than expected under random distribution. Using the KDE-based density surface, we derived a distance surface to high-use corridors and used it as a predictor variable. We then tested the relationship between this covariate and site locations using the rhohat function from spatstat, which models point pattern intensity relative to an environmental variable, returning a 95 % confidence interval (Baddeley 2017; Baddeley et al. 2016; Baddeley and Turner 2025; Kempf 2021; Kempf and Denis 2024; Kempf and Günther 2023; Mcrae 2016).

To stabilize the model, distances from the top 25 % KDE density (i.e., the third quartile) were treated as "zero" effectively considering those areas as high-corridor zones. This formal statistical framework strengthens the interpretive robustness of our movement models, an improvement over conventional, visually assessed LCP outputs.

Finally, a *network model* developed by Ducke and Suchowska (2022) was generated from the archaeological sites (Figure 4). This involved constructing cost-based networks for 34 Bronze Age and 22 Neolithic sites using the v. net.models algorithm in GRASS GIS. Individual cost surfaces were created with r. cost, using a resampled 100 m DEM derived from SRTM-90 (Jarvis et al. 2008a, Jarvis et al. 2008b, Kempf et al. 2025).

Neolithic sites showed clear spatial clustering. To reduce overrepresentation and produce a manageable large-scale network, we performed a KDE analysis using spatstat and sf in R, testing kernel radii (σ) of 1,000, 2000, and 3,000 m. A σ of 3,000 m with 100 m raster resolution best captured observed clustering. KDE values were reclassified to a 0–1 scale, with values below 10 % discarded. Remaining areas were polygonized and centroids extracted using the terra package. This produced 56 representative points: 34 Bronze Age sites and 22 Neolithic locations, including cluster centroids and spatial outliers. These were used to generate a cost surface and construct the final network model using v. net.models.

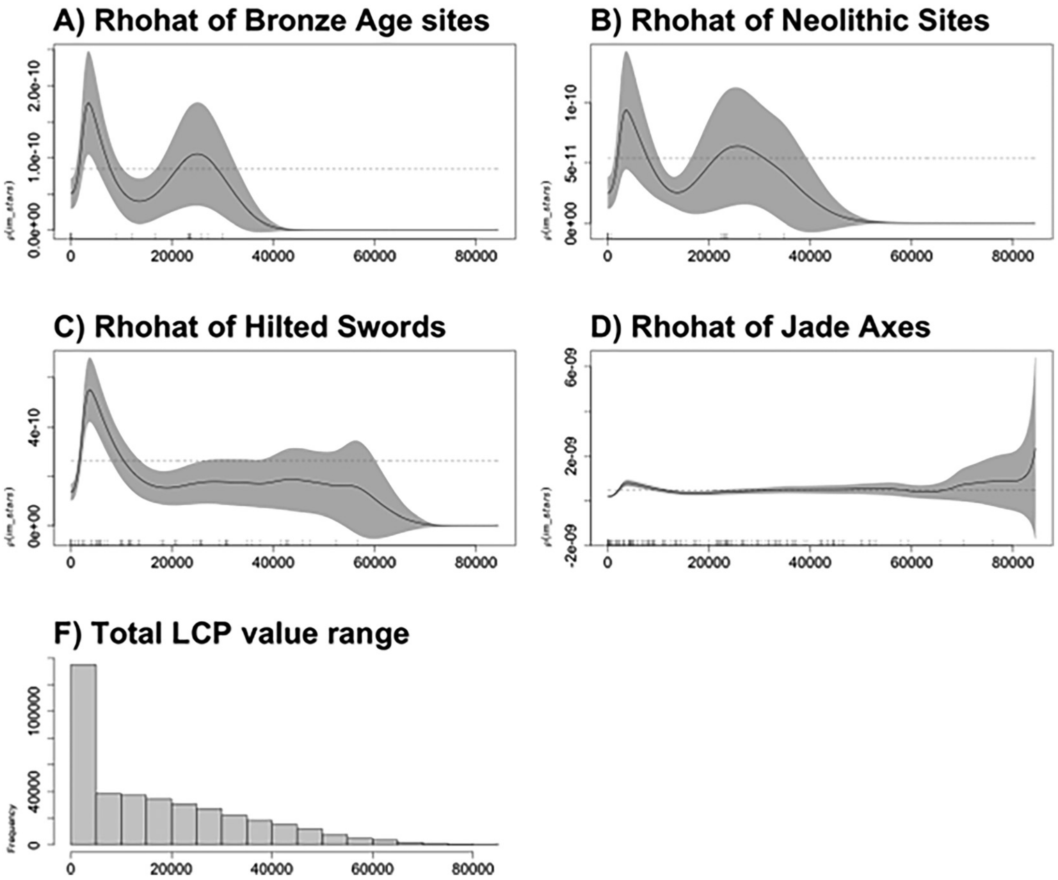

Figure 3: Displays rhohat probability plots indicating site intensity in relation to LCP Density. These plots visually illustrate how site distribution deviates from expected random patterns across different data categories. Plots by GB.

