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Walking commodities: A multi-isotopic approach (δ^{13}C, δ^{15}N, δ^{34}S, ^{14}C and $^{87/86}$Sr) to trace the animal economy of the Viking Age town of Birka

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ABSTRACT

Carbon (δ^{13}C), nitrogen (δ^{15}N), and strontium ($^{87/86}$Sr) isotope analyses have been applied widely over the past four decades to reconstruct human and animal dietary and mobility patterns. Sulfur (δ^{34}S) has recently shown great promise to further enhance isotope analyses of the geologic and hydrologic contexts in which organic material formed. For this case study we applied this suite of multi-isotopic analyses to a dataset of 45 animal bones and teeth from the urban Viking Age town of Birka located in present-day Sweden. This research falls in line with previous studies as a potential way to bridge the understanding of relationships between centers and hinterlands by tracing socioeconomic networks of subsistence and food provisioning utilizing the animal economy as a proxy. The utilization of δ^{34}S values enables terrestrial, marine and freshwater food niches to be disentangled when δ^{13}C and δ^{15}N values may be overlapping between each of the niches. The incorporation of five $^{87/86}$Sr samples further allowed us to carefully interpret the movement of animals across the landscape. We identified cattle potentially originating $>$ 180 km from Birka during the earliest stages of occupation (early 8th century CE), while pigs and ovicaprids were more locally reared, indicating the dimensions of the early market economy in the Viking period was complex and multifaceted.

1. Introduction

The Viking Age (793–1050 CE) has long been associated with sea voyages, plundering, and turmoil representing a period of change in social developments which would be foundational to the growth of later European economic systems (Barrett, 2008, Kalmring, 2016). Within the discourse of the Viking Age and archaeology at large, two distinct models for what caused these development have emerged: the “Big Bang Theory,” where an explosion of trade, contacts and movement occurred in the 8th century following the collapse of the Roman Empire; or the “Long Dawn Theory” in which these changes have long lineages back to prior periods within the Bronze Age and Iron Ages without a single point of origin (Barrett, 2008, Baug et al., 2019, Crabtree, 2018, Lund and Sindbæk, 2021, Runge and Henriksen, 2018). Interconnections between urban centers and rural hinterlands in prehistory have long been presumed but have proven difficult to fully trace (Callmer, 1994, LaViolette and Fleisher, 2005, Helle, 1994, Crabtree, 2018). Further, the so called "urban debate" that entails how places specifically of central importance developed in the prehistoric past has been a topic of great discussion within the field and falls under one of the "grand challenges in archaeology" (Kintigh et al., 2014).

The research history of the central places that developed in the Viking Age which included Birka, Hedeby, Kaupang and Ribe within Scandinavia, have to a large extent focused on the context of urbanism as these places served as economic centers, also referred to as Viking Age towns, connecting the flow of trade for the mostly rural Scandinavian market (Sindbæk, 2007a, Sindbæk, 2007b, Kosiba et al., 2007). The long-distance trade connections of the Viking world have been attested

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to by artifacts from places as far away as northern India being found in central places (Kalmring and Holmquist, 2015). Artifacts and DNA analyses have attested to the diverse population and material goods of these central places, however, their subsistence practices have often been reconstructed from the zooarchaeological material or isotope analysis of human populations alone (Linderholm et al., 2008, Wigh, 2001, Lund and Sindbæk, 2021). In the context of Viking archaeology, regions outside these select towns are generally conceived as “hinterlands,” which were areas positioned outside the centers of power and plunder (Skre, 2012, Sindbæk, 2007a, Sindbæk, 2007b, Becker and Grupe, 2012, LaViolette and Fleisher, 2005, Crabtree, 2018). For many social-scientists, hinterlands are treated as places that existed and provided subsistence to the core, however the networks and connections between the towns and hinterlands have not been traced sufficiently in their early stages, and have generally just been assumed in their socioeconomic relations (LaViolette and Fleisher, 2005, Gaastra et al., 2020, Callmer, 1994, Liden and Nelson, 1994, Arnold et al., 2018, Becker and Grupe, 2012).

Recognizing the dependence of urban centers on their hinterlands to meet their subsistence needs falls under generally one of two models of subsistence provisioning: indirect or direct (Zeder, 1998, Zeder, 1988). Indirect provisioning occurs when foodstuffs go through several places (nodes) to reach their destination, meaning there are several points of contact and medial organizational schemes to provide for a larger organization, like an urban center (Zeder, 1988). Direct provisioning occurs when households themselves acquire their own subsistence needs directly from farmers, pastoralists, self-provisioning or other providers of foodstuffs (Zeder, 1988). Neither model is mutually exclusive of the other as different goods can be sourced in different ways. Consequently, in distinguishing different animal economy systems, another approach to interpreting the function of these places can be reached without resorting to the traditional checklist or royal-association approaches where central places are often associated with certain stages of development adhering to a checklist of attributes in order to be recognized as urban; or it must have wielded royal power to be determined as central (Gaastra et al., 2020, Skre, 2012, Barrett, 2008).

The aim of this study was to contextualize the animal economy of an urban Viking Age town by elucidating the isotope ecology of archaeological remains from Birka. To do this, we conducted a multi-isotopic analysis of domesticated faunal material, with a special focus on sulfur isotopes (^{34}S), to highlight the movement of animals across the local landscape, as has been shown in previous studies by Sayle et al. (2013) and Hamilton et al. (2019) amongst others. Radiocarbon dating (^{14}C) was also undertaken to assess previously published dates, which were based on relative dating techniques according to Callmer’s (1977) bead chronology (Kalmring et al., 2021) and a few ^{14}C samples of wood (Kalmring et al., 2021). Along with previously published excavations (Ambrosiani et al., 1996, Kalmring, 2012, Ambrosiani, 2013, Kalmring and Holmquist, 2015, Kalmring et al., 2021), we situate Birka here temporally and contextually as an economically developed center in the early Viking world in which there were contrasts between commercial and residential zones in relation to the central harbor; this concept is discussed further in Wadstål (2021) and is based on observations in the osteological material. Our research demonstrates that the roots of multi-tendril commercial systems that characterize later Viking and Medieval European societies of northern Europe were possibly established prior to the formally recognized advent of the “Viking Age”.

2. Background

2.1. The Viking Age and the urban center of Birka

The beginning of the Viking Age is traditionally marked with the raid of Lindisfarne in 793 CE, but the social formations that characterized it are known to have extended deep into the Iron Age (Barrett, 2008). Birka was a Viking Age town that flourished between 750 CE and 975 CE, and it is situated on an archipelago in what is today Lake Mälaren. During the Viking period, the town occupied a geographically strategic position amongst the trading routes that existed at that time (Risberg et al., 2002, Kalmring and Holmquist, 2015, Hedenstierna-Jonson, 2016). Today, Lake Mälaren is one of the largest freshwater lakes in Sweden, however, during the Viking Age it was still connected to the Baltic Sea and was surrounded by brackish water due to post-glacial isostatic uplift (Fig. 2, Risberg et al., 2002). During the Viking Age, Birka consisted of two smaller islands than the single large one of today and was part of the larger North Atlantic seafaring world (Fig. 1, Fig. 2).

Birka was a trading place during the Viking Age, and the town has an extensive and somewhat eclectic research history, much of which has not been formally published (Kalmring, 2012). The town has caught the attention of archaeologists and researchers since the 18th century when it was recognized as hosting significant deposits of a bygone era known from historical sources, but it has been subject to increasingly more detailed excavations which now includes tens of thousands of artifacts (Kalmring, 2012). Early investigations of the site focused on the many grave mounds that can still be seen in the landscape today, and Hjalmar Stople was one of the first to investigate these between 1871 and 1878 (Hyenstrand, 1991, cf Kalmring et al., 2021). Between 1969 and 1971 the harbor structures, also known as "*stenkistan*" and now found on land, were excavated by Björn Ambrosiani and his team (Fig. 2, Ambrosiani, 2013).

The central portion of Birka is situated on a thick anthropogenic layer known as the “Black Earth,” which is derived from the main area of settlement and activity during the main occupation period (Kalmring and Holmquist, 2015). More recently, excavations (by Centre for Baltic and Scandinavian Archaeology (ZBSA) and Archaeological Research Laboratory SU) of the harbor basin area identified multiple natural and anthropogenic layers (L1-37) from which large quantities of well preserved animal bones were recovered from so called "Black Earth" discarded settlement waste contexts (Fig. 2, Fig. 3, Kalmring et al., 2021). To date, the chronology of the excavation layers has been established based on Callmer’s (1977) bead seriation and material typologies developed from Ambrosiani’s 1970/1971 excavations; see Kalmring et al. (2021) for full chronology and excavation report.

The layers have been interpreted as follows: L31 consisted of marine clay and is considered to be the oldest layer. L30 is considered as a geologic stratum with some early anthropogenic activity. L32 consisted of silt and sand and L23, which is the biggest layer in form of mass and volume and is divided into sublayers, is considered as a waste-layer of anthropogenic activities from the town and included a large number of fire-cracked rocks. L36 is considered a dumping event and is embedded in L23, while L37 is interpreted as an attempt to install a jetty post more thorough description can be found in the report by Kalmring et al., (2021) (Fig. 3). The dating of the layers has been based on Callmer (1977) bead chronology. Additionally, two ^{14}C analyses were conducted on jetty posts (wood) from for wiggle matching the dendrochronology age (dendro no. 57335) AD 853/54 or AD 767/68 (Table 1, Fig. 3, Kalmring et al., 2021).

