

**Challenges in Reconstructing Past Exploitations of
Atlantic Cod:
A Zooarchaeological Case Study from Early Medieval
England**



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This thesis is submitted for the degree of Doctor of Philosophy

Declaration

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any work that has already been submitted before for any degree or other qualification at the University of Cambridge or any other University or similar institution except as declared in the preface and specified in the text. It does not exceed the prescribed word limit for the Archaeology and Anthropology Degree Committee.

**Challenges in Reconstructing Past Exploitations of Atlantic Cod:
A Zooarchaeological Case Study from Early Medieval England**

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Abstract

The thesis presents a novel zooarchaeological, statistical, and ecological analysis of fish bone assemblages from early medieval England. Comprehensive evidence is presented of coastal and pelagic fishing of larger bodied, healthier populations in England from the 8th cent.CE, pushing back the assumed rise in marine fishing commonly referred to as the 'Fish Event Horizon', or the FEH, by 300 years. The findings are an important contribution to assessing past human impacts on aquatic ecosystems, which to date have not been widely researched.

Atlantic cod (*Gadus morhua*) was selected as the main focus of the study due to its prominence in modern and historical fishery economies, based on studies of modern and archaeological materials.

Identifications of diverse marine taxa, including cod, were part of the zooarchaeological analysis of a previously unexamined, exceptionally large assemblage from the pre-FEH monastic site of Lyminge. Lyminge was chosen for analysis due to its early occupation dates, which precede the previously theorised onset of marine fishing, and its exceptionally large fish bone assemblage. Fish body sizes were estimated from both newly developed and preexisting regression models. The novel models were constructed from a uniquely large and diverse dataset of modern cod specimens collected for this purpose, and applied to new data from Lyminge and to a legacy dataset from Coppergate. The estimated archaeological cod sizes were further compared to modern trawl survey data. A significant temporal decrease was observed between both archaeological datasets and the modern data. The larger archaeological cod body sizes suggest significantly improved weights, reproductivity, and health of cod populations prior to the onset of commercial fishing in the North Sea. Furthermore, shifts in past food web interactions are also suggested, revealing shifting ecologies of other species interacting in the same food web.

Combined with the positive identifications of other pelagic species, the larger archaeological sizes indicate that the fish were sourced from pelagic environments. The contextualization of these findings in the wider study area of northwest Europe

suggests that early medieval communities had the technological abilities and traditional knowledge required to conduct offshore marine fishing as early as 1,300 years ago. The analysis of skeletal elements and butchery patterns of the Lyminge cod further indicate that stockfish was prepared for local consumption, and possibly for trade, in the same era.

Unique statistical tools are presented for estimating past cod sizes, expressed as Total Length (TL), through both newly defined and preexisting measurements of archaeological bones. The robustness and convenience of estimating cod TLs from previously unutilized vertebrae and cranial measurements is demonstrated through the reported accuracy of the developed regression models, and their application to the archaeological case studies where such elements are common but have remained unutilized.

Lastly, the ecological results based on the developed regression models highlight the damaging effects of intensified fishing practices in later periods, a trajectory that has led to diminished health, and even complete collapse, of modern populations.

Preface

Ecological, historical and archaeological terms and abbreviations that appear throughout this thesis are listed below.

Abbreviations

AV - Abdominal Vertebrae

AICc - Akaike Information Criterion for small samples

CE - Common Era

Cent. - Century

CV - Caudal Vertebrae

FEH - Fish Event Horizon

FL - Fork Length

ICES - International Council for the Exploration of the Sea

MNI - Minimum Number of Individuals

NISP - Number of Individual Specimens

NSIBTS - North Sea International Bottom Trawl Surveys

TL - Total Length

Sem- Standard error of the mean

Std - Standard Deviation

V - Vertebrae

Spp. - Multiple Species

Glossary of historical, archaeological and ecological terms

Appendicular elements - Fish bones from the appendicular (i.e. shoulder region of the fish skeleton), including the following elements: radial, basipterygium, cleithrum, coracoid, postcleithrum, scapula and supracleithrum (Wheeler & Jones, 1989).

Baseline population - Populations of organisms that existed prior to human exploitation and to large scale harvesting (Pitcher & Pauly, 1998).

Benthic - Organisms that solely live at the bottom of a body of water, a subcategory of demersal organisms (Froese & Pauly, 2023).

Cranial elements - Fish bones from the cranial (i.e. head region of the fish skeleton), including elements from the basicranial, branchial, branchiocranium, hyoid, and oromandibular regions (Wheeler & Jones, 1989).

Demersal - Organisms that dwell near, or relate to, the bottom of a body of water (Froese & Pauly, 2023).

Domesday book - A manuscript record of the "Great Survey" of England and of Wales, conducted by King William I (William the Conqueror), to list his holdings and dues owed to him (Higham, 1993).

Euryhaline fishes - Fishes that have wide salinity tolerance ranges and inhabit waters with varying ranges of salinities, due to inner mechanisms regulating osmoregulatory strategies such as the retention and secretion levels of salt and water (Kültz, 2015).

Fork Length - Length of a fish measured from the tip of the snout to the posterior end of the middle caudal rays, i.e. the fork of the tail (Froese & Pauly, 2023). For Atlantic cod (*Gadus morhua*), the Fork Length equals the Total Length, due to its fan-shaped tail, as illustrated in Fig.1.

Keystone species - A species with a disproportionately large effect on its natural environment relative to its abundance (Power et al., 1996).

Medieval period - The period roughly spanning the 5th cent.CE to the 15th cent.CE in Europe, and in England specifically. The period can be divided into early medieval, 5th cent.CE to the 10th cent.CE, and late medieval, 10th cent.CE to the 15th cent.CE (Hoffman, 2014).

Native - The locality to which an animal or plant is indigenous, as opposed to the locality to which that animal or plant has been imported (Denyer-Green, 1983).

Post-cranial elements - Fish bones from the post-cranial (i.e. posterior region of the fish skeleton), including the median fins and vertebral column regions (Wheeler & Jones, 1989).

Pelagic zone - Open, free waters away from the shore, where marine life may swim in any direction without topographical constraints (Froese & Pauly, 2023).

Penitentials - Handbooks of penance relating to the church which were first developed in the 6th cent.CE onwards, and contained dietary rules, regulations and prescriptions (Frantzen, 2014).

Stockfish - Air-dried or salted fish which were beheaded and gutted, resulting in a product with a storage life of several years (Inderhaug, 2020).

Total Length - The length of a fish from the most forward point of the head to the farthest tip of the tail, illustrated in Fig.1 (Froese & Pauly, 2023).