3 Results

3.1 LCP Analysis

The *rhohat* function provides a nonparametric estimate of point process intensity as a function of a covariate, in this case the distance from high LCP (Least Cost Paths) density. This analysis evaluates whether the observed spatial distribution of archaeological sites deviates from what would be expected under complete spatial randomness (Baddeley et al. 2016).

Figure 3 presents the results of the *rhohat* analysis, with distance from high LCP density as the covariate. The *x*-axis represents the distance from identified movement corridors, while the small black tick marks along the axis indicate the individual locations of sites. The red line shows the expected site intensity under a random (null) distribution, serving as a reference baseline. The black line represents the observed intensity of sites as a function of the covariate, and the grey shaded area shows the confidence interval around this estimate.

Where the black line lies above the red line, it indicates that sites occur more frequently than expected by chance at those distances, suggesting a positive association with movement corridors. Conversely, when the black line falls below the red line, it indicates a lower-than-expected site frequency, implying avoidance or weak association with those areas.

Figures 4 and 5 illustrate the probable distribution and routes for the Neolithic and Bronze Age periods, highlighting differences in site distributions. Neolithic sites are predominantly clustered near areas of high accessibility, particularly along major movement corridors. This pattern is tentatively supported by the rhohat analysis (Figure 3). In panel B, Neolithic sites show a slight but consistent increase in spatial intensity near the

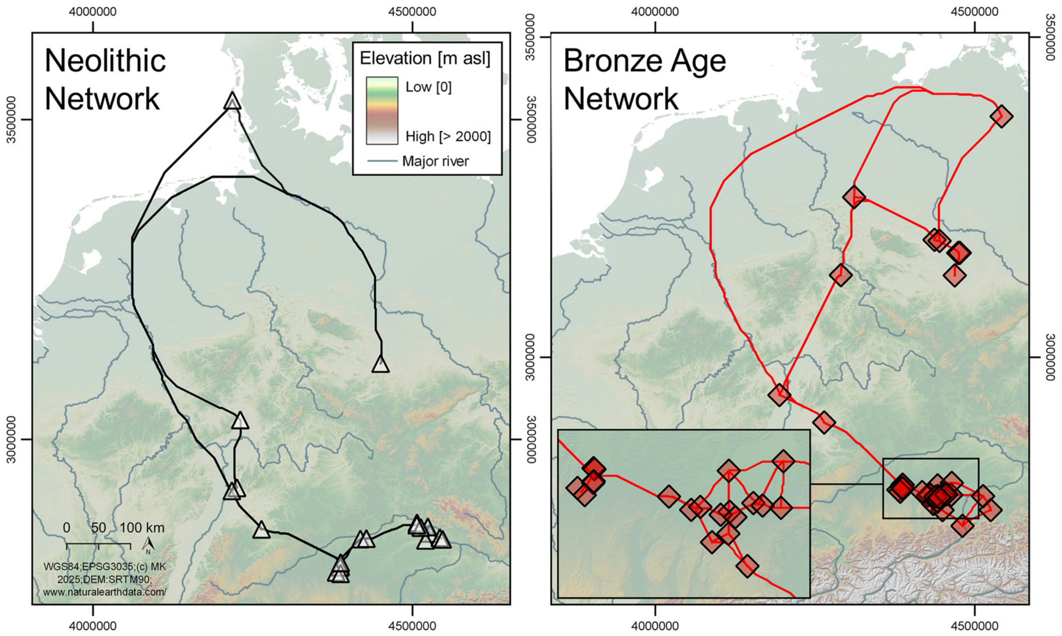

Figure 4: Neolithic (left) and Bronze Age (right) networks in the study area based on topography and cost surfaces. Neolithic networks were created using centroids of site clusters with a KDE of sigma = 3,000 *m*. Neolithic sites = white triangles, Bronze Age sites = red rectangles. Map by MK.

modeled movement corridors (within ca. 0–10 km), suggesting a weak association with these routes. The effect is less pronounced than for Bronze Age sites (panel A) or hilted swords (panel C), but still indicates some degree of alignment between Neolithic settlement locations and accessible pathways. In contrast, Bronze Age sites are more dispersed and generally located further from high-mobility areas. The spatial distribution of Neolithic sites also shows clustering near large rivers, whereas Bronze Age sites do not exhibit the same degree of clustering near rivers. These findings point towards potential differences in the spatial organization of Neolithic and Bronze Age sites, highlighting varying patterns of site selection and accessibility between the two periods.