Research of the human population utilizing isotope analysis has been published by Price et al. (2018), Linderholm et al. (2008), Linderholm and Kjellström (2011), these studies demonstrate that there was a high degree of mobility among the inhabitants of the town. Price et al. (2018) calculated that Birka during the Viking Age hosted an estimated 500 to 1500 inhabitants per generation during its heyday on a landmass too small to independently sustain such a large human population (Fig. 2). It is thus assumed that some substantial proportion of the food consumed among the population would have been imported from elsewhere by boat, however no further investigation of where the food source for Birka came from has been done (Wigh, 2001). Research in the

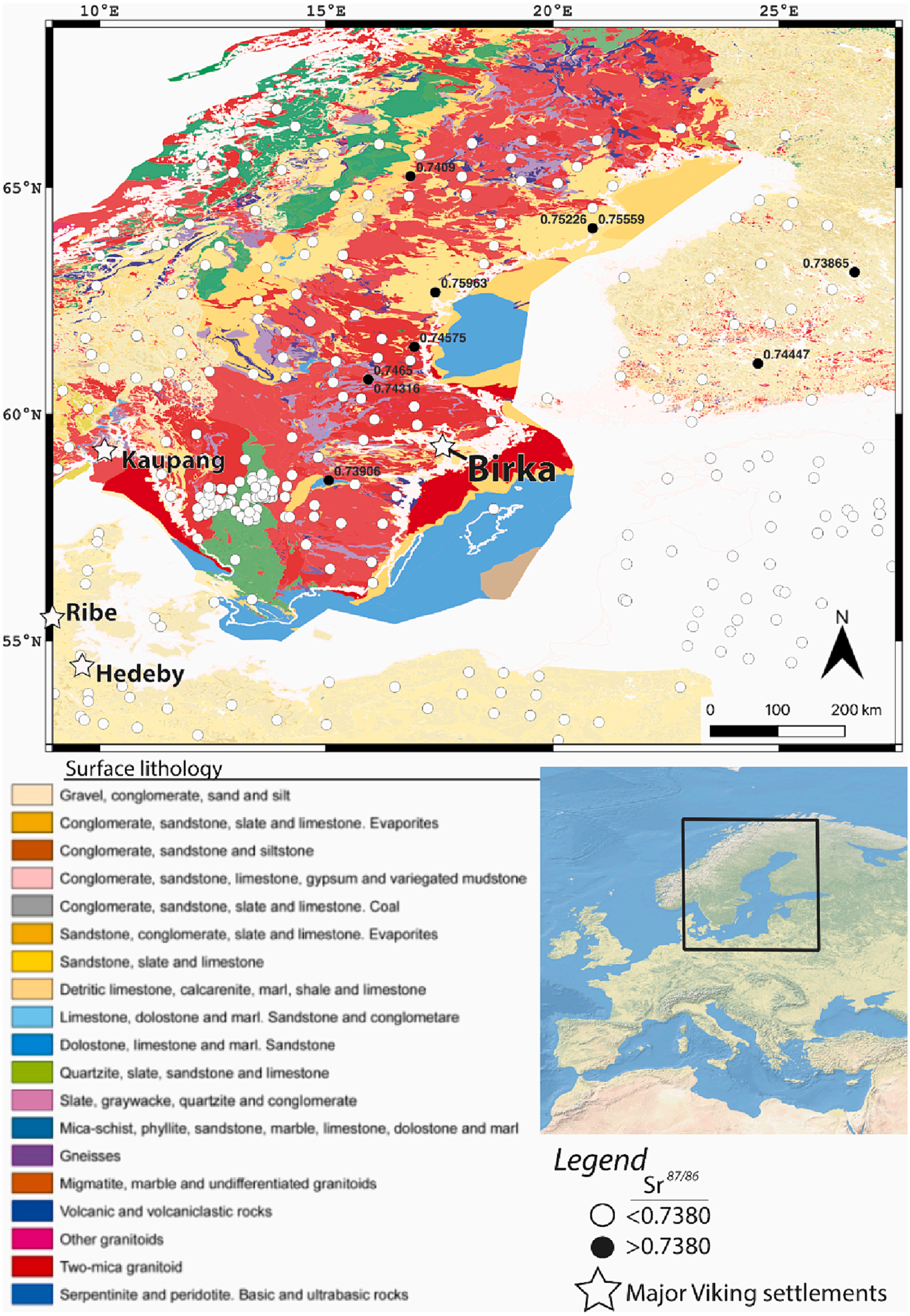

Fig. 1. Location of the study region within Europe and previously sampled and published locations of bioavailable strontium ($Sr^{87/86}$) (Blank et al., 2018, Hoogewerff et al., 2019, Price et al., 2018, Price et al., 2014, Wilhelmson and Ahlström, 2015, Eriksson et al., 2018) relative to key Viking settlements. Background geology map extracted from EGDI 1:1 Million Pan-European Surface Geology server (https://www.europe-geology.eu/map-viewer/).

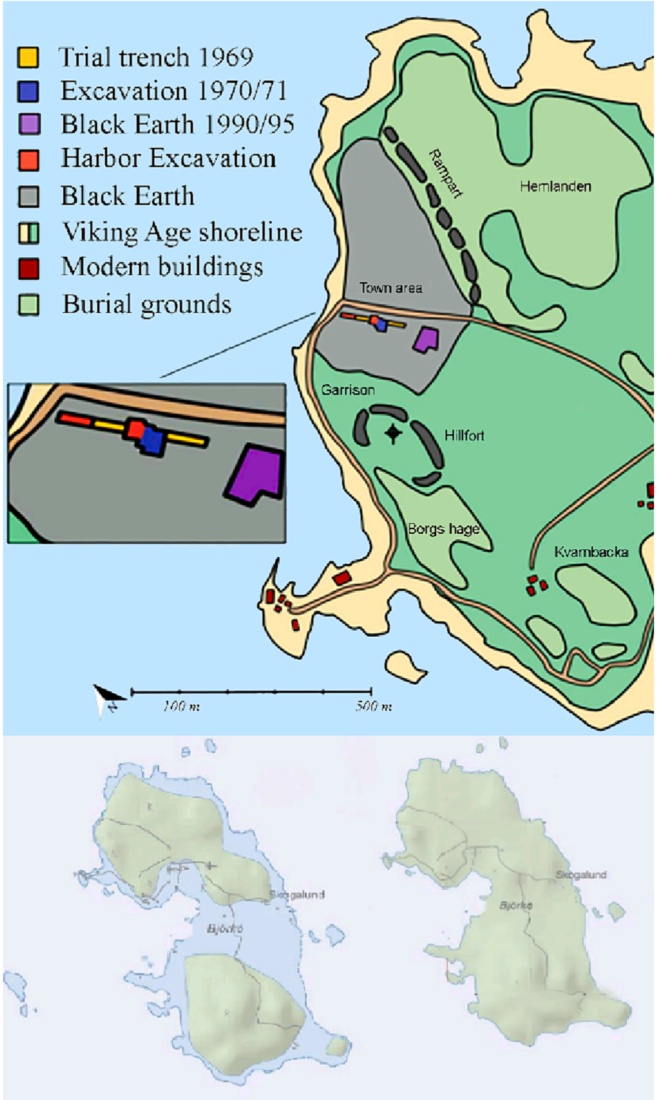

Fig. 2. Top: Archaeological excavation areas in Birka from 1969 to 2016 and general town plan map. *Bottom left:* Birka shoreline during the Viking Age. *Bottom right:* Shoreline of Mäleren Island today. Birka shorelines reconstructed from Geological Service Sweden SGU, Topographic background: GSD-Terrängkartan©.

Table 1
Previous dating of the Harbour material: the bead dates are taken from Table 6 in Kalmring et al. (2021) and are based on Callmer (1977) bead chronology, only layers also dated in this case-study are represented. ^{14}C samples are reported in the excavation report by Kalmring et al. (2021) and the dendrochronology is referred to Daly (2019), all LuS samples are from year rings and Ua samples from wickwork, all from jetty posts.

Layers	**Bead dates** Callmer (1977)
Layer 23/V	935–955 CE
Layer 32	845–875 CE
Layer 35	875 CE (terminus post quem)
Layer 23/III	965–990 CE
14C dates	**2σ range**
Ua-57138	770-970CE (twig)
Ua-57139	760-900CE (timber)
Ua-57140	770-970CE (timber)
LuS 11,694	676–886 (year rings)
LuS 11,695	661–876 (year rings)

hinterlands, known today as the Mälaren Valley and other areas of Sweden has yielded an extensive isoscape, especially for strontium isotopes and general environmental conditions like glacial events, have been published by Blank et al. (2018), Price et al. (2014) and Price et al. (2018) and Liden and Nelson (1994).

2.2. *Isotopic background*

Stable isotopes values of carbon (δ^{13}C) and nitrogen (δ^{15}N) have been used extensively in archaeology for decades to trace diet, while $^{87/86}$Sr has been utilized more for the geological aspect of mobility and migration (Ben-David and Flaherty, 2012, Katzenberg, 2008). Recent advances in continuous-flow isotope-ratio mass spectrometry (CF-IRMS) has allowed for sulfur isotope values (δ^{34}S) to be measured alongside δ^{13}C and δ^{15}N values, whereas previously, a considerably larger, separate sample was required to conduct the analysis (Sayle et al., 2019). By conducting multi-isotopic studies, many questions about diet, mobility and residency are more answerable within the field of archaeological research (Sayle et al., 2013, Nehlich, 2015).