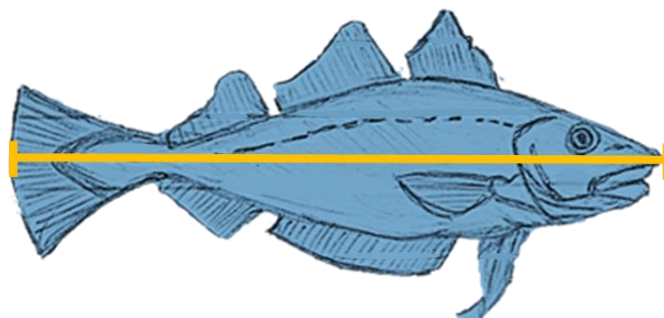


Figure.1. Total Length (TL) measurement used in analysis of fish size estimations (Froese & Pauly, 2023).

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1.Introduction

1.1. Thesis objectives and key findings

This research investigated the earliest marine exploitation efforts in the English Channel and the North Sea, with special emphasis placed on cultural and ecological temporal effects on Atlantic cod populations (*Gadus morhua*, henceforth referred to as cod). Special focus was given to the early exploitation of baseline cod populations in the North Sea and in the English Channel prior to their widespread exploitation in the later Middle Ages and by industrialised fisheries in modern times. The resulting distributions of estimated cod sizes from the archaeological study sites of Lyminge and Coppergate revealed significantly larger body sizes compared to modern populations, with important implications for past shifts in measures of reproductivity (i.e. fecundity), biomass, and potential trophic cascade effects.

The analysis revealed significantly larger sizes of additional species from Lyminge compared to modern populations, including Atlantic herring (*Clupea harengus*); whiting (*Merlangius merlangus*) and Atlantic mackerel (*Scomber scombrus*) prior to anthropogenic influences such as commercialised fishing. Similar to the findings for cod, these results also demonstrate that early medieval marine ecosystems contained fish of larger sizes, indicating healthier past populations.

This research also utilised zooarchaeological methods to assess fish bones from early, pre-exploitation periods, in order to evaluate regional variability in the rise of sea fishing in medieval Britain and North West Europe, i.e. the 'Fish Event Horizon' (henceforth referred to as the FEH and described in Introduction Section 1.5.2). The study site of coastal monastic Lyminge was selected for analysis of taxonomic compositions, size estimations and taphonomic processing of fish remains, revealing marine fishing practices from as early as the 8th cent.CE. This date precedes the currently accepted start of the FEH by 300 years (Barrett; 1997; Barrett et al., 2000; 2004.b; Orton et al., 2014; 2017). The size estimations of the archaeological cod, and the taphonomic analysis of the assemblage, revealed that the captured cod at Lyminge were likely processed by decapitation, to preserve them as stockfish for local consumption or for trade.

The zooarchaeological analysis provides a significant addition to a number of key studies focused on fish remains from early medieval sites (Barrett, 1997; 2004.a; Gardiner et al., 2001; Dobney et al., 2007; Hamilton-Dyer, 2001; Reynolds, 2015; Nicholson, 2015; Orton et al., 2014), which serve to refine evaluations of the temporal and spatial rise in marine fishing.

The archaeological cod sizes were estimated from newly developed regression models, based on both new and preestablished vertebrae and cranial measurement variables from modern specimens. The dataset of modern specimens used for the vertebrae measurements was exceptionally large and diverse, further improving the accuracy of previous models (Enghoff, 1994; Jones, 1991; Klippel & Sichler, 2004; Watt et al., 1997). The constructed regression models were critical for evaluating body sizes of the archaeological cod remains, expressed here as Total Length (TL), prior to the introduction of commercialised fishing endeavours in the North Sea and in the English Channel. The models were innovative in their applicability to previously unutilized fish skeletal elements, and can enable future studies on the body sizes of archaeological cod remains, including from sites with only limited element types.

The collective findings in this thesis highlight both the intensity and range of anthropogenic influences on marine ecosystems, beginning as early as 1,300 years ago and extensively shifting early, baseline populations, and the importance of consolidating archaeological, statistical and ecological analyses to reconstruct past ecologies of marine fauna.

1.2. Research objectives

1.2.1. Research framework and objectives

The main study objectives of this thesis, i.e. the reconstructions of body sizes (expressed as TL) of cod from the archaeological study sites of Lyminge and Coppergate, emerged from the aforementioned biological and archaeological premises, which are further elaborated on in the following sections.

The refined estimations of past cod sizes in this study shed light not only on the ecological characteristics of their populations prior to the advent of commercial fishing activities, i.e. body sizes and related measures of health, such as weight and

reproductive capabilities, but also on past fishing techniques and fishing grounds. In particular, the development of more accurate methods for cod size estimations contributed to a more detailed understanding of the fluctuations in cod imports into Europe as part of the FEH phenomenon, and their presence or absence at medieval sites. Smaller cod specimens have often been noted to indicate more local, coastal fishing, where cod populations mainly consist of juveniles throughout most of the year (Cohen et al., 1990; Uzars & Plikshs, 2000). Larger cod, inhabiting more open waters, could indicate more pelagic fishing, which might reflect advanced social and economic structures at the fishing sites (Barrett et al., 2011).

A key aspect of this study was the reconstruction of cod sizes based specifically on vertebrae measurements and analysis. Past studies have relied mainly on cranial (i.e. premaxilla) and appendicular (i.e. cleithra) elements for size reconstruction (Gabriel et al., 2012; Harland et al., 2016; Jones, 1991; Rojo, 1988; Watt et al., 1997). However, cranial and cleithrum elements were often left at the fish-processing sites, while vertebrae were left in the finished product (Orton et al., 2017). The addition of data from commonly recovered archaeological vertebrae therefore greatly enhances the body of knowledge on past cod populations where such elements are common, particularly their body sizes, their corresponding reproductive abilities, and how they were exploited by past societies. The new data further enabled comparisons of estimated cod sizes from both vertebrae from Lyminge and cranial elements from Lyminge and from Coppergate, constituting a strong method for the identification of traded, processed fish.

In order to address the main objective of the study, three auxiliary goals were outlined in regards to the use of cod vertebrae measurements:

- (1) Establish morphological vertebrae groups to improve the accuracy of regression models constructed from vertebrae measurement variables, in the absence of known vertebrae number in archaeological materials;
- (2) Develop regression models for the estimation of cod TLs based on the most suitable vertebrae measurement variables;
- (3) Examine the accuracy and usability of the models as demonstrated by the case study of archaeological vertebrae from 8th – 9th cent.CE Lyminge, and compare to cranial models (predeveloped from the literature and new from this study) from 10th –

16th cent.CE Coppergate. Details on the nature of the two study sites are in Methods and materials Section 3.1.1.