3.2 Strontium

Boxplots were created using the ggplot2 (Wickham and Wickham 2016) package in R for each site from the BIAD database that contained $^{87}Sr/^{86}Sr$ data. Each boxplot corresponds to a specific archaeological site, providing a visual representation of the range and central tendency of $^{87}Sr/^{86}Sr$ isotopic compositions within its respective context. The length of each box conveys the variability in $^{87}Sr/^{86}Sr$ ratios observed within the dataset. Median lines within the boxes demarcate the central tendency, while whiskers extend from the minimum to the maximum values, excluding outliers, data points beyond whiskers, often indicative of unique or anomalous $^{87}Sr/^{86}Sr$ signatures potentially associated with mobility or non-local origins. (Figures 6 and 7). presents boxplots of the $^{87}Sr/^{86}Sr$ isotopic ratios derived from human samples at various archaeological sites, categorized into Neolithic and Bronze Age periods. The boxplots illustrate the distribution of $^{87}Sr/^{86}Sr$ values for each period, with the Neolithic sites showing a wider interquartile range (IQR) for the median, indicating more variability in the central tendency of these values. However, the overall range of $^{87}Sr/^{86}Sr$ values for the Neolithic period is narrower. In contrast, the Bronze Age sites exhibit a more stable median, as indicated by a narrower IQR, but the overall range of $^{87}Sr/^{86}Sr$ values is wider, reflecting greater variability in the strontium isotope ratios. This difference suggests that while the central values (medians) of $^{87}Sr/^{86}Sr$ were more variable in the Neolithic period, the Bronze Age saw a broader spread of values, potentially indicating more diverse sources of strontium.

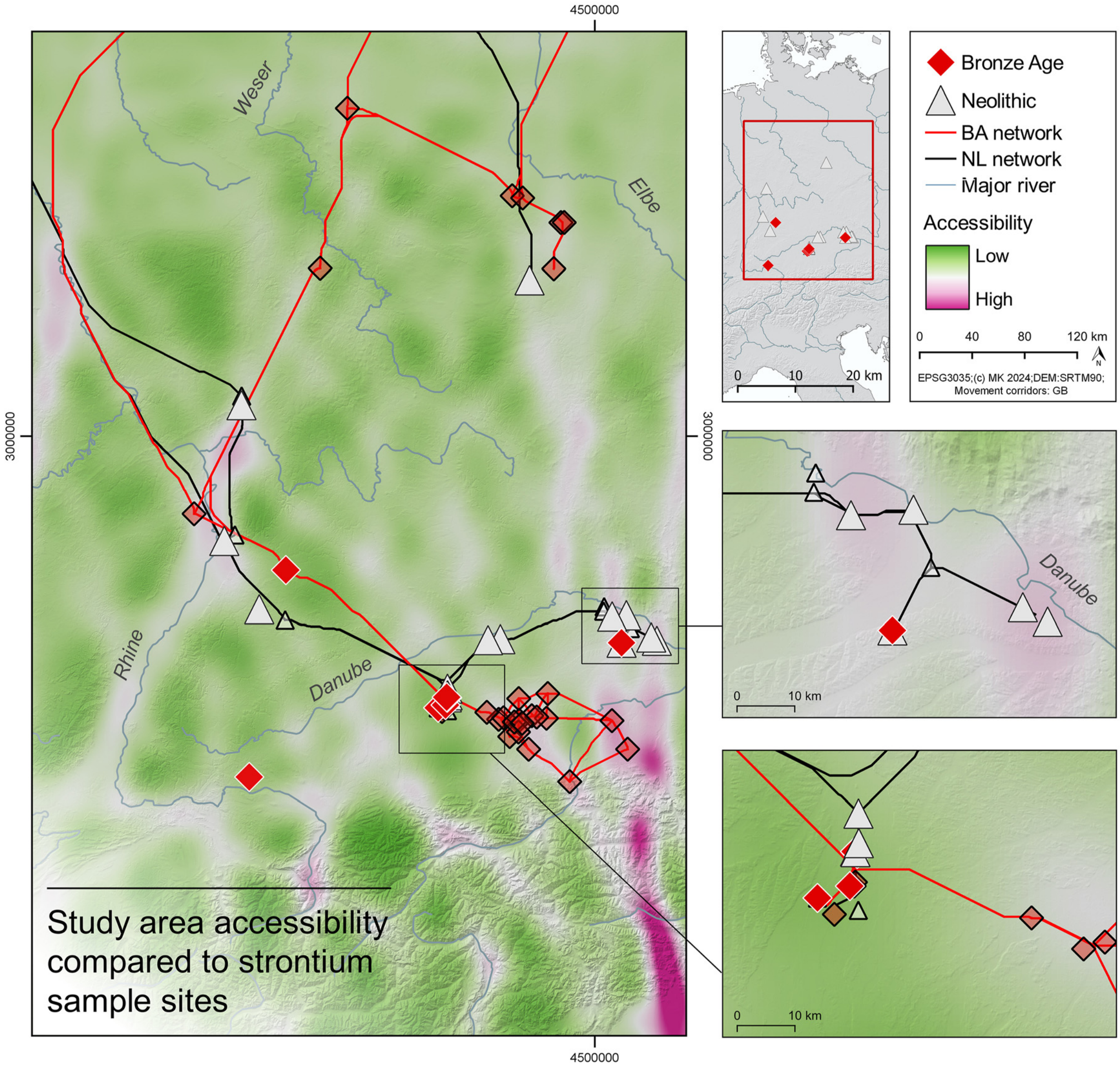

Figure 5: Network models with a visualization of the LCP movement corridors corresponding to the Rhohat, with the addition of the networks, the bold icons symbolize the sites with corresponding ^{87}Sr/^{86}Sr data. Map by MK.