Integral to developing a multi-isotopic approach, it is necessary to understand the geological context of a site in order to identify the relationship between location and isotopic values within skeletal materials (Ben-David and Flaherty, 2012). The geology at Birka is for the most part derived from the Bergslagen lithographic unit of the Svecokarelian orogeny, which is an uplifted and folded craton consisting of metamorphosized sandstones as well as intrusive gneiss, granite and granodiorites, and is one of the oldest rock formations in Europe (Risberg et al., 2002; Price et al., 2014; Blank et al., 2018; Price et al., 2018). There is some degree of regional variability to the geology owing to the brittle tectonic development and complex surficial history of glaciation. The sediment types that dominate northern and central Sweden are derived from Precambrian sedimentary rocks unrelated to the craton due to glaciation during the late Weichselian Ice Age (Blank et al., 2018, Price et al., 2014, Price et al., 2018). The bedrock underlying Birka itself is comprised of gneisses and granites, however surface deposits consist of clay, silt and glacial till from the last Ice Age (Risberg et al., 2002).

2.3. *Isotopes utilized in this study*

Carbon isotopes are incorporated into plant tissues during photosynthesis, and mainly follow three different pathways relating to the metabolic processing of sugars derived from CO_2. Discrimination against ^{13}C during the production of sugar is based on the photosynthetic supergroups of plants (C_3, C_4 or CAM) as well as canopy cover and sunlight availability (Brown and Brown, 2011, Bonafini et al., 2013). The trophic shift between diet and consumer is relatively low for this isotope (~0–2 ‰), but edaphic conditions tend to concentrate heavier ^{13}C vs lighter ^{12}C by as much as 50 % based on detrital content, microbial turnover and/or soil organic matter content (Schimel et al., 1994, Bocherens and Drucker, 2003). In Scandinavia, the absence of indigenous C_4 plants means that terrestrial variability of ^{13}C is primarily a function of canopy cover, which recycles carbon, and edaphic conditions, with a significant amount of contribution potentially coming from marine sources (Bonafini et al., 2013). The gradient which can occur due to CO_2 recycling and the decomposition of leaves on the forest floor in such environments causes δ^{13}C values closer to the forest floor to be more negative, with measured values as low as − 37 ‰ in the Amazon rainforest (Van der Merwe and Medina, 1991, Bonafini et al., 2013). Atmospheric moisture δ^{13}C in a C_3 photosynthesis normally reflect the discrimination effect against ^{13}C and the atmospheric δ^{13}C value of − 8 ‰ will have a fractionation value of δ^{13}C − 26.6 ‰, respectively (Tieszen and Boutton, 1989). Marine sources of carbon tend to have higher concentrations of ^{13}C than terrestrial sources due to the pooling of heavier isotopes in oceans, which are taken up by aquatic organisms (Schwarcz and Schoeninger, 1991).

Nitrogen (^{15}N) is often juxtaposed with carbon in isotopic studies

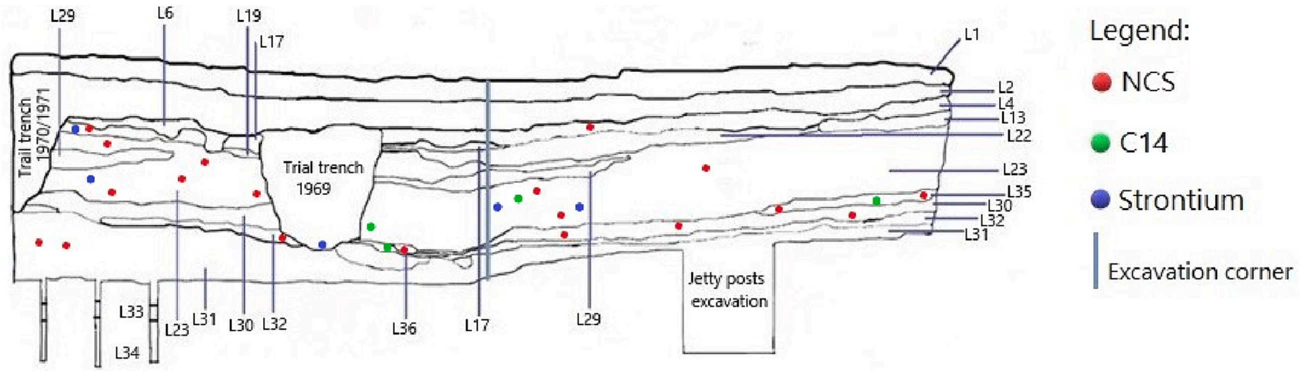

Fig. 3. Stratigraphy of the 2015/2016 Harbour excavation at Birka with excavation layers referred to as L, adapted with permission from figures 60a (northern profile trench 1) and figure 61a (western profile trench 2) from Kalmring et al. (2021). The gray line represents where the layers go around a corner only represented here as continues straight profile for visualization. Relative reference to where the different samples were taken from the 2015/2016 Harbour excavations at Birka. Some deviation from the exact placement is expected as we do not have concrete provenience information within the layers from which each bone was taken. Adapted with permission from figures 60a (northern profile trench 1) and figure 61a (western profile trench 1) from Kalmring et al. (2021).

and gives an indication of metabolic sources of protein. The ^{15}N isotope is measured against the mean concentrations of the more abundant form of nitrogen, ^{14}N, that makes up the majority of earth's atmosphere. The food web is multilayered from single celled organisms to higher-end consumers such as herbivores, carnivores and omnivores, which can be best determined by measuring nitrogen values of the target organism to indicate its trophic position (Nehlich, 2015, Brown and Brown, 2011, Bocherens and Drucker, 2003). There is a trophic level increase of δ^{15}N, generally increasing between 3 and 5 ‰ with each trophic level (Bocherens and Drucker, 2003). In addition, δ^{15}N values in marine environments are more positive compared to terrestrial environments due to the longer food chain, creating a distinguishable of isotopic values between both environments (Brown and Brown, 2011, Balasse et al., 2001). Penning and manuring of animals also increase the δ^{15}N values (Makhad et al., 2022, Gillis et al., 2020, Larsson et al., 2019), while higher amounts of precipitation tend to reduce the values (Craine et al., 2015, Amundson et al., 2003), so equifinality is a confounding problem when considering the expression of this isotope in the metabolic pathway of the sample in question.

Soil sulfur (S) values are predominately reflective of sulfides and sulfates that have leached from the local bedrock during weathering processes and can range between − 60 ‰ and 40 ‰, additionally the soil characteristics and hydrological and evaporative factors alter the bioavailable δ^{34}S values from the original bedrock. Estuarine environments typically have δ^{34}S values between 0 and 10 ‰, while coastal soil baseline values can be influenced by a phenomenon known as the 'sea-spray effect', where oceanic sulfate particles with a δ^{34}S value of $\sim +21$ ‰ are blown inland. The sea-spray effect can vary from a few kilometers to affecting entire islands based on wind strength and prevailing conditions, however the commonly set threshold is $<$ 50 km inland for the sea-spray effect (Rees et al., 1978, Wadleigh et al., 1994, Stack and Rock, 2011). The common threshold value for sea-spray affected δ^{34}S is + 14 ‰, however it is also possible for terrestrial sulfur to mimic sea-spray effect values, usually caused by evaporitic rocks causing the geological sulfur values to be quite high (Nehlich, 2015, Warren, 2010).

Plants uptake sulfur via their root systems, which then passes to the consumer, whether it be grazing animals or omnivorous humans. It is assumed that plants are depleted by approximately 1.5 ‰ due to fractionation that occurs relative to soil and/or atmospheric δ^{34}S values (Claypool et al., 1980, Peterson and Fry, 1987, Sayle et al., 2013, Trust and Fry, 1992). Hence, the spatial variation of sulfur in soil and water can aid in addressing the isotopic input when analyzing δ^{34}S of organic material to understand the food niches or migratory behavior of animals and humans (Stack and Rock, 2011).

Considering the collagen-to-collagen comparison of trophic levels as outlined by Bocherens and Drucker (2003), adjustments are necessary for δ^{13}C and δ^{15}N isotopic values, which typically range from 0 to 3 ‰ with a median at 1 ‰ for δ^{13}C, and from 3 to 5 ‰ with a median at 4 ‰ for δ^{15}N for each trophic level effect from source to consumer. δ^{34}S collagen-to-collagen comparison most likely has no trophic effect on the isotopic values (Krajcarz et al., 2019), however ^{34}S has considerable differences between marine ($>$15 ‰), freshwater and terrestrial ($<$15 ‰) sulfur sources and marine sulfates being more or less constant at 21 ‰, making the identification of different environments possible to trace (Rees et al., 1978). The effect of sea-spray on δ^{34}S values has been attested to by several studies including Bondy et al. (2017), Zazzo et al. (2011) and Wadleigh et al. (1994) and will affect isotopic values of δ^{34}S considerable distances inland as mentioned above.

Strontium isotope analysis can be used to trace mobility as geological areas have different strontium values derived from the local bedrock, which is mineralized in the hydroxyapatite of bones and enamel of teeth as a substitute for calcium. Both ^{86}Sr and ^{87}Sr are stable isotopes, however the latter is derived from the radiogenic element rubidium-87 (^{87}Rb), which decays to ^{87}Sr (Balasse et al., 2002, Bentley, 2006). Bioavailable strontium usually occurs from rocks and minerals weathering into soil and surface water that is then taken up by plants and passed up the trophic web to animals. Ratios of $^{87/86}$Sr are location dependent but can overlap across large geographic regions with complex geologies. To relate archaeological strontium values to a specific geologic region, a local baseline for the site or region in question must be established from which a mapped isoscape distribution can be generated (Bentley, 2006, Price et al., 2014).