The second, supporting objective was to reevaluate the rise of sea fishing (i.e. the FEH) in medieval Britain and in North West Europe. This objective was addressed through the comprehensive zooarchaeological analysis of the fish bone assemblage from Lyminge, dated prior to the currently defined start of the FEH. This included reconstructions of the fishing and fish processing activities at Lyminge, including the types of fish selected for consumption, the fishing locations utilised by the fishermen, and the fish products prepared by the site's inhabitants, e.g. fresh fish for local consumption and preserved fish for consumption and trade.

1.2.2. Detailed research questions

To further define the study objectives, they were divided into three types of questions: methodological, archaeological, and historical/ecological. Within each type, the research objectives have been listed as a series of discrete tasks, each of which can be phrased as a separate question.

Methodological

- Can vertebrae measurements of cod be used in regression models for accurate reconstructions of vertebrae numbers and TLs?

Archaeological

- What were the relative frequencies of cod at Lyminge compared to other identified taxa
- What were the size distributions of medieval cod, based both on the newly-developed vertebrae regression models and on preexisting cranial regression models?
- Which other fish taxa were present at Lyminge and which marine habitats did they originate from?
- What were the skeletal element representation profiles of the identified fish at the site?
- What taphonomic processes were the identified taxa at the site subjected to?

What were the fish procurement activities, the taxa selected and their economic significance at the coastal, high-status monastery of Lyminge, and how do these compare with contemporary sites in medieval England?

Historical/Ecological

- What were the size distributions of cod before the introduction of intense commercial fishing in the 8th – 9th cent.CE, just prior to the FEH? Do these distributions reflect baseline populations?
- Can a significant, quantifiable change be observed in the size distributions of cod from medieval periods to modern times, and what are the ecological implications of this change?

1.3. Thesis structure

The thesis is divided into four sections. The first section introduces the background of this study and its core research questions. This section reviews the contribution of the analysis of fish remains in reconstructions of timelines of past interactions between humans and their marine environments, and presents some remaining challenges in these reconstructions. Additionally, historical relevance is established - the concept of the FEH and the beginning of intensified marine fishing in England and in Europe are linked to the study of fish remains from the main study site of Lyminge (zooarchaeological analysis and size estimations) and from the secondary study site of Coppergate (only size estimations) (Fig.1.1.A,B). The section ends with the introduction of cod as a key species in investigating the FEH, primarily through the development of practical methods for accurate size estimations.

The second section describes the materials and methods selected to address the research questions based on the ecological and archaeological topics in this thesis. Materials consisted of measurement data from modern and archaeological cod skeletal elements. The modern data included calliper measurements of vertebrae and cranial elements from modern cod reference specimens, as well as TLs of modern cod populations in the southern North Sea and English Channel from bottom trawl survey data (detailed in Methods and materials Section 2.1.2). The archaeological data included a fish bone assemblage originating from the 2009 excavation season of Lyminge, and similar measurements on fish bones from the two study sites in the United Kingdom: 8th – 9th cent.CE phases of medieval monastic Lyminge, Kent (vertebrae and cranial elements from the excavated fish bone assemblage), and 10th - 16th cent.CE phases of medieval urban Coppergate, York (legacy dataset of cranial element measurements) (Harland, P.C). Estimates of cod TLs from the two study sites

established a timeline spanning the 8th – 16th cent.CE, and subsequent observations of potential temporal shifts in TLs.

The aforementioned research methods included regression models constructed for cod size estimations from previously unutilised vertebrae and cranial elements (described in Methods and materials Section 2.1.5 - 2.1.6). The methods also included a zooarchaeological toolkit consisting of morphological identifications of skeletal elements and taxa from the Lyminge fish bone assemblage. Cod elements identified in this manner were measured and used in the constructed regression models. The zooarchaeological toolkit also included observations of taphonomic surface modifications of fish bones and additional size reconstructions of all identifiable fish taxa (described in Methods and materials Section 2.5). Beyond the purpose of developing methods for estimating past fish sizes, these methods were further used to reconstruct fishing and fish processing activities at the site.

The third section presents the results of the above measurements, their significance with respect to the research questions proposed in the first section of this study, and the main inferences relating to the zooarchaeological data from the study sites. The results include estimated sizes of cod and several other species from the study sites; taxonomic identification of the Lyminge fish remains and their corresponding aquatic habitats; skeletal element representations of the various identified taxa, and taphonomic processes observed on the fish bones.

The fourth section discusses the results both within the specific context of the research questions and within the wider context of corresponding historical and ecological events, through comparisons with key sites in England and in Europe.

This discussion, as well as concluding remarks stemming from the results of this thesis, focus on the usability of the hereby constructed regression models and their application to archaeological fish remains from the study sites. Additional results from the zooarchaeological analysis of the Lyminge fish bone assemblage were further discussed in connection with reassessments of the FEH and the rise of marine fishing in the English Channel and in the North Sea.

The section also raises suggestions for future research, both directions and challenges.