4 Discussion

We hypothesized that the spatial placement of Neolithic and Bronze Age sites in southern and central Germany was conditioned by proximity, operationalized here as low accumulated movement cost to major landscape travel corridors (Rhine–Danube axis and associated low-resistance valleys). Our objective was to evaluate whether modeled mobility ease (LCP cost) provides a primary explanatory covariate for site and find distributions, or whether departures from that relationship imply additional structuring factors (resource access, territoriality, social signaling) that varied through time. Additionally, we wanted to test if this somehow was reflected in the mobility by looking at ^{87}Sr/^{86}Sr from the two periods.

To test this, we fit rhohat models (spatstat) relating point intensity (sites/finds) to the continuous LCP cost surface (Figure 3). In these plots, the solid line is the estimated relative intensity as a function of cost; the red dashed line is the intensity expected under a covariate-independent (null) model; gray envelopes show

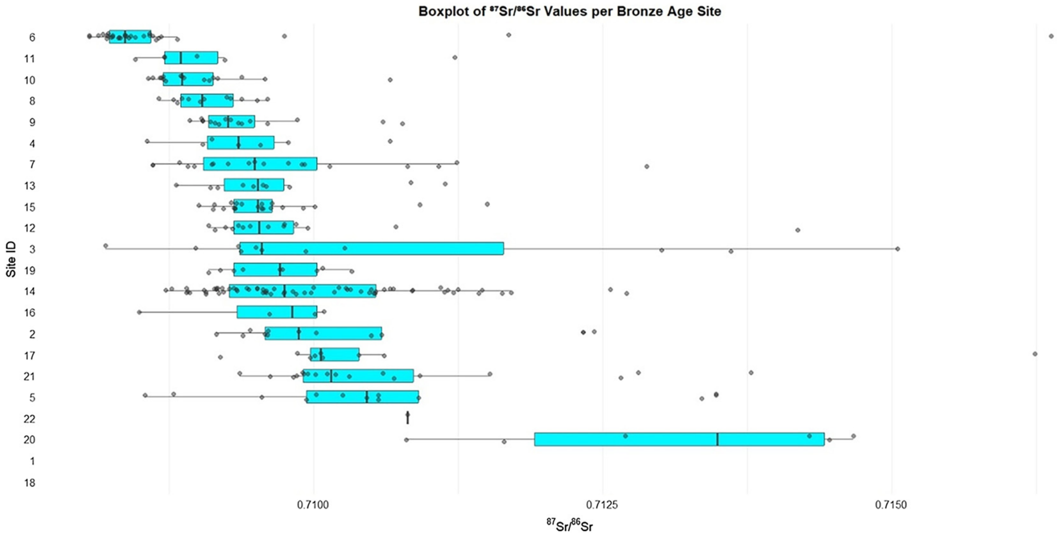

Figure 6: Boxplot of Neolithic sites from the BIAD database. Plot by NS. The raw data used to generate the plot is provided in the SI.

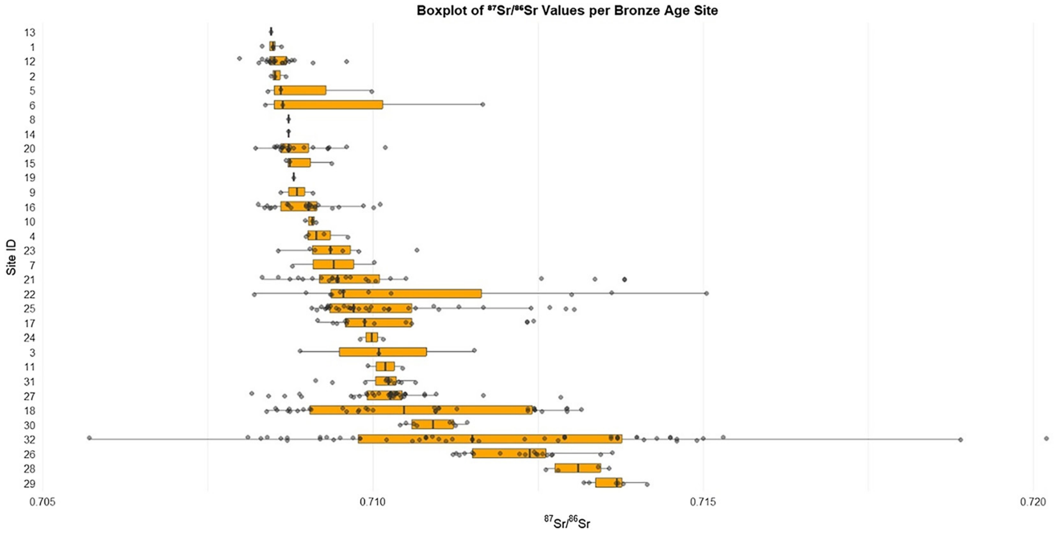

Figure 7: Boxplot of Bronze Age sites from the BIAD database. Plot by NS. The raw data used to generate the plot is provided in the SI.