Independently, the four isotopes utilized for this study provide only general information about diet and or location of an animal's grazing habits. However, when combined, deep insights can be provided about animal ecology, husbandry practices, slaughter and or consumption. Therefore, we utilized a multi-isotopic approach with emphasis on δ^{34}S values of faunal (archaeological) and geological (modern and archaeological) data to triangulate mobility of animals to a certain area.

3. Methods

The study consisted of two parts, an isotopic component and an osteological component. Domesticated livestock recovered from the 2015/2016 Black Earth Harbour excavation ("Harbour" is used as shorthand to refer to this excavation itself) at Björkö (Birka) were utilized and the osteological investigation was completed in the autumn of 2020 at Stockholm Museum, which included the identification of faunal remains to species level, counting minimum numbers of individuals and numbers of identifiable specimens present (Wadstål, 2021). The destructive analysis of the assemblage was sampled using a Dremel tool to extract the bone and teeth samples for collagen and dentine analysis.

The samples were taken from the layers that was determined to be stratigraphically and taphonomically representative (Fig. 3). Bulk collagen/dentine extraction and enamel preparation followed standard protocols of the SUERC Radiocarbon Laboratory (Dunbar et al., 2016). A total of 45 samples were selected for analysis; 40 bones were sampled for δ^{15}N, δ^{13}C and δ^{34}S analysis (collagen) and five teeth (enamel/dentine) were selected for both $^{87/86}$Sr (enamel) and δ^{15}N, δ^{13}C and δ^{34}S (dentine) analysis. The four samples for ^{14}C were conducted on cattle to avoid dietary interferences with the dating. The division of teeth vs. bone from the different layers were first based upon preservation; then, second, the teeth were chosen based on taxonomic species and those that were determined to be best suited from the different layers for inter-comparability. Pseudoreplication was avoided to the best of our ability by sampling only right or left side bones from the same layers or bones that did not seem to have any counterparts in the material. Lastly, the division of samples was based on cost and what would give this case study the most informative results within our budget constraints.

3.1. Collagen extraction

The SUERC Radiocarbon Laboratory practices a modified version of the Longin (1971) protocols to extract collagen/dentine from archaeological bone and tooth samples. Approximately ~ 1 g of sample was added to 100 mL 1 M HCl solution for approximately 24 h to dissolve the apatite. The acid was then decanted, and the sample was washed three times with ultrapure water. Following this, 100 mL of ultrapure water was added and the weakly acidic solution was heated on a hotplate at 80 °C for approximately 4 h. The solution was then filtered, dried down to < 20 mL and transferred to a glass vial. The final step entailed freeze drying to obtain the collagen/dentine powder from the sample solution (Dunbar et al., 2016, Schjerven, 2021). NaOH treatment was deemed unnecessary based on sample coloration as all the collagen samples were white in color.

3.2. Enamel preparation

Tooth enamel pre-treatment involved placing the sample in 100 mL of ultrapure water and in a sonic bath for removal of tissue. The tooth sample was then rinsed and a Dremel multitool was utilized to remove the crown, and the internal dentine was removed with a dissecting needle (Dunbar et al., 2016). The crown was then placed in a 10 M NaOH (sodium hydroxide) solution and heated to 80 °C. Dentine was scraped from the enamel and the sample was rinsed in 0.5 M HCl to remove any remaining NaOH, before rinsing again with ultrapure water. The enamel was then dried in an oven and transferred to a glass vial (Dunbar et al., 2016, Schjerven, 2021).

3.3. Strontium analysis

$^{87/86}$Sr analysis was conducted in a Class 100 clean room laboratory. Samples were weighed into a Teflon beaker and dissolved in 2 × distilled dilute HCl. A known amount of ^{84}Sr reference spike was added to calculate Sr concentrations in the samples (Dunbar et al., 2016). The dissolved samples were dried before column chemistry. The method of TrisKem Sr spec resin column was utilized as described in Pin and Bassin (1992). Following column chemistry, the sample was dried prior to loading into the mass spectrometer (VG Sector 54–30 thermal ionization mass spectrometer). Samples were loaded onto single Re filaments with a Ta-activator similar to that described by Birck (1986).

3.4. NCS isotopic analysis

Stable nitrogen (δ^{15}N), carbon (δ^{13}C), and sulfur (δ^{34}S) isotopic compositions were determined on a Delta V Advantage continuous-flow isotope ratio mass spectrometer (CF-IRMS) coupled via a ConfloIV to an IsoLink elemental analyzer (Thermo Fisher Scientific, Bremen). Collagen samples (~1.2–1.5 mg) were combusted in the presence of oxygen in a single reactor containing tungstic oxide and copper wires at 1020 °C to produce nitrogen (N_2), carbon dioxide (CO_2) and sulfur dioxide (SO_2). A magnesium perchlorate trap was used to eliminate water produced during the combustion process, and the gases were separated in a gas chromatography (GC) column heated between 70 °C and 240 °C. Helium was used as a carrier gas throughout the procedure. N_2, CO_2, and SO_2 entered the mass spectrometer via an open split arrangement within the ConfloIV and were analyzed against their corresponding reference gases (Sayle et al., 2019).

The International Atomic Energy Agency (IAEA) reference materials USGS40 (L-glutamic acid, $\delta^{13}C_{VPDB} = -26.4$ ‰, $\delta^{15}N_{AIR} = -4.5$ ‰), USGS41 (L-glutamic acid, $\delta^{13}C_{VPDB} = +37.6$ ‰, $\delta^{15}N_{AIR} = +47.6$ ‰), USGS88 (marine collagen, $\delta^{13}C_{VPDB} = -16.1$ ‰, $\delta^{15}N_{AIR} = +15.0$), and USGS89 (porcine collagen, $\delta^{13}C_{VPDB} = -18.1$ ‰, $\delta^{15}N_{AIR} = +6.3$ ‰) were used to calibrate δ^{15}N and δ^{13}C values. In addition, two in-house standards calibrated to the International Atomic Energy Agency (IAEA) reference materials IAEA-S-2 (silver sulfide, $\delta^{34}S_{VCTD} = +22.7$ ‰) and IAEA-S-3 (silver sulfide, $\delta^{34}S_{VCDT} = -32.3$ ‰), and the International Atomic Energy Agency (IAEA) reference materials USGS88 (marine collagen, $\delta^{34}S_{VCDT} = +17.1$ ‰) and USGS89 (porcine collagen, $\delta^{34}S_{VCDT} + 3.9$ ‰) were used to calibrate δ^{34}S values. Results are reported as per mille (‰) relative to the internationally accepted standards VPDB, AIR and VCDT. Measurement uncertainty was determined to be ± 0.1 ‰ for δ^{13}C and δ^{15}N, and ± 0.4 ‰ for δ^{34}S on the basis of repeated measurements of an in-house collagen standard and the well characterized Elemental Microanalysis IRMS fish gelatin standard B2215. Four fish gelatin samples of known weight were also used to calculate %N, %C, %S and determine C/N, C/S and N/S anomic ratios (Dunbar et al., 2016, Sayle et al., 2019; Schjerven, 2021).

3.5. Radiocarbon dating

Samples were weighed into a quartz insert and then placed into a cleaned quartz combustion tube containing copper oxide to provide oxygen for the reaction to occur. Silver foil is utilized to not introduce impurities of gaseous form (Dunbar et al., 2016, p 9). The SUERC laboratory in-house quality assurance involves primary and secondary known-age standards, and a tertiary in-house standard referenced directly to the oxalic acid primary standard (SRM-4990C) (Dunbar et al., 2016, p. 9). The SUERC Radiocarbon Laboratory has two different AMS instruments for radiocarbon dating, one is National Electrostatics Corporation (NEC) 5MV tandem accelerator mass spectrometer and a 250 kV single-stage accelerator mass spectrometer (SSAMS) (Dunbar et al., 2016, pp.9–11). The NEC utilizes two sources and the SSAMS utilizes one. When analyzing the samples are usually divided into 13 groups with 10 samples in each group. Then each group has three standards used, oxalic acid II primary standard, humic acid is the secondary standard, the last one is often a barley mash, and then seven unknowns (Dunbar et al., 2016, pp. 12-13). The process follows the protocols and methods in Dunbar et al. (2016) and as described in Sayle et al. (2019) and Schjerven (2021).

4. Results

For the stable isotope analysis, all samples had sufficient collagen (atomic) yields above 1 %, and C:N ratios were within the acceptable range ratio of 3.1–3.4, indicating good quality bone preservation as described in Guiry and Szpak (2021). Sulfur concentration was within the acceptable quality criteria of 0.15–0.35 S%, and N:S (200 ± 100) and C:S (600 ± 300) ratios were also within the acceptable range set out in Nehlich and Richards (2009).

Cattle δ^{13}C values ranged from − 21.8 ‰ to − 20.9 ‰ with a mean of − 21.4 ± 0.3 ‰. δ^{13}C values for pigs varied between − 22.2 ‰ and − 21.0 ‰ and had a mean of − 21.5 ± 0.4 ‰. Sheep δ^{13}C values ranged between − 21.5 ‰ and − 20.8 ‰ and had a mean of − 21.1 ± 0.2 ‰

Table 2
Mean values for the different taxonomic groups studied from Birka. A detailed overview of the raw data can be found at: https://doi.org/10.6084/m9.figshare.25523059.