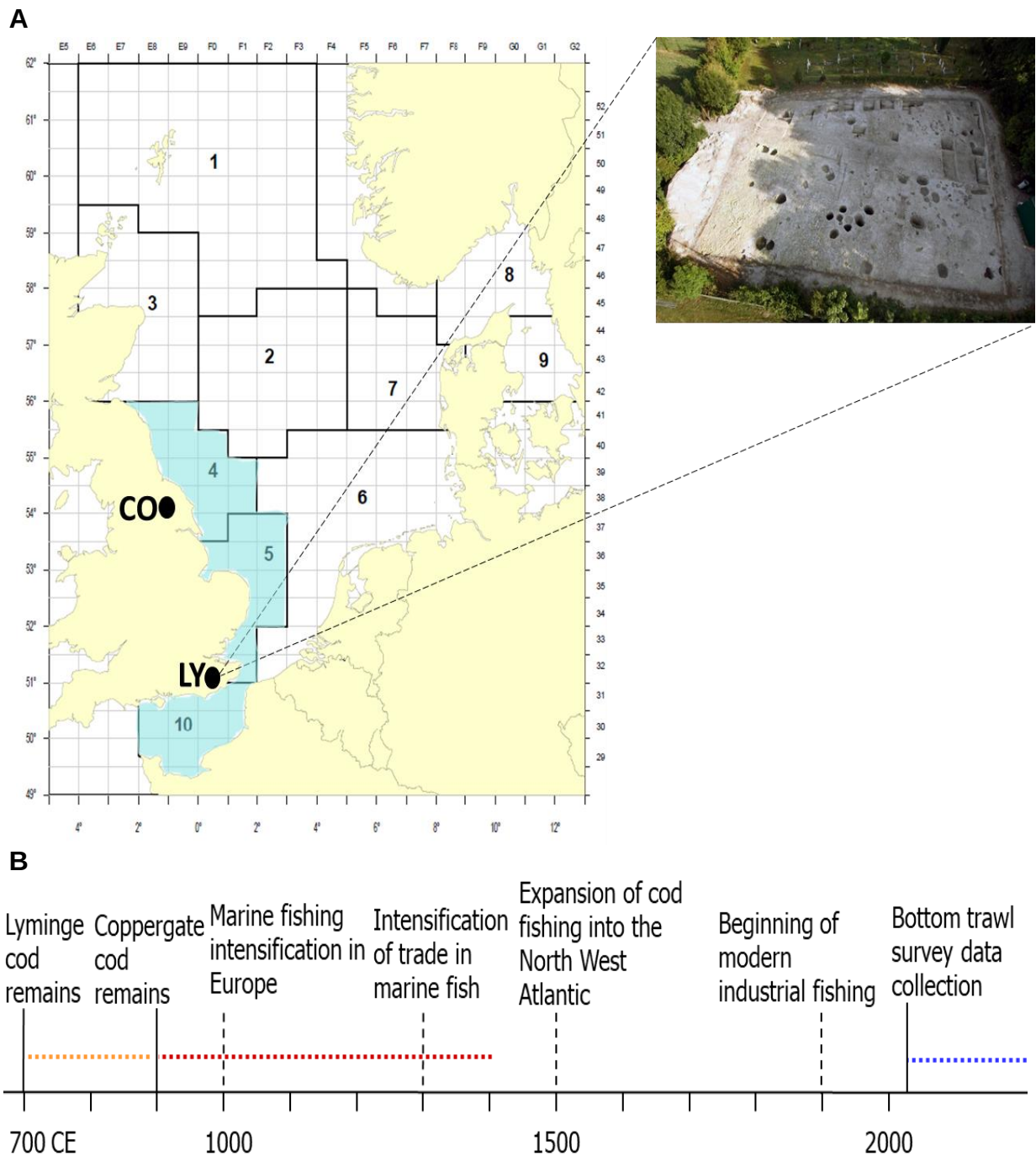


Figure.1.1. Locations and timeline of the archaeological and modern materials.

A. Map of relevant International Council for the Exploration of the Sea (ICES) marine areas and of sites analysed in this study (adapted from ICES, 2018; Lyminge Archaeology, 2023, aerial photograph, 2009 trench). Coppergate marked CO, Lyminge marked LY. Blue shading indicates bottom trawl survey areas used in this study. Area of Lyminge excavations in right-hand photograph.; B. Timeline of main historical fishing events relevant to this study. The main time periods of this study are marked in dotted lines: orange for Lyminge, red for Coppergate and blue for modern bottom trawl survey data (Thomas & Knox, 2017, Harland et al., 2016; Barrett et al., 2004.b; DATRAS Specification Document).

1.4. Ecology of Atlantic cod (*Gadus morhua*)

The Atlantic cod, from the Gadidae family, is native to the North Atlantic Ocean, the Labrador Sea, Norwegian Sea and the North Sea (Fig.1.2; Narberhaus et al., 2012). The species inhabits marine and brackish waters with a depth ranging from 150 m to 200 m, and a temperature range of 0 °C to 20 °C. Juveniles usually inhabit shallow, sublittoral waters of less than 30 m depth, while adults usually inhabit deeper, colder waters (0 °C to 5 °C) of 600 m maximum depth (Cohen et al., 1990; FAO, 2023).

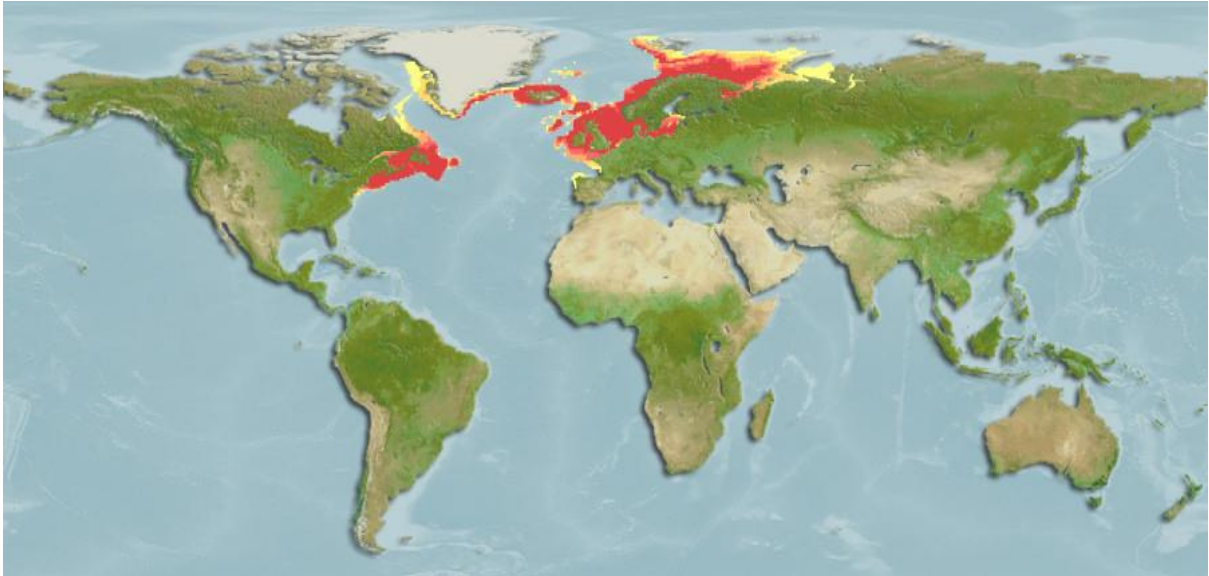


Figure.1.2. Distribution map of the native range of Atlantic cod (*Gadus morhua*) (from Kaschner et al., 2019).

The species matures at ~65 cm TL, and the adult range is between 31 cm to 74 cm TL, with a recorded maximum TL of 200 cm. During the day the adults form schools and disperse at night to feed on fish (including younger cod) and on invertebrates (Cohen et al., 1990). Spawning is mostly gonochorous, occurring in benthic, offshore waters between February and April, resulting in pelagic or demersal eggs. Cod larvae are pelagic and later benthic, with nursery areas within the inner coastal zone (Cohen et al., 1990; Uzars & Plikshs, 2000).

The species is semi-migratory (i.e. philopatric) and displays spawning-site fidelity. Migrations of cod populations depend on ocean temperatures, and in the UK populations larger individuals tend to move to colder Scandinavian waters in the summer, while smaller specimens stay in UK waters year-round (André et al., 2016; Spotowitz et al., 2022). Stocks have recently moved as far north as Svalbard, Norway, due to increased ocean temperatures (Spotowitz et al., 2022).