simulation-based confidence bounds; and tick marks along the *x*-axis indicate observed covariate values at point locations. Panel histograms summarize the areal distribution of LCP costs across the study window (Figure 3F).

Neolithic sites show elevated intensity in the lowest cost range i.e., they occur preferentially in areas that the model identifies as high-mobility corridors. Intensity declines across much of the intermediate, high-cost domain but exhibits a secondary rise at moderate costs, suggesting that some Neolithic settlement also extended into more resistive terrain (Figure 3B). This two-mode tendency implies that while mobility corridors structured a significant component of Neolithic land use, site placement was not confined to them; other ecological or social criteria likely mediated occupation away from the most efficient routes.

Bronze Age sites display an even stronger concentration within the very lowest LCP costs, with intensity dropping sharply once costs increase (Figure 3A). The pattern indicates that Bronze Age settlement in the present dataset was more tightly coupled to high-mobility terrain than the Neolithic pattern. This may signal an increasing reliance on established communication/exchange routes or a narrowing of habitable/strategic locations linked to sociopolitical integration along the river corridors.

The hilted sword find spots mirror the Bronze Age site trend: intensity peaks in the low-cost domain and falls below the null expectation across most higher-cost values (Figure 3C). This pattern could reflect corridor-dependent movement, exchange, or conflict, but may also be shaped by selective deposition practices or socially regulated placement along major axes of circulation (Fontijn 2002, Brück and Fontijn 2013). The contrast between the pronounced low-cost association of swords and the broader envelope for Bronze Age habitation suggests that circulation of prestige or martial equipment may have been more corridor dependent than settlement itself, while acknowledging potential ritual or symbolic constraints.

In contrast, jade axes show little to no enhancement in the lowest cost range; the intensity curve is comparatively flat across low–moderate costs and only drifts upward (with wide uncertainty) in the extreme high-cost tail (Figure 3D). Within the limits imposed by small counts, this pattern may indicate that jade axe deposition was less constrained by modeled mobility ease, consistent with symbolic, ceremonial, or socially marked placement outside principal corridors (Fontijn 2002).

Interpretation of the near-zero cost end requires caution. The LCP cost distribution is highly right-skewed (Figure 3F): a large share of the study area falls into low to very low cost categories, and the precise “zero” bin represents a very small areal fraction associated with the modeled core corridors themselves. Low observed intensity at cost ≈0 does not imply avoidance; instead, it reflects limited spatial extent and potential edge effects. The substantive signal lies in the sharp elevation of intensity across the broader low-cost neighborhood immediately above zero, where most sites and find spots cluster.

Taken together, the rhohat results support a temporal and functional differentiation in landscape use. Neolithic occupation engaged mobility corridors but was more dispersed into costlier terrain, whereas Bronze Age settlement and especially hilted sword distributions became increasingly corridor-focused, consistent with intensified movement networks, exchange traffic, or emergent sociopolitical structuring around major routes. Jade axes decouple from this pattern, implying alternative logics of deposition that were less sensitive to modeled travel efficiency. Sample and model assumptions (cost surface parametrization, smoothing) should be considered when inferring behavioral differences; however, the observed covariate effects are sufficiently patterned to motivate targeted hypothesis testing within this dataset.

Funerary monuments situated in relation to major movement axes, especially river corridors have been interpreted as navigational markers, territorial signals, and instruments of social communication (Bakker 2010, Duffy 2020, Helms 1994, Johannsen and Laursen 2010, Müller 1907). Framing the Neolithic–Bronze Age transition as one in which land tenure, emergent hierarchy, and claims over productive landscapes intensified renders spatial positioning relative to *ease of movement* analytically central. Our rhohat models against accumulated Least Cost Path (LCP) cost values (Figure 3) show that archaeological patterning across southern and central Germany is structured by differential engagement with low-cost mobility terrain linking the Rhine, Danube, and associated valleys. These models estimate relative point intensity as a smooth function of modeled movement resistance; interpretation is aided by the accompanying histogram (Figure 3F), which demonstrates that the absolute minimum cost cells occupy very little area. Consequently, depressed intensity exactly at cost ≈0 should not be read as avoidance; the behavioral signal lies in the elevated intensities spanning the immediately adjacent low-cost envelope the landscape band that would have offered energetically efficient travel, communication, and exchange.