		δ^{15}N	δ^{13}C	δ^{34}S
Cattle	Mean	6.4	−21.4	4.9
(n = 24)	S.D	0.7	0.3	3.2
	Min	4.3	−21.8	−3.2
	Max	7.4	−20.9	10.6
Pig	Mean	9.1	−21.5	5.4
(n = 17)	S.D	2.8	0.4	6.6
	Min	5.5	−22.2	−5.9
	Max	14.1	−21.0	14.9
Sheep	Mean	7.1	−21.1	2.8
(n = 12)	S.D	1.7	0.2	4.0
	min	5.0	−21.5	−2.8
	max	11.0	−20.8	10.4

(Table 2). The standard deviation for cattle and sheep is indicative of a narrow dietary niche with respect to carbon, as a standard deviation below 0.3 ‰ is considered a homogenous deviation (Lovell et al., 1986). Pigs had on average a standard deviation of 0.4 ‰, which indicates a slightly more varied dietary niche.

Average δ^{15}N values for cattle ranged between 4.3 ‰ and 7.4 ‰ and had a mean of 6.4 ± 0.7 ‰ (Table 2). Pig values ranged from 5.5 ‰ to 14.1 ‰ and had a mean of 9.1 ± 2.8 ‰, while sheep values ranged from 5.0 ‰ to 11.0 ‰ with a mean of 7.1 ± 1.7 ‰ (Table 2). Six pig samples and one sheep (GUsi10312, GUsi10318, GUsi10320, GUsi1030, GUsi1031, GUsi1032, GUsi10334), have δ^{15}N values above 10.6 ‰ compared to the rest of the samples who have a δ^{15}N value of below 8.0 ‰.

Cattle δ^{34}S values ranged from − 3.2 ‰ to 10.6 ‰ and had a mean of 4.9 ± 3.2 ‰ (Table 2). Pig values ranged from − 5.9 ‰ to 14.9 ‰ and had a mean of 5.4 ± 6.6 ‰, and sheep values ranged from − 2.8 ‰ to 10.4 ‰ and had a mean of 2.8 ± 4.0 ‰. These results are indicative of a variance in the sulfur component of the diet, as indicated by the greater than 0.3 ‰ standard deviation (Fig. 4).

Radiocarbon dating was conducted on selected samples from the 2015/2016 Harbour material, four of which were cattle samples from different layers showing statistical overlap at hpd range (highest posterior density/2-σ) for all assays ranging between 665 and 884 CE (Table 3, Fig. 5). A depositional model was created from previously published radiocarbon ages (Kalmring et al., 2021) and the median ages (95.4 % probability at calibrated median age, 2-σ) indicates an earlier-than-previously-recognized occupation of Birka compared to the bead seriation method developed by Callmer (1977). The ages predate or occur in the early phase of the formal “Viking Period” of Scandinavia and illustrate a potential rapid increase in Black Earth deposits in the harbor associated with settlement of the commercial sector of the town (Wadstål, 2021).

The five samples chosen for strontium $^{87/86}$Sr analysis had values ranging between 0.7274 and 0.7418. Results indicate that the cattle derived from an area with a different geological composition compared to the pigs. For each taxonomic group, the standard deviation for the strontium values is indicative of grazing that occurred within the same geological formation (Table 4, Bentley, 2006).

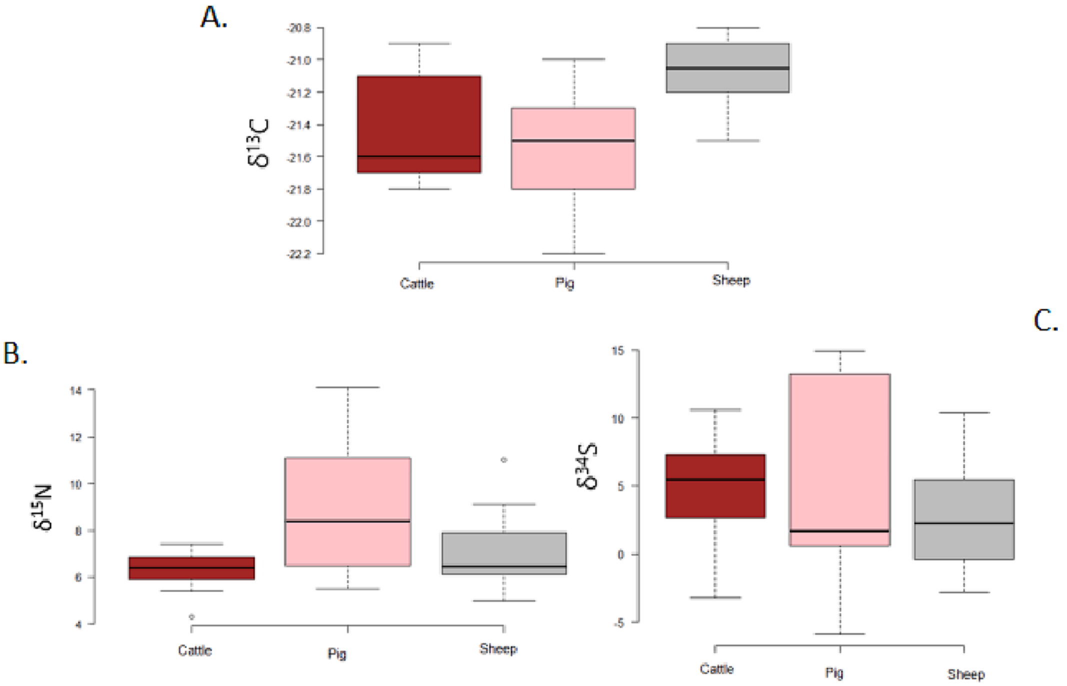

Fig. 4. Boxplots for niche widths of the taxonomic groups from selected fauna at Birka based on A. δ^{13}C, B. δ^{15}N and C. δ^{34}S isotopic values. The thick black line represents the median value, the whiskers are the standard deviations, and the small circle is an outlier value (Hu, 2020).

Table 3
Radiocarbon dating results on archaeological animal bone collagen from Birka, calibrated utilizing the IntCal20 calibration curve (Reimer et al., 2020). SUERC ^{14}C results can be found here: https://doi.org/10.6084/m9.figshare.16903003.v2 (Dunbar et al., 2016).

Sample ID	δ^{13}C (‰)	Uncalibrated age BP	Calibrated age 2σ	hpd range (2σ)	Layer	Taxon
SUERC-96796 (GU56884)	−21.6	1275 ± 26	665–820 CE	726 CE	Layer 23/V	Cattle (bone)
SUERC-96797 (GU56885)	−21.6	1245 ± 26	677–878 CE	754 CE	Layer 32	Cattle (bone)
SUERC-96798 (GU56886)	−20.9	1252 ± 26	674–876 CE	735CE	Layer 35	Cattle (bone)
SUERC-96799 (GU56887)	−21.1	1228 ± 26	686–884 CE	806 CE	Layer 23/III	Cattle (bone)

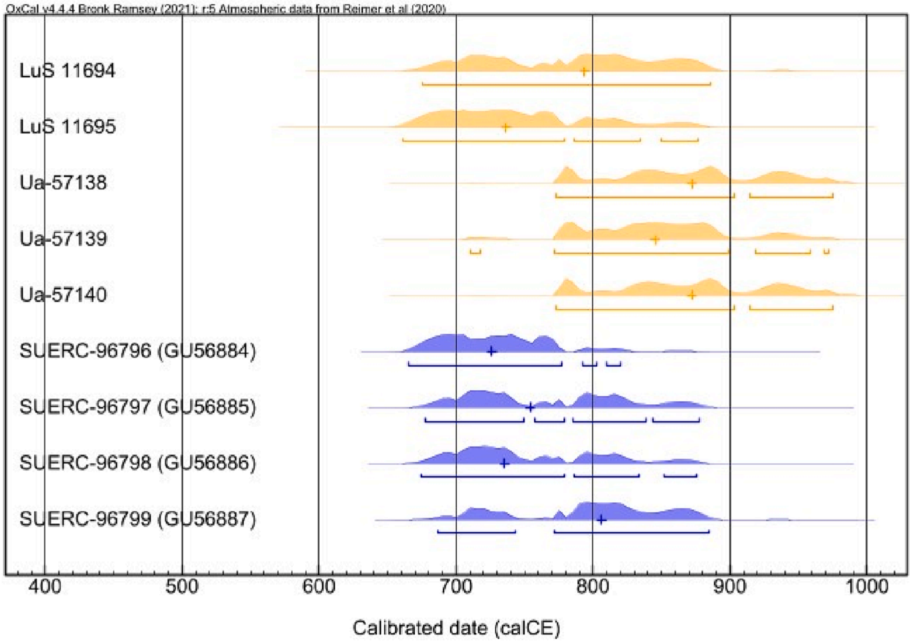

Fig. 5. Comparison OxCal model of ^{14}C SUERC dates (blue) and LuS and Ua Lab (orange) from Kalmring et al. (2021), LuS samples from year rings and Ua samples from wickwork/wood. Calibrated with IntCal20 in OxCal version 4.4 (Reimer et al., 2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Strontium $^{87/86}$Sr results from selected faunal remains from Birka.