There are several close species within the Gadidae family (order Gadiformes) with similar osteological morphology. These species, which include saithe (*Pollachius virens*), pollack (*Pollachius pollachius*), haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), and pouting (*Trisopterus luscus*) (Watt et al., 1997), are all currently distributed in the Atlantic Ocean, mostly in the northeast, with *Gadus morhua* in the North Atlantic and Arctic, and *Pollachius virens* in the eastern Atlantic. All of the species are found in waters around the British Isles (Appendix.1).

Atlantic cod is considered a keystone predator within its natural habitat. Its presence is directly linked to the stability of marine ecosystems across the northern Atlantic Ocean, as demonstrated by the detriment of ecosystems in which stock collapses have been observed (Bundy et al., 2009; Sodeland et al., 2022).

Studies on modern cod have established that their fecundity is positively and curvilinearly related to their TL and weight (Carr & Kaufman, 2009; Froese, 2004; Marshall et al., 2003; May, 1967). This relationship has prompted fishery scientists to base their recommendations for cod fishing practices on changes in TL frequencies (Froese, 2004).

Influence of Atlantic cod TLs on population health Thesis structure

Studies have shown direct correlations between cod TL and estimations of both fecundity and biomass. For fish, fecundity is generally defined as the number of eggs produced during each reproductive cycle, or the potential reproductive capacity of an organism or population (Froese & Pauly, 2023). In this research, fecundity is defined as the numbers of yolked eggs produced by a female, following studies on relationships between fecundity and cod TL (Marshall et al., 1998). Biomass is generally defined as the total weight of the fish in a stock that are old enough to spawn, or the biomass of all fish beyond the age or size class in which 50% of the individuals are mature (Froese & Pauly, 2023). In this research, biomass is defined as the weight of freshly caught specimens in grams, following studies on relationships between biomass and cod TL (Wilhelms, 2013).

Larger TLs and biomass contribute to population health through higher numbers of successful recruits (i.e. fish that reach maturity), due to their direct links to higher reproductive capacities, higher egg counts, and longer spawning periods (Carr &

Kaufman, 2009; Kjesbu et al., 1996; Marteinsdottir & Thorarinsson, 1998; Ottersen et al., 2006). In line with these studies, fishery scientists have based their recommendations for cod fishing practices on observations of changes in TL frequencies (Froese, 2004).

Distributions of cod TLs are further linked to food webs and trophic cascade structures in their ecosystems. Definitions of food webs and trophic cascades in this study follow Pimm, 1982. Food webs are diagrams depicting which species in a community interact through their diet, and can also be viewed as the natural interconnection of multiple food chains. Each food chain is comprised of a series of links starting with producer organisms, which produce their own food through photosynthesis, and ending with predators, detritivores or decomposer species, which decompose dead or decaying organisms. The trophic level of an organism refers to its specific position within the food chain or web (Egerton, 2007; Lindeman, 1942; Pimm, 1982).

The role of cod TL in food web interactions is demonstrated by numerous observational studies of cod prey and predators. The diet of small cod (under ~65 cm TL) mainly includes crustaceans and Annelida, with proportions of fish increasing gradually with ontogeny, including other cod, herring, Norway pout (*Trisopterus esmarkii*), haddock, whiting, sand eel (*Ammodytes* spp. *Ammodytidae*), Common dab (*Limanda limanda*) and other cod (Link et al., 2009). Furthermore, maximum sustainable cod yields are strongly dependent on herring abundance due to herring predation on cod eggs and larvae. Trophic cascade models from the International Council for the Exploration of the Sea (ICES) catch data show that reductions in cod stocks can lead to herring abundances due to lack of cod predation, which in turn further inhibits cod stock recovery due to herring predation (Speirs et al., 2010). These combined observations have demonstrated that shifts in cod TL distributions drastically affect their prey types, further affecting their trophic structures and the health of cod populations.

This section has demonstrated that accurate estimations of cod TLs, and their conversion to fecundity and biomass values, can reveal the overall health of sampled populations. Estimations of cod TLs prior to widespread exploitation in both the Middle Ages (i.e. the FEH) and in modern times can subsequently reveal the extent of human influences on cod populations. Such information is necessary for the future management efforts of cod and additional species interacting in the same food web,

especially when considering the modern use of cod in numerous commercial products described in the following section.

1.5. Exploitation of Atlantic cod in the North Sea region

1.5.1. Atlantic cod as a modern commodity

Gadidae species such as cod and haddock have high commercial value thanks to their high reproductive rates, low fat content and mild flavour. Cod is well known as a prime food item and is marketed fresh, dried or salted, smoked and frozen (FAO, 2023; Frimodt, 1995). Cod is also targeted for cod liver oil (Nelson, 2006) and its fish waste is commonly used as fishmeal (Wheeler, 1969). For centuries the species has had a central role in providing coastal communities with both food and with their principal source of income (Rosenlund & Skretting, 2006).

Cod fisheries have been established throughout their natural distribution (Fig.1.2). Their major fishing grounds are boreo-arctic, convening around Iceland, in the Barents Sea, off Newfoundland and West Greenland, in the Norwegian Sea, off Svalbard, and around Bear Island (FAO,2023; Lilly et al., 2008).

Although fluctuations in cod population declines have increased in recent decades, the species is currently categorised as vulnerable (FAO, 2023; Sobel, 1996; Tveteraas, 2004). Recent observations of slower breeding rates and stock depletions have been linked to numerous episodes of overexploitation in recent decades and to fishing practices that include capturing juveniles and discarding dead fish to preserve quotas (FAO, 2023; Sherwood, 2019). Furthermore, although individuals can live up to 20 years (Cohen et al., 1990), overfishing has resulted in individuals fished at increasingly younger ages (Ottersen et al., 2006). Studies addressing the vulnerability of this species have included recommendations to increase the management of fishing efforts and to decrease catch rates (Engelhard, 2008). These studies indicate that gradual recoveries of target biomass levels can be achieved through reductions in cod fishing rates (Horwood et al., 2006).

Market demands for cod have spurred farming attempts in the last decade, and year-round production of juveniles and significant hatcheries have been established (Rosenlund & Skretting, 2006). Several problems currently challenge the economic

viability of cod farming, including high production costs, competitive wild fisheries, early sexual maturity, and soft flesh (Hagen & Johnsen, 2016; Otterå et al., 2016).

1.5.2. Past exploitation of Atlantic cod and the Fish Event Horizon (FEH)

The FEH

Intense cod trade, usually in the form of stockfish- air-dried or salted fish which were beheaded and gutted (Inderhaug, 2020), has been traced back to the 11th cent.CE towards the end of the Viking age and the start of the Norman conquest (Barrett; 1997; Barrett et al., 2000; 2004.b; Orton et al., 2014; 2017). This intensification is part of the FEH, i.e. the rise in sea fishing, particularly in cod and herring, approximately during the start of the 11th cent.CE in the North Sea (Barrett et al., 2004.b).