Within this envelope, Neolithic sites (Figure 3B) show an elevated intensity across low costs with a tail into moderate costs, indicating strong engagement with high-mobility terrain yet tolerance for settlement in more resistive areas where ecological opportunity, ritual practice, or social factors outweighed travel efficiency. Bronze Age sites (Figure 3A) exhibit a steeper rise and sharper decline, implying tighter coupling to low-cost corridors overall (sample size caveat noted in the widening envelopes at higher costs). This pattern is compatible with models positing increased integration of settlement systems with exchange and communication networks in the Bronze Age (Frei et al. 2019, Furholt 2021, Kristiansen 2002, Kristiansen and Larsson 2005, Miera 2025, Miera et al. 2019). It also resonates with arguments that monumentality and mortuary display were deployed strategically relative to traffic routes, as signals legible to those moving through the landscape, but often positioned to command rather than coincide with pathways (Duffy 2020, Klassen 2014). Whether such offset placement emphasized visibility to approaching parties, control over agricultural frontages, or mediated access to localized resource nodes remains open; all are plausible within the cost-based pattern.

Hilted swords (Figure 3C) are strongly concentrated in low-cost terrain, underscoring the role of major corridors in the circulation and deposition of martial prestige goods (Horn and Kristiansen 2018, Kristiansen 2002, Suchowska-Ducke 2015). Regionally variable find contexts, graves in Scandinavia, hoards in northern Germany and the Carpathian Basin, wetland/river placements across much of Western Europe (Suchowska-Ducke 2015), suggest that while deposition practices differed, transit along energetically efficient arteries structured where swords entered the archaeological record. Jade axes (Figure 3D) diverge: intensity is comparatively flat across low costs and becomes noisy with increasing uncertainty at higher costs. This accords with long-standing work showing that Alpine jade axes (Monte Viso and related sources) were transported widely but deposited in socially charged settings, rock shelters, boulder forecourts, watery locales, graves, hoards, according to ritualized logics rather than utilitarian routing (D'amico 2005, Pétrequin et al. 2013, Pétrequin et al. 2015). Pétrequin et al. (2013) characterize broad "gaps" in jade distributions; evaluated at the scale of southern/central Germany (Figures 1 and 3), the patchiness persists, supporting the interpretation that deposition was episodic, symbolic, and selectively tied to landscape features. Thus, the observed differences between Neolithic and Bronze Age patterns may reflect not only altered mobility structures but also a fundamental shift in depositional practices and their social meanings. Neolithic acquisition networks and depositional grammars appear only partially coupled with pathways of movement, whereas by the Bronze Age, circulation and deposition became more spatially aligned along the major corridors of exchange.

Comparative studies within northern and central Europe further underscore that depositional traditions, rather than mobility alone, structured where objects entered the archaeological record. Classic analyses (Darvill 2008, Mathiassen 1948) first identified the distinct spatial grammars of Late Neolithic and Early Bronze Age deposition across the North European Plain. Subsequent work (Bakker 1976, Breuning-Madsen et al. 2012, Johansen et al. 2004) demonstrated how hoards, graves, and settlement finds cluster differentially with respect to topography, watercourses, and territorial boundaries, reflecting socially encoded choices rather than random discard. Later syntheses (Bakker 2010, Johannsen and Laursen 2010) have refined these interpretations, linking shifting depositional practices to evolving systems of communication, prestige exchange, and landscape signaling. Within the present dataset, these insights reinforce the view that changing artifact distributions between the Neolithic and Bronze Age reflect transformations in the social and ritual logics of deposition as much as shifts in mobility or transport efficiency.

Large-scale contrasts in material emphases jade in the west; copper/gold (and associated weaponry) *to the east* remain analytically useful (Ling et al. 2019, Pétrequin et al. 2013, Rassmann 2013, Suchowska-Ducke 2015). At finer scale, our dataset highlights central Germany, especially the Rhine–Main region, as an interaction hinge where these material spheres overlap (Figure 2). River catchment geometry helps explain this: although many European drainages are north–south oriented, the Danube provides a major east–west axis that intersects with the Rhine system, while the Elbe and Weser link additional basins (Duffy 2020, Hussain and Floss 2016, Kristiansen and Suchowska-Ducke 2015, Ling et al. 2019, Pétrequin et al. 2013, Suchowska-Ducke 2015). Hussain and Floss (2016) emphasized the Rhine–Danube as fluvial highways structuring flows of people and goods; our LCP cost surface reproduces these valleys as energetically efficient corridors, lending quantitative support to those historical-geographic arguments. Because central Germany lacks major physiographic barriers (Miera 2025), persistence of regionalized material traditions there likely reflects cultural and political choice layered onto landscape opportunity.