Sample Name	$^{87/86}$Sr	% Std Error	2σ abs error	Sr conc (ppm)	2σ (%)	Taxon	Material
GUsi10327	0.738787	0.0012	0.000018	232.3	0.36	Cattle	M2 (dentine)
GUsi10328	0.741783	0.0014	0.000021	258.7	0.41	Cattle	M2 (dentine)
GUsi10329	0.739416	0.0013	0.000019	158.2	0.22	Cattle	M2 (dentine)
GUsi10330	0.729232	0.0012	0.000018	113.6	0.21	Pig	M2 (dentine)
GUsi10332	0.727375	0.0012	0.000017	138	0.26	Pig	M2 (dentine)

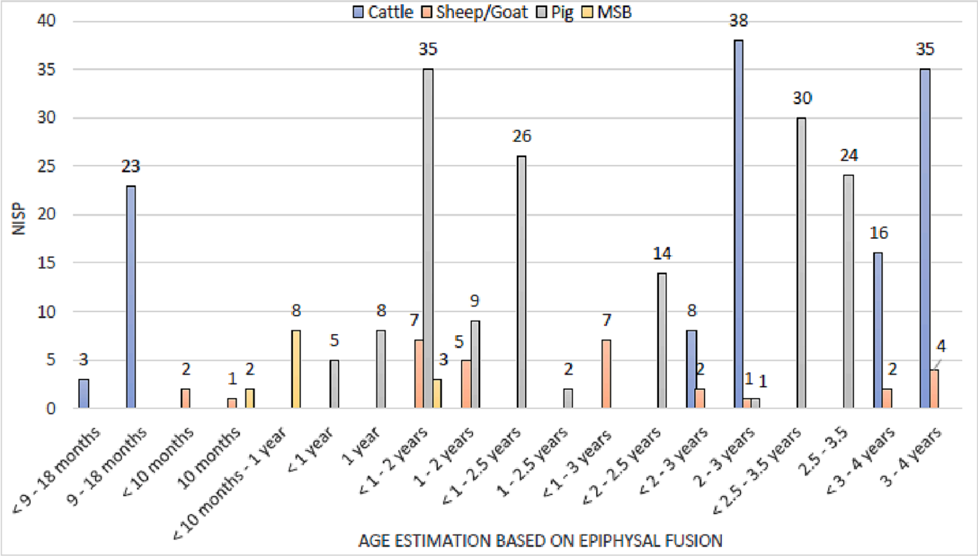

Fig. 6. Taken from Wadstål (2021) Figure 29., showing distribution age between the domestics, relative age of slaughter based on fusion, mbs = meadium sized bones.

Osteologically, the bulk of the assemblage consisted of cattle bones, followed by pig, with sheep the least-represented overall (Wadstål, 2021). The bones had butchery and cut marks, which varied between the layers and were indicative of a more standardized butchery technique from L30 (Fig. 6, Tables 5 and 6). Cattle and pigs were, for the most part, represented by the entirety of the skeleton, while the sheep material was fragmented and less represented across the layers (Wadstål, 2021).

Table 5
Summary of NISP between the different animal species identified in the material, see Wadstål (2021) for further information.

Common name	Taxonomic category	NISP	Weight (kg)
Cattle	*Bos taurus*	1249	23
Pig	*Sus domesticus*	803	4.4
Sheep	*Ovis aries*	10	0.21
Goat	*Capra hircus*	3	0.12
Caprine	*Fam. Caprinae*	265	0.97
Hare	*Lepus timidus*	30	0.012
Squirrel	*Sciurus vulgaris*	14	0.001
Fox	*Vulpes vulpes*	15	0.0074
Dog	*Canis familiaris*	6	0.0026
Cat	*Felis catus*	7	0.011
Weasel	*Mustela erminea*	5	0.0008
Marten	*Martes martes*	1	0.0002
Deer	*Fam. Cervidae*	1	0.062

Table 6
Summary of osteological results across the different layers, taken from Wadstål (2021) Appendix Table 8.

Layer	NISP	NSP	Weight (g)	Median (g)	Median per fragment (g)
17	1521	2232	4341	4.0	1.7
23/I	697	994	4194	5.5	3.6
23/II	587	1164	4087	5.7	3.9
23/III	284	554	2468	4.1	2.6
23/IV	1050	2051	2051	3.9	2.2
23/V	618	1187	5795	3.5	1.9
30	844	1542	6024	4.4	2.2
32	138	402	803	5.0	3.8
35	292	654	1561	3.7	1.7
36	55	95	2026	3.0	2.5
37	247	584	2543	6.6	3.4

5. Discussion

Based on the osteological investigation of the animal bone material from previous studies by Wigh (1998, 2001), the majority of the pigs were slaughtered at a subadult to young adult age, this is true for the osteological material investigated herein as well. This is a common practice when pigs are kept in small spaces such as urban settlements, so they do not grow too big (Wigh, 2001). The pigs have two peaks when it comes to their age of slaughter one peak at 1–2 and one at 2.5–3.5 years of age (Fig. 6). The sheep has a relative mix of subadult and adult individuals from 10 months to 1–2 years and 1–3 years of age (Fig. 6), in addition to bone fragments, which might indicate secondary use of sheep for wool (Wigh, 1998, Wigh, 2001). Further, the majority of the cattle were slaughtered at mature ages of 3–4 years (Table 5, Table 6 and Fig. 6), and the representation of the entirety of the skeleton further indicates that the cattle were transported on foot and then slaughtered on site. The osteological investigation of the Harbour material discussed in Wadstål (2021) further supported this conclusion (Table 5, Table 6, Fig. 6), due to space we will not elaborate further on this here and refer to the cited reference for further elaboration on the osteological evaluation.

The δ^{13}C values indicate that all the animals consumed a wholly C_3 diet, which is the natural land cover for southern Scandinavia (DeNiro and Epstein, 1978, Krueger and Sullivan, 1984, Vogel, 1978) with values ranging from – 20.8 to – 22.2 ‰, however inter-individual variations in their δ^{15}N and δ^{34}S values imply that some of the animals derived their foodstuffs from different locales (Fig. 4 and Fig. 7). Based on this, the cattle can be discriminated into two slightly different groups for their δ^{13}C values with one closer to – 20.2 ‰ and one closer to – 22.2 ‰ as indicated in Fig. 4 and Fig. 7 despite their diet containing C_3 terrestrial plants, and this pooling is consistent when also comparing their δ^{34}S and δ^{15}N values (Fig. 4 and Fig. 7). Further, the sheep are very consistently within the group closer to – 20.2 ‰ δ^{13}C values while the pig are more scattered. Consequently, this division could indicate grazing in different areas with slight variances in δ^{13}C values within the local environment as a result of differing canopy and or foddering habits (Hamilton et al., 2019, Tieszen and Boutton, 1989).

To date there are no large-scale sulfur isotope baselines established for vegetation in Sweden, however comparing the measured values from this study with the values of the European granite, which encompasses the substrate at Birka (range values − 4 ‰ to + 9 ‰), makes it possible to determine an approximate local value for the δ^{34}S values around Birka (Nehlich, 2015). Because vegetation is generally depleted in ^{34}S by ~ 1.5 ‰ compared to their ^{34}S source the values indicating local adherence values should then fall around − 5.5 ‰ to + 7.6 ‰ (Nehlich, 2015, Sayle et al., 2013). Previous research by Risberg et al. (2002) indicates that the water around Birka at this time was more brackish than saltwater, which would have resulted in intermediate δ^{34}S values in the vegetation around Birka (see also Guiry et al., 2021).

As demonstrated in Fig. 8, different categories of δ^{34}S values can be detected in the analyzed material. The general categorization is based on the different δ^{34}S niches from Sayle et al. (2013) a marine niche with a δ^{34}S mean of + 15.6 ± 1.5 ‰, terrestrial niche with a of mean + 5.6 ± 2.8 ‰ and a freshwater niche with a mean of – 2.7 ± 1.4 ‰. To further elaborate, the values break into two broad categories: sea-spray with values of δ^{34}S above > 10 ‰ and terrestrial δ^{34}S values, which are below < 10 ‰. When compared to the general δ^{34}S values of the European granite (−5.5 ‰ to + 7.6 ‰), we can estimate an approximate terrestrial δ^{34}S source with some ambiguity at the margins of these estimates. The last category is based on animals with enriched δ^{15}N values above > 10 ‰ but with δ^{34}S values below < 10 ‰, which we interpret as falling within the range of terrestrial sulfur metabolization. Taking into account the trophic enrichment of ^{34}S is virtually non-existent based on studies like Krajcarz et al. (2019) we interpret the isotopic values of δ^{34}S as reflective of the source to consumer value, at the same time we are aware that nuance of soil and local ^{34}S might not accurately be reflected by this precise cut off point.

In interpreting the isotopic results based on trophic level increases and the collagen-to-collagen comparison of the δ^{34}S, some scenarios need to be considered. The variance in δ^{34}S (Fig. 4, Fig. 7 and Fig. 8) illustrates different food niches for the animals, the cattle and sheep are for the most part pretty homogenous in their δ^{34}S values (<10 ‰) values falling within the terrestrial δ^{34}S values with a few enriched δ^{34}S values (>10 ‰) which we interpret as deriving from different geological areas based on δ^{34}S values, possibly reflecting different grazing areas which is further attested to by their δ^{13}C values (Fig. 7 and Fig. 8).