The early medieval shift to sea fishing in Europe gradually expanded into deeper waters, eventually establishing European fisheries off the coasts of Iceland and Newfoundland in the 15th – 16th cent.CE, as evidenced by osteological and isotopic analysis of archaeological remains and by historical sources (Barrett et al., 2011; 2004.b; Holm, 2019; 2022.a, b; Steane & Foreman; 1991; 1988). European markets were attracted to the previously unexploited and highly productive waters of the western North Atlantic, resulting in a 15-fold increase of cod imports to Europe by the late 16th cent.CE (Pope, 2004).

Similar to the observed expansion of marine fishing into Western Atlantic waters, the initial shift from freshwater to marine fishing has also been observed with zooarchaeological, historical, and isotopic methods. This initial shift has been attributed to several factors, including climatic shifts; the rise in urbanism and rapid development of both ecclesiastical and secular settlements; the rise of Christianity; population growth, and increased demands for more variety of fish kinds, which put pressure on freshwater species and encouraged more marine fishing (Barrett et al., 2004.a; Hoffman 2001; 2005; Star et al., 2017). The state of research on each of the contributing factors varies.

A contributing factor with unknown extent of influence is climatic change. Past research has particularly emphasised the potential contribution of the Medieval Warm Period (MWP) between 900 - 1300 CE (Rafferty, 2023), which coincided with the estimated

start of the FEH (Barrett et al., 2004.b). The MWP is currently defined as a climatic episode, in which relatively warmer conditions (by approximately 1 - 2 °C) are thought to have been present mainly in the Northern Hemisphere (from Greenland eastward through Europe and parts of Asia). These warmer conditions are thought to have been caused by a relative lack of volcanic activity and an increased atmospheric penetration of solar radiation. The concept of the MWP is highly controversial. Research claims include both significant shifts in average temperatures globally, and the occurrence of no appreciable shifts. The range of claims are all based on temperature reconstructions from ice and sediment cores; tree rings, and historical documents (Rafferty, 2023).

If the influence of the MWP extended to the North Sea, the increase in temperature would have led to unsuitable ranges for cod, as the North Sea is the southernmost border of the geographic distribution of the species, and represents the highest temperatures suitable for cod habitation (Barrett et al., 2004; Brander, 2000; O'Brien et al., 2000). Furthermore, the MWP would have led to shifts in additional environmental conditions, such as wind patterns; water column stability; movement of water masses and light conditions (Brander, 2000; O'Brien et al., 2000). The combination of these shifts could have further impeded cod habitation, and could have led to subsequent declines in productivity.

As the rise in Christianity is supported by a large body of research and is well documented, it has been selected for focus as a contributing factor to the start of the FEH in the present study. The connection between fish as a dietary component and Christian fasting practices is still under debate (Barret et al., 2004.a; Frantzen, 2014; Knapp, 2019; McDonnell 1981; Reynolds, 2015). Fish are a well-known symbol of Christianity since ancient times and have served as an allegory for Christ (Frantzen, 2014; Wetzel, 2012). Their Christian status in medieval periods is less clear, and previous studies have categorised fish as both a fasting food (Barret et al., 2004.a; Harland et al., 2016; Knapp, 2019) and a delicacy fit for feasts (Frantzen, 2014; Reynolds, 2015). The rise in Christianity in medieval periods, accompanied by dietary guidelines outlined in St. Benedict's Rule (Dembinska, 1986), may have led to the occasional need for fish for fasting days, and thus contributed to the intensification in marine fishing to meet increasing demands (Barrett et al., 2004.a; Harland et al., 2016; Knapp, 2019). Textual sources such as charters, monastic rules, and penitentials do not seem to clearly connect Christian fasting with fish consumption practices. However, this claim is complicated by the various different sources and interpretations of Old

English texts (Barrett et al., 2004.a; Frantzen, 2014). The application of additional methodologies can assist in understanding the relationship between fish and Christian practices. Recent isotopic analysis studies have shown that medieval diets from various social rankings were all relatively low in animal proteins, in direct contrast to lists of foodstuffs in the textual evidence (Lambert & Leggett, 2022; Leggett & Lambert 2022). The zooarchaeological record can also assist in interpreting sites as ecclesiastical or secular in nature. An absence of meat and a presence of fish at medieval sites is often considered in keeping with Christian dietary rules, while the opposite pattern may imply a more secular attitude (Dobney, 2007; Ervynck, 2004).

Zooarchaeological evidence of marine fishing at several English sites suggests a potentially earlier start to the FEH phenomenon, as detailed in the next sub-section. Similar evidence has been observed outside of England. Marine fishing from the 9th cent.CE has been observed at the elite settlement of Earl's Bu, and at the simpler settlement of Quoygrew, on the coasts of northern Scotland. Large fish bone assemblages were retrieved from both hand collected and sieved materials spanning the 9th – 12th cent.CE. Many skeletal elements, approximately 10,000 and 19,000 from Quoygrew and Earl's Bu respectively, were identified to species level, revealing a dominance of gadids, including cod, haddock, ling (*Molva molva*), and saithe (Barrett, 1997; Harland, 2007). An increase in estimated cod sizes from Quoygrew, based on comparisons of the archaeological specimens with reference specimens of known sizes, indicated a shift to offshore fishing from the 11th cent.CE (Harland, 2007).

Further away, at the 9th – 10th cent.CE coastal site of Saint-Georges-sur-l'Aa, France, relatively large gadids dominated the fish bone assemblage (n=40), suggesting offshore fishing (Oueslati, 2019). Additional evidence of marine fishing and inland transport dated to the 10th cent.CE was discovered at coastal and inland sites (n=27) in the Iberian Peninsula, through zooarchaeological identifications of hake (*Merluccius merluccius*), and stable isotopic $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis of their biogeographical origins (Llorente-Rodríguez et al., 2022). In Poland, at the coastal site of Kędrzyno, intensified evidence of local herring consumption dates back to the 8th cent.CE, and cod to the 9th cent.CE (Makowiecki et al., 2016).

FEH case studies in England

The geographical and temporal scope of the FEH remains unclear, although it has been positively attributed to England (Fig.1.3) (Barrett et al., 2004.a; Harland, 2007; Hoffman, 1994; 2001; 2005; Dierickx et al., 2022; Nicholson, 2015; Orton et al., 2014; Reynolds, 2015; Star et al., 2017) and to other sites in northern and western Europe (Barrett, 2019) and in the low countries (Ervynck et al., 2004; Van Neer & Ervynck 1996; 2016). The latter shifted to marine fishing from the 12th cent.CE onwards, succeeding the shift in England (Çakırlar et al., 2019). The key sites of the FEH in both England are presented in this section.



Figure.1.3. Distribution map of the discussed study sites participating in the FEH phenomenon in England. B= Bishopstone; C= Canterbury; F= Flixborough; Ly= Lyminge; Lo= London; S= Sedgeford; Y= York sites.