Resource provenance data underscore the corridor linkage. Copper supply chains into Central and Northern Europe drew variably on Rhine-Westphalia, the Black Forest, North Tyrol, Iberia, Sardinia, Slovakia, and the Mitterberg district, with temporal restructuring and a stronger Alpine contribution after ~1500 BCE (Frei et al. 2019, Ling et al. 2014, Ling et al. 2019, Nørgaard 2018). Jade axe raw materials from Monte Viso and allied Alpine ophiolite belts explain westward/northward dispersal arcs (D'amico 2005, Pétrequin et al. 2013, Pétrequin et al. 2015). When plotted against modeled low-cost pathways (Figure 3), plausible transalpine crossing sectors correspond broadly to known modern pass zones, suggesting that reconstructed prehistoric exchange likely exploited similar or adjacent corridors. Such patterning invites comparison to macroeconomic approaches (world-systems, core/periphery) (Kristiansen and Larsson 2005, Nicoll and Zerboni 2020, Sherratt 2006), but here "cores" may best be understood as *nodal aggregations of resource access + corridor control* rather than centralized polities in the strict sense.

The boxplots illustrate differences in the distribution of ^{87}Sr/^{86}Sr values between Neolithic and Bronze Age sites, though these differences are relatively subtle. During the Neolithic (Figures 6 and 7), there is a broad range of median ^{87}Sr/^{86}Sr values across sites, indicating that communities were established in geologically diverse regions. This inter-site variation likely reflects the occupation of distinct geological zones, consistent with relatively localized movement patterns across heterogeneous landscapes. At the same time, most Neolithic sites exhibit narrow intra-site distributions, with tight interquartile ranges and few extreme outliers. This suggests low individual-level mobility within sites and limited incorporation of non-local individuals. In other words, while Neolithic communities may have differed substantially in their geological settings, each community was internally homogenous in terms of strontium isotope signatures, pointing to residential stability and limited integration of individuals from different isotopic regions.

The ^{87}Sr/^{86}Sr isotope evidence provides an independent mobility proxy that aligns with the cost-based spatial signal. Neolithic sites display more constrained inter-individual variability within sites, often consistent with movement inside geologically similar provinces, even as those sites concentrate in low-cost corridor terrain (Figures 3 and 5). Together, these patterns suggest regionally mobile Neolithic communities positioned to take advantage of energetically efficient movement corridors.

In contrast, the Bronze Age dataset (Figure 7) shows only a slightly different structure. The spread of median ^{87}Sr/^{86}Sr values across sites is somewhat less pronounced, implying that many communities were situated within geologically similar areas or that the catchment zones of different groups increasingly overlapped. This may reflect subtle changes in regional connectivity, territorial organization, or land-use strategies that led to greater convergence in the geological zones occupied. Intra-site variability increases modestly in the Bronze Age, with several sites showing wider interquartile ranges and more frequent outliers, indicating a slightly higher degree of individual mobility or the presence of people from different geological backgrounds within single sites. Bronze Age assemblages show a broader range of ^{87}Sr/^{86}Sr values, implying integration across more geologically varied source regions and, by extension, slightly wider or more frequent long-distance connections (Figures 6 and 7).

To explore whether large-scale movement affordance influences isotopic variability, we tested the relationship between Least Cost Path (LCP)–derived movement corridors and the intra-site standard deviation of ^{87}Sr/^{86}Sr values (Supplementary Figure 1). The results indicated a negative relationship between corridor density and isotopic variability, with higher variability in areas of low accessibility and reduced variability in areas of high corridor density; a complementary pattern is observed when using distance to corridors. Although this relationship is not commonly addressed in strontium isotope studies and is therefore presented here as exploratory, it is consistent with the possibility that enhanced connectivity along movement corridors may reduce locally constrained isotopic variability, while relative isolation accentuates it. These results are intended to highlight a potentially important structuring effect of connectivity on isotopic datasets rather than to provide a definitive behavioral interpretation.

Taken together, these data suggest a cautious interpretation of a gradual shift from the relatively geologically discrete and internally homogeneous Neolithic communities to more isotopically mixed Bronze Age populations. While the difference between the two periods is not large, it may reflect incremental increases in mobility, connectivity, and changes in community structuring. Bronze Age networks, though possibly socially selective, appear to link distant geologies through energetically efficient routes (Frei et al. 2019, Kristiansen and Larsson 2005, Nørgaard 2018, Reiter and Frei 2023, Reiter et al. 2023). These interpretations remain cautious given the small number of sites analyzed, and additional data could refine or alter these patterns. Nonetheless, the current evidence provides an initial indication of subtle changes in mobility and landscape use across the later prehistoric period.