The pigs are more heterogenous in their δ^{34}S values where there are two distinct groups: one with more terrestrial δ^{34}S values (<10 ‰), and one group with enriched δ^{34}S values (>10 ‰). This group of pigs were then probably feeding in areas closer to the coast or areas affected by sea-spray based on the calculated δ^{34}S values (Fig. 4, Fig. 7, and Fig. 8). In juxtaposing the measurements between δ^{34}S values with δ^{15}N and δ^{13}C values, it is also evident that the pigs with these enriched δ^{34}S values did not have a marine, nursing or weaning diet as their δ^{15}N values are quite low < 10 ‰ and their δ^{13}C around –22.8 to –21.0 ‰ are indicative of a terrestrial diet and not showing enrichment with would be typical if they consumed considerable amounts of marine fish (Kamjan et al., 2020, Jones and Mulville, 2016). Since sea-spray does not affect δ^{13}C and δ^{15}N values (Bondy et al., 2017), it is reasonable to further elucidate the herein observable enriched δ^{34}S values as sea-spray effect.

Further, for the other group of pigs that has enriched δ^{15}N (>10 ‰) and low δ^{34}S (<10 ‰) we consider three scenarios that would lead to enriched δ^{15}N values in five pigs and one sheep, the first being that these animals were nursing, the second that these animals were eating freshwater fish or alternatively as a third option these animals were kept in penned environments, all in which would lead to an enrichment in their δ^{15}N values (Arnold et al., 2018, Linderholm et al., 2008, Sayle et al., 2013, Claypool et al., 1980, Jenkins et al., 2001, Reynard and Tuross,

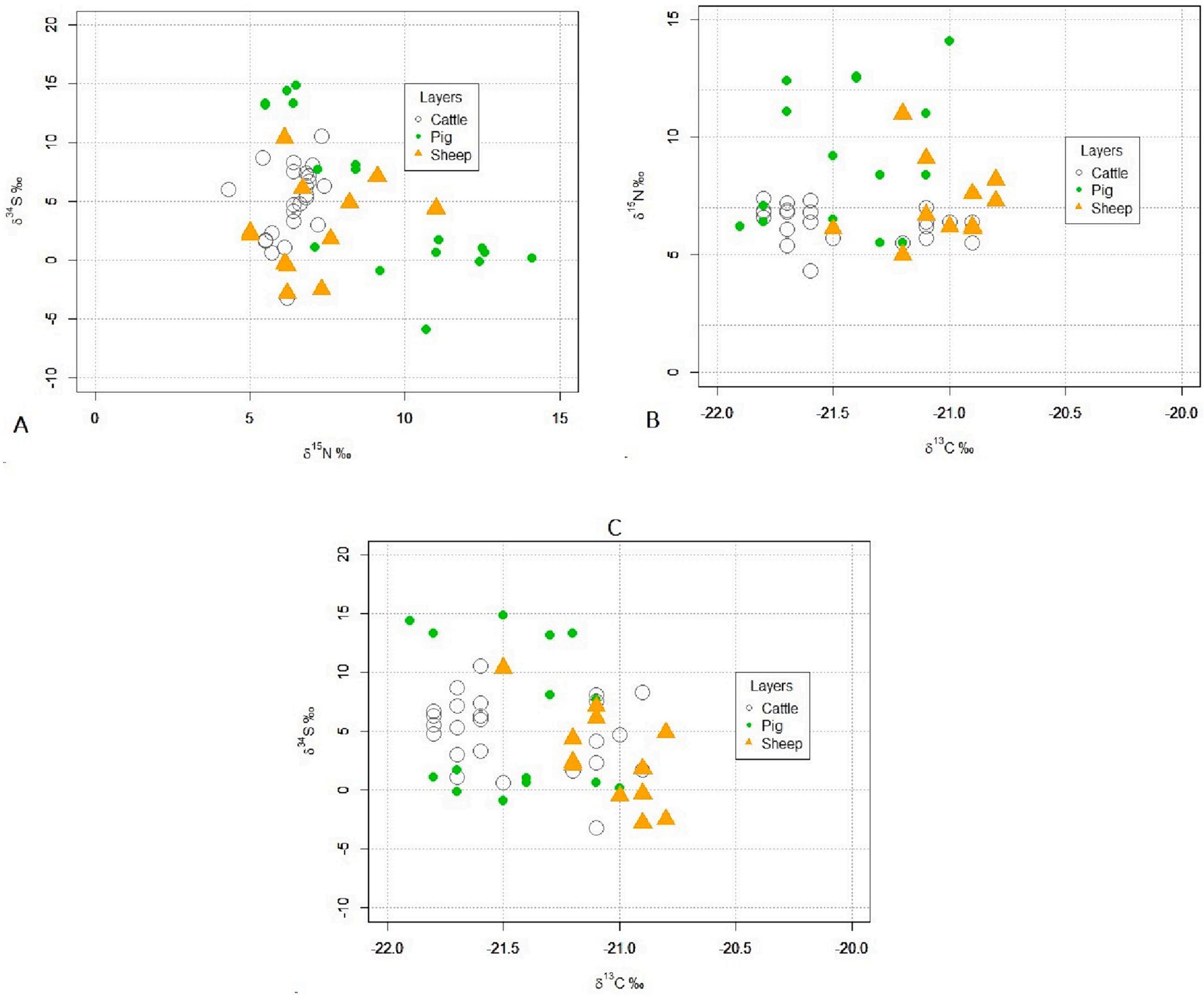

Fig. 7. Combined scatterplots of A. δ^{15}N and δ^{34}S values, B. δ^{13}C vs δ^{15}N values and C. δ^{13}C vs δ^{34}S values from selected fauna at Birka.

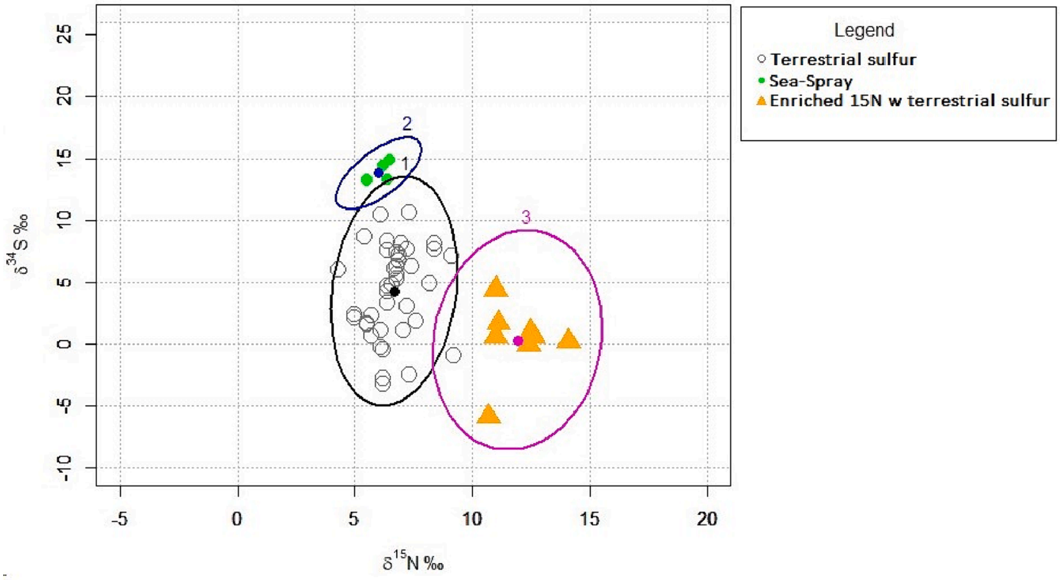

Fig. 8. Food niches with ellipses relevant to δ^{34}S and δ^{15}N values the categorization of the different niches are based on research done by (Sayle et al., 2013) and (Nehlich, 2015) categories as follows: sea-spray δ^{34}S > 10 ‰, terrestrial δ^{34}S < 10 ‰, terrestrial δ^{34}S with enriched δ^{15}N.

2015). When interpreting the osteological material (Table 4, Table 5 and Fig. 6.) the majority of the pigs were 1–3 years of age (Fig. 6), therefore probably weaned so nursing is not suspected to have enriched δ^{15}N values. Previous research of weaning pigs and their and δ^{15}N values has suggested that the nursing period would be between 0 and 1 years of age and after that the δ^{15}N values would drop to near adult δ^{15}N consumption values (Reynard and Tuross, 2015). However, this does not leave out that some of the younger individuals from the material (Fig. 6) might show enriched δ^{15}N values due to nursing. The one sheep sample with the same enriched δ^{15}N values we interpret as either a goat which have a much broader diet than sheep (Wigh, 2001, Bartosiewicz, 1999), or a nursing animal based on the varied slaughter age of sheep (Fig. 6).

Considering that Birka was an island and surrounded by brackish water (Fig. 2, Dury et al., 2018, Risberg et al., 2002), it is plausible that these pigs consumed freshwater or brackish water fish. The study by Robson et al. (2016) on freshwater fish consumption indicates δ^{15}N values 5.4 ± 0.4 ‰ and δ^{13}C values – 24.2 to – 19.3 ‰ for freshwater fish, the consumer would be 3–5 ‰ above that due to the enrichment of δ^{15}N up the food chain and an increase in δ^{13}C with 0–3 ‰ as mentioned by Bocherens and Drucker (2003) fits this conclusion. This interpretation falls in line with some animals being kept locally on the island of Birka (Wigh, 2001), perhaps also penned as animals living in their own manure would have enriched δ^{15}N values (Makhad et al., 2022, Gillis et al., 2020, Larsson et al., 2019).

Additionally, since the majority of the pigs were slaughtered by the age 1–3 years according to the osteology in Fig. 6, the isotope signatures of the animals would not have had the time to change and adapt due to the turnover rate of bone compared to the age in which they were slaughtered, the turnover rate is much faster in younger individuals due to rapid growth (Ben-David and Flaherty, 2012, Sayle et al., 2013). Therefore, in addressing the results herein, the observable enriched δ^{15}N for some of the pig samples are likely to be reflective of a combination of omnivorous diets of freshwater fish and penned animals that were for the most part weaned when incorporating the age of slaughter.