At Lyminge, Kent (reviewed in detail in Methods and materials Section 2.1.1 as a study site in this research), marine fish were recovered from the fills of sunken floors of timber buildings. Identifications of marine fish increased from NISP = 156 to NISP = 3,703 in the 8th – 9th cent.CE and has been attributed to the emergence of elite hierarchies (Reynolds, 2015). This rise in marine fish was synchronous with increases in both chickens and exploited wild mammals from feasting layers. The combined shifts have been linked to the synchronous establishment of a double monastery at the site and to the rise of Christianity in these periods (Knapp, 2019; 2017; Sykes, 2014). The analysis of the Lyminge fish bone assemblage from the 5th – 7th cent.CE (NISP = 156) and from the 7th – 9th cent.CE (NISP = 3,686) pointed to the exploitation of marine fish for elites, particularly cod, before the widespread medieval growth of marine fishing and well before industrialised fishing. The Lyminge cod remains are thus uniquely suited to reflect the size distribution of early, baseline populations in the southern North Sea and English Channel, prior to major human impacts (Reynolds, 2015; 2016; Thomas & Knox, 2017).

At nearby Canterbury, a large fish bone assemblage from the 8th – 9th cent.CE included exclusively marine species (NISP = 5,447). The assemblage was dominated by eel (*Anguilla anguilla*), whiting, cod, and right-eyed flatfish (plaice/flounder/dab) (Nicholson, 2015). St Augustine's Abbey was founded at the site in the 6th cent.CE, which developed into a prominent ecclesiastical centre from the 11th cent.CE (Baker, 1990; Smith, 1978).

An example of a shift to marine fishing was also seen at the site of Coppergate (reviewed in detail in Methods and materials Section 2.1.1 as a study site in this research), located between the rivers Foss and Ouse in north Yorkshire, approximately 60 kilometres from the North Sea coast. Representations of freshwater and migratory species, e.g. eels, cyprinids, and pike (*Esox lucius*), were replaced by marine species, e.g. cod, haddock, whiting and herring in the 10th – 11th cent.CE (Harland et al., 2016; Jones, 1988). A recent analysis of flatfish remains from both Coppergate and Blue Bridge Lane, York, has revealed a shift from riverine to marine species, further supporting the overall trend of intensification of marine fishing in northwest Europe species in the 11th cent.CE (Dierickx et al., 2022).

Similarly, at Fishergate, York, large quantities of herring, eel, and cyprinids were recovered from the 7th – 9th cent.CE, followed by smaller amounts of gadids (i.e. cod,

whiting and haddock) and flatfish in the 9th – 12th cent.CE, reflecting a temporal shift from estuarine and freshwater to marine resources. Herring was likely transported upstream from a fishery on the Humber Estuary, indicating high demand and the existence of trade networks for marine fish (O’connor, 1991; Reynolds, 2015). The site is thought to have functioned as an ecclesiastical centre from as early as the 8th cent.CE (Spall & Toop, 2008).

Additional elite sites such as Bishopstone, in East Sussex, on the English Channel coast, contained substantial evidence of diverse marine fishing (NISP ~ 2,340) in the 8th – 10th cent.CE, mainly herring, cod, whiting and eel. Plaice/flounder was also recovered in significant amounts. The recovered fish remains may have resulted from local provisioning of coastal estates, or from the early introduction of commercialization. The presence of some large cod (roughly > 100 cm TL based on cranial regression models or comparisons with reference specimens of known sizes) could indicate offshore fishing involving elite investment (Barrett, 2016; Reynolds; 2015; 2016). The Bishopstone community likely converted to Christianity with the rest of the Kingdom of Sussex, during the 7th cent.CE (Schoss, 2007).

A similar picture of local fish exploitation from various aquatic habitats was seen at the elite and ecclesiastical site of Sedgeford, Norfolk, approximately 8 kilometres from the North Sea coast. Fish remains from the 7th – 9th cent.CE included marine (NISP =877), freshwater (NISP = 27) and estuarine taxa (NISP =249) which were likely caught in the local Wash estuary and surrounding rivers (Reynolds, 2015).

Shifts in cod procurement throughout the medieval period were also seen in London. Zooarchaeological analysis of the fish remains from the fish-consumer city revealed surges in cod consumption in the 11th, 13th, and 15th – 16th cent.CE, while possible declines occurred in the late 14th, 16th, and 17th cent.CE (Orton et al., 2014; Pope, 2004). Ratios of cranial to postcranial cod bones have shed light on these fluctuations and helped determine if site activities included processing fish for export, e.g. from the site of Robert’s Haven in Scotland (Barrett, 1997), or importing fish for consumption, e.g. to London (Orton et al., 2014). Cod were often decapitated prior to transport, typically leaving cranial elements at processing sites, while post-cranial elements remained in the dried cod product and were consequently left at consumption sites (as noted earlier). Appendicular elements were sometimes left in the dried product but could also be attached to the crania, depending on the butchery method. Based on this

method, an increase in imports of relatively fresh cod from nearby waters in the 11th cent.CE was observed, with imports of possibly more preserved cod from distant, northern waters increasing only in later centuries (Barrett, 1997; Orton et al., 2014).

At Flixborough, located along the river Trent in North Lincolnshire (eight kilometres south of the Humber Estuary and approximately fifty kilometres from the North Sea coast), one of the largest fish bone assemblages from an elite, rural site from the 7th – 9th cent.CE was recovered (NISP = 6,000). Marine fish (e.g. cod and flatfish), and cetaceans were recovered in low numbers from the mid Anglo-Saxon period (8th – 9th cent.CE) (Loveluck, 2001). The seven main taxa from Flixborough, interpreted as local catches from marine, estuarine and freshwater sources, included eel, smelt (*Osmerus eperlanus*), plaice/flounder (*Pleuronectes platessa/Platichthys flesus*), pike (*Esox lucius*), carp family (Cyprinidae), perch (*Perca fluviatilis*), and salmon and trout family (Salmonidae). The fish remains likely reflect food rent paid by servile classes to elites as part of the social hierarchies developed in early medieval periods. Fish taxa such as salmon, eel, herring, and “river or sea fish” were listed as food rents in estate tracts and land grants from the 8th – 11th cent.CE (Dobney et al., 2007; Hodges, 1982; Swanton, 1996). The lack of representation of marine fish at Flixborough, a rural site, suggests that the FEH might have started as an urban phenomenon, or as a gradual shift to marine fishing through an intermediate phase of targeting migratory species in estuarine environments.