Weaponry, violence, and social regulation show additional temporal texture. Although Bronze Age swords proliferate materially, paleopathological data indicate declining per-capita skeletal injury relative to Neolithic peaks associated with enclosure building and the onset of copper metallurgy; injury frequencies drop toward the

Late Neolithic and into the Bronze Age even as fortifications increase (Müller et al. 2024). This decoupling between armed display and bodily trauma suggests changing conflict regimes, deterrence, strategies for conflict resolution ritualized combat, or alliance maintenance, rather than uniformly escalating interpersonal violence (Kneisel et al. 2024, Müller et al. 2024). In this context, jade axes have been characterized as "object-signs" (Pétrequin et al. 2013) potent but not necessarily used, whereas hilted swords manifest overt martial identities and shifting sociopolitical orders (Horn & Kristiansen 2018; Kristiansen 2002; Suchowska-Ducke 2018). Maintaining far-flung social and exchange networks requires ongoing effort (Murrieta-Flores 2010); breakdowns may trigger friction, but successful maintenance leaves patterned deposition in the very low-cost zones where contact recurred.

Despite this substantial evidence for human mobility, regional material asymmetries persisted. Temporal overlap between jade axes and later sword traditions was limited, yet sword distributions continue to reflect broad east–west structuring (Ling et al. 2019; Pétrequin et al. 2013; 2015; Suchowska-Ducke 2018). Central Germany's corridor nexus shows that interaction need not erase cultural distinctions: materials could move farther than most people (Stojanowski & Knudson 2011), and when people *did* move, participation was socially filtered. The rhohat LCP results, combined with ^{87}Sr/^{86}Sr mobility data portray, therefore, a landscape in which corridors supported communication, but temporally-variant social rules, politics, deposition traditions, territorial display, alliance politics, resource control had a great say in who and what moved where across the Neolithic–Bronze Age transition.

5 Conclusions

By integrating landscape cost modelling, spatial point-pattern (rhohat) analysis, artifact distribution, and ^{87}Sr/^{86}Sr data, this study provides an initial, data-driven view of how prehistoric communities in central and southern Germany engaged with topographic and simulated movement structures. The LCP surface identifies a network of low-cost corridors, many aligned with major river valleys that appear to have shaped both site locations placement and the circulation of high-value materials. Rhohat results show that Neolithic and Bronze Age sites were concentrated within a broader low-cost mobility envelope rather than uniformly scattered across the landscape. The Bronze Age signal is steeper: site intensity rises sharply in low-cost terrain and falls rapidly with increasing cost, suggesting tighter coupling between settlement and major communication axes during the Bronze Age than in the Neolithic.

Artifact classes respond differently to the same landscape structure, reflecting not only functional constraints but also temporal changes in how the landscape was perceived, used, and socially marked across the Neolithic and Bronze Age. Hilted swords display strong low-cost association, consistent with movement and deposition along principal transit routes. Jade axes do not; their intensity varies little across the low-cost range and remains patchy coherent with previous work that links Alpine jade circulation to contextually structured deposition rather than transport efficiency alone. That contrast indicates that proximity to mobility corridors facilitated access but did not dictate where meaning-laden objects were ultimately placed.

The isotopic data provides additional context for mobility trends. In the Neolithic, median ^{87}Sr/^{86}Sr values across sites vary more widely than within individual sites, suggesting communities were positioned in geochemically distinct catchments but most individuals within each site derived from similar local environments. Bronze Age sites, in contrast, show more uniform site medians yet greater internal variability in individual ^{87}Sr/^{86}Sr values, consistent with selective incorporation of people (or life histories) from multiple geological provinces. This internal heterogeneity aligns with the stronger corridor association observed in the Bronze Age rhohat curve and with archaeological evidence for expanded exchange networks.

Taken together, these results indicate continuity in the strategic value of landscape connectivity across the Neolithic–Bronze Age transition but transformation in how that connectivity was socially mobilized. Neolithic groups positioned settlements within reach of efficient movement routes, yet mobility patterns appear more locally constrained. Bronze Age networks linked more distant geological sources through individuals and artifacts that circulated preferentially along low-cost pathways. Materials and people did not always move in lockstep: jade flows and sword flows map differently onto the corridor system, and isotopic evidence shows socially structured participation in long-distance interaction rather than generalized population mobility.

Several limitations temper these conclusions. LCP results depend on input surface parameterization; different friction models (hydrology weighting, slope cost functions, seasonal passability) could shift corridor geometry. Rhohat confidence envelopes widen where data are sparse. $^{87}Sr/^{86}Sr$ comparability rests on consistent baseline calibration and diagenesis screening. Spatial equifinality, different behaviors producing similar patterning remains a concern; modeled accessibility is a proxy, not a direct record of actual route use. As Kempf (2023) notes, all reconstructions rely on present-day quantifiable data to approximate past decision landscapes.

Despite small sample sizes in key categories, convergent signals from cost modeling, artifact patterning, and isotopic variability suggest that natural corridors framed opportunity structures leveraged by prehistoric communities in period-specific ways. Future research could expand these insights by integrating environmental proxies, demographic models, and predictive approaches such as site exploitation territories (SETs) (Miera et al. 2019, Miera 2025), to test more explicitly how mobility, material circulation, and social organization co-evolved with landscape connectivity during the Neolithic and Bronze Age. Such approaches would allow for more nuanced, multi-scalar reconstructions of human–landscape interactions, complementing the pilot analyses presented here.

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