Previous research of the $^{87/86}$Sr isoscape for Mälaren and Birka has set the baseline value of the region between 0.723–0.733 (Fig. 1, Table 4, Blank et al., 2018, Price et al., 2014, Price et al., 2018). Based on the $^{87/86}$Sr results, cattle and pigs came from different areas as their values represent distinct geologies from which their food sources derived. The $^{87/86}$Sr for the cattle samples with values 0.739–0.742 appear to come from the regions to the west (with values above 0.7380) located > 180 km to the west of Birka based on contemporary isoscapes and bioavailable baselines for Sweden and the Mälaren region (Fig. 1). Alternatively, they could have derived from areas located within the modern-day country of Finland to the east, which have several previously assessed geologies that statistically overlap $^{87/86}$Sr values with Birka (Fig. 1). On the other hand, the pig values of 0.729 and 0.727 are within range of the general Mälaren isoscape values (Blank et al., 2018, Price et al., 2018) adding to the argument that they were local or circum-locally reared.

Overall, the balance of the evidence leads to the conclusion herein that the cattle could have been imported from great distances from the site, possibly from at least two different grazing areas based on their δ^{13}C values and their $^{87/86}$Sr values, and smaller animals like sheep and pigs were divided between two groups, one kept locally and one brought from somewhere with higher δ^{34}S values (Fig. 4, Fig. 7 and Fig. 8, , Åberg and Wickman, 1987, Blank et al., 2018, Price et al., 2018, Price et al., 2014, Wigh, 2001). The complexity of the geology in the Lake Mälaren region allows for some ambiguity in the definitiveness of this conclusion, but the absence of the discovery of a significant statistical outlier in $^{87/86}$Sr values in the local geology and evaluation of published isoscapes (Fig. 1, Blank et al., 2018, Price et al., 2018) allows for a tentative conclusion at this point in time, which necessitates further analyses to validate. At this point, we differentiate cattle from pigs and sheep as deriving non-locally or circum-locally, respectively.

In discussing the ^{14}C results, it is important to acknowledge the limitations inherent in the few samples dated in this study, recognizing that they may not fully represent the entire archaeological assemblage. Nevertheless, these results offer valuable insights and pave the way for further investigation (Table 1, Table 3 and Fig. 5). The contrast between the ^{14}C dates and previous chronologies such as the bead chronology by Callmer (1977) and the typology dating by Ambrosiani from the 1970/1971 excavations (Ambrosiani, 2013, Ambrosiani and Erikson, 1996, Philippsen et al., 2022) suggests some adjustment to the early settlement timeline of the site (Table. 1, Table 3 and Fig. 5), pushing it back to around 726 CE or even earlier with the earliest possible date falling around 665 CE (Fig. 5 and Table 3.). Previous ^{14}C analysis on the material has a range of the 661–970 CE which spans almost the entire occupation period (Table 1 and Fig. 5). Consequently, the ^{14}C samples from this study gives a tentative alternative anchoring for the earlier dates. This shift prompts us to reconsider the dynamics of early settlement patterns at Birka. Consequently, we propose that the animals analyzed in this case study were likely sourced from various locations, indicating the existence of a well-developed provisioning network at Birka by around 726 CE. This interpretation underscores the complexity of economic and social interactions within the Birka community during this early period.

Supporting the isotopic results, previous archaeological research from Birka has identified the presence of Finnish grave goods and material supporting a connection with that region in the Viking Age (Linderholm et al., 2008, Linderholm and Kjellström, 2011, Price et al., 2018). Our isotopic osteological investigation hints that populations reflected in the ossuary studies did not come alone. Cattle are easy to transport alive and on foot, as a walking commodity, especially when imported from great distances (Löffelmann et al., 2023, Zeder, 1988, Wigh, 2001). The osteological evidence suggests slaughter on site, and is even further underlined by a complete cattle skull with a smashed frontal injury, suggesting local butchery practices were common (Wadstål, 2021, Kalmring, 2021). Although our sample size is relatively small, based on the combined archaeological evidence, and on the analysis of the Harbour material in this case-study, we hypothesize that there may have been a specialized economy of cattle pastoralism present at Birka from the earliest phases of its settlement (ca. 725 CE), following as previously discussed an indirect provisioning system.

Consequently, long distance movement of cattle for subsistence networks is not a new phenomenon to the Viking Age and import networks of cattle has been demonstrated even in Neolithic times in Falbygden in Sweden. Sjögren and Price (2013) attest to a large proportion of cattle coming from non-local areas based on measurements of $^{87/86}$Sr reflecting deviating values compared to the local baseline of the study area. This type of movement of cattle for subsistence has also been indicated at late Neolithic Durrington Walls UK (Evans et al., 2019), and even from the Funnel Beaker Culture in Sweden (Gron et al., 2016). This poses the foundation for the possibility of an early and substantially developed exchange import network for subsistence to Birka, with deep temporal and economic roots in earlier times.

Other commodities such as tar by Hennius (2018), cod by Barrett et al. (2008), Greenland walrus ivory by Star et al. (2018) and reindeer combs from Hedeby by Ashby et al. (2015) demonstrate economic specialization combined with long-distance trade is a defining feature of the early Viking world. Evidence of special economies for animal husbandry and other commerce has been shown in studies like Jones and Mulville (2018) and Kosiba et al. (2007) in discussion of the Norse culture in island environments. These economic connections had profound impacts on the genetic structure of Viking communities, which were among the most diverse in Europe at this time (Margaryan et al., 2020, Jones and Mulville, 2018, Price et al., 2018), and Birka likely had similar long-distance connections to the hinterlands via a deep-rooted import network for animals.

The location of the Black Earth excavations close the harbor of the site indicates that disposal of slaughtered animals was likely from commercial butchers. The pigs and sheep studied were more locally obtained with a split of coastal and further inland locations, but they likely reflect a rural industry (Wadstål, 2021). Previous studies of Viking settlements in Iceland have shown economic differentiation in house construction indicating social divisions in labor and specialized economies (Bathurst et al., 2010, Vidal, 2013). Further, another example of this differentiation is from the Middle Iron Age from a Viking contexts in Estonia, differentiation of settlement spaces are interpreted here as reflecting economic inequalities baked into society as village-to-urban transitions took root (Mägi, 2013). Thus, Birka does not stand alone in its time or place demonstrating complex economic and social differentiation, although certainly the distances associated with the importation of cattle are of importance in understanding the nature of early Viking settlements.

6. Conclusion

The degree of isotopic diversity and inferred mobility of the animal groups at Birka attests to the potential presence of a far-reaching and complex indirect provisioning system. The utilization of δ^{34}S provided valuable results to further understand animal mobility and subsistence practices as it was possible to differentiate between animal groups based on their dietary niches; had only δ^{15}N and δ^{13}C values been considered, the interpretation of these niches would have been limited to terrestrial or marine components in the diet. This type of analysis utilizing animal mobility as a proxy for understanding socioeconomic networks is crucial for tracing the previously untraceable within the archaeological record. The combination of this multi-isotopic approach can further elaborate on current perceptions of the utilization of socioeconomic networks, migration and mobility networks, which have previously been traced based on artifact seriation and typologies.

In addition, the few ^{14}C dates provides potential new chronological anchoring of the urban development at Birka, which, based on the socioeconomic network of animal import, was one of the earliest Viking towns in the North Atlantic. These new ages offer potential for further exploration of the chronology of the site, however further sampling would be necessary for a more definite conclusion.

While the lines between “rural” and “urban” spaces are fluid and contested among archaeologists, and the degrees of economic interdependence between them are open for interpretation, the evidence presented here supports the notion of deep temporal roots of the evolution of a critical exchange node at Birka within the North Atlantic region which situates itself as a well-developed urban center by the end of the Viking Age (Eriksen et al., 2014, Callmer, 1994, Barrett, 2008). It attests to a well-developed socioeconomic network, which further elaborates on the long dawn of development in Scandinavia as mentioned by Barrett (2008), and the small-world system of networks connecting places like Birka to the broader socioeconomic world extending into the Mediterranean and beyond since before the onset of the Viking Age (Sindbæk, 2007b, Sindbæk, 2007a, Skre, 2012). This study suggests that the view of subsistence networks only pertaining to immediate hinterlands be reevaluated as part of the broader socioeconomic context in the Viking Age. The authors acknowledge that the modest dataset makes the conclusions and interpretation somewhat limited, and further sampling and ^{14}C dates are necessary to support this case study’s working hypothesis, but it opens up avenues for further research and archaeological discussion.

CRediT authorship contribution statement

Nicoline Schjerven: Conceptualization, Data curation, Investigation, Project administration, Writing – original draft, Writing – review & editing, Formal analysis, Methodology, Visualization, Validation. **Molly Wadstål:** Data curation, Formal analysis, Project administration, Writing – original draft, Writing – review & editing, Investigation, Methodology. **Kerry L. Sayle:** Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing, Validation, Visualization. **Laszlo Bartosiewicz:** Data curation, Formal analysis, Investigation, Resources, Supervision, Writing – original draft. **David K. Wright:** Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing, Conceptualization, Investigation, Methodology, Validation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Dataset: https://doi.org/10.6084/m9.figshare.25523059, ^{14}C results: https://doi.org/10.6084/m9.figshare.16903003.v2.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104543.

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