Regarding the role of Christianity at Flixborough, the excavations contained evidence of both secular and monastic phases. The former was evidenced by high proportions of meat between the 7th – 10th cent.CE, which didn’t follow the rules of St. Benedict, while the latter was evidenced by the presence of wild avian remains and of large proportions of flatfish and large smelt in the 9th cent.CE, matching eight additional monastic assemblages in the 6th – 16th cent.CE (Albarella & Thomas, 2002; Dobney et al., 2007).

To sum, recent observations of regional variability in the rise of sea fishing show that the FEH was more complex and gradual than previously thought. A shift to marine fishing well before the FEH has been observed in several locations in northwest Europe (Llorente-Rodríguez et al., 2022; Makowiecki et al., 2016; Oueslati, 2019). In England, such early shifts were noted at the coastal sites of Bishopstone, Canterbury, Lyminge, Sandtun, and Sedgford (Hamilton-Dyer, 2001; Nicholson, 2015; Reynolds, 2015;

2016), while evidence from the inland sites of Coppergate, Fishergate, Flixborough and London suggested a later shift, in line with the currently accepted start date of the FEH (Barrett, 1997; Dierickx et al., 2022; Orton et al., 2014; Harland et al., 2016; Jones, 1988).

Limitations of research on the FEH theory

The research regarding the FEH theory is presently limited by several factors:

Within England, archaeological studies covering the FEH mainly focus on periods between the 9th – 12th cent.CE, and regions in the east and south. The few studies focused on preceding periods (7th – 9th cent.CE) are further limited to the east (Reynolds, 2015). These limitations are partially due to the lack of ceramics and faunal remains in the west and north, which may result from relatively acidic soils (Rippon & Morton, 2020; Webster, 2008). Additionally, the distribution of ichthyo-archaeological reports from a mostly limited region in southeast England (Reynolds, 2015) further complicates statements on the shift to marine fishing in the whole of Britain, particularly the chronology and pace of change.

Outside of Britain, studies on the shift to marine fishing have been limited to select parts of northwest Europe, mainly Poland (Makowiecki, 2001; 2016) and Belgium (Barrett, 2019; Ervynck, 1997), with more recent additions from Iberia and France (Llorente-Rodríguez et al., 2022; Oueslati, 2019). Indeed, past exploitation patterns of freshwater and marine taxa have not been systematically analysed from an archaeological perspective in greater Europe.

FEH research is also limited by the lack of systematic sieving strategies in over half of the reported excavations (total number of sites~100), with the other half reporting a sieving strategy, but often not specified to mesh size (Cowie & Blackmore, 2008, Reynolds, 2015). Fine mesh sizes of 3 mm or less, needed for the retrieval of complete fish bone assemblages, have rarely been utilized, contributing to a lack of studies on fish remains (Cowie & Blackmore, 2008; Coy, 1980; Noddle, 2006; Reynolds, 2015; Zohar & Belmaker, 2005). The relatively recent increase in focus on past human-marine interactions in archaeological research, including in this study, has resulted in higher levels of fine mesh sieving, and more in-depth analysis of fish remains (Gardiner et al., 2001; Barrett, 1997; 2004.a; Dobney et al., 2007; Hamilton-Dyer 2001; Reynolds, 2015; Nicholson, 2015; Orton et al., 2014).

Finally, studies of the FEH phenomenon have focused on the chronology of marine fishing and it's starting date, to construct timelines of events that eventually led European fisheries to the coasts of north America. The speed, intensity and location of

this shift in various regions, i.e. the regional variability, has not been examined to the same degree. Furthermore, current research rarely differentiates between coastal and pelagic fishing, though some exceptions include Barrett et al., 2011 and Orton et al., 2011. This lack of differentiation is due in part to the complexity of using zooarchaeological methods for identifications of taxa that solely inhabit coastal or pelagic habitats. Such identifications are rare, as spawning migrations for many fish species involve transitions between the two habitats (Froese & Pauly, 2023).

Thesis contributions- addressing FEH research limitations

the analysis of the Lyminge fish bone assemblage contributes to limitations listed above that have rarely been addressed in past studies, expanding the temporal scope of the phenomenon; applying and reporting comprehensive sieving strategies; and assessing regional variability in the rise of marine fishing in northwest Europe.

The comprehensive statistical and zooarchaeological analysis of the Lyminge assemblage broadens the temporal scope of the FEH phenomenon by presenting significant levels of marine fishing from as early as the 8th cent.CE, 300 years prior to the previously assumed onset of the FEH.

Secondly, analysis of the Lyminge assemblage contributes to a limited number of studies of contemporary sites with well sieved assemblages between the 7th – 9th cent.CE (Hamilton-Dyer, 2001; Nicholson, 2015; Reynolds, 2015; 2016). The sieving strategy at Lyminge has yielded an exceptionally large and diverse fish bone assemblage that enabled more comprehensive and accurate assessments of morphologically identified taxa; skeletal element representations, taphonomic modifications and fish body size estimations.

Regarding regional variability, analysis of the Lyminge assemblage, reflecting a site that is high-status, early medieval, monastic and coastal, combined with comprehensively analysed, contemporary sites inside and outside of England (Harland, 2007; Llorente-Rodríguez et al., 2022; Makowiecki et al., 2016; Oueslati, 2019) suggests distinct regional variability in the timing and location of the start of marine fishing appearance, potentially driven by religious and geographic factors.

The Lyminge analysis, conducted partially through morphological taxa identifications, including coastal and pelagic species, further reveals evidence of offshore, pelagic fishing.

By overcoming the past research limitations on the FEH phenomenon, the added evidence highlights the role of archaeological fish remains in reconstructing fishing strategies, dietary preferences and potential trade networks of mediaeval populations. It should be noted that the geographic limitations noted above are beyond the scope of this study, and are therefore discussed as a direction for future research in the Discussion and conclusions Section.

1.5.3. Atlantic cod fishing gear and size selectivity

To assess the degree to which the archaeological cod remains from the study sites represented natural baseline populations, the type of gear and its selection on fish size were evaluated based on evidence from several sources. These included historical texts, iconographic manuscripts, archaeological reports, and recent studies on relationships between fish size, gear size and gear type (Berners, 1881; Hall, 1984; Heinrich, 1986; Ingólfsson et al., 2017; Lucy et al., 2009; Myers & Hoenig, 1997; Ottaway, 1992; Reynolds, 2015; Rogers, 1993; Rogerson, 1976; Wheeler, 1979).

Modern gear

Cod is currently fished throughout the year, mainly with trawls, seines and gillnets; the latter replacing historically utilised handlines and cod traps. Major fishing grounds include the Gulf of Maine, boreo-arctic areas around Iceland, the Barents Sea, the Norwegian Sea, and off of Svalbard (Cohen et al., 1990). Factory freezer trawlers are the latest addition to cod fishing vessels in the Atlantic. Freezer trawling is considered the most efficient capture method to date, capable of processing 150,000 tons of fish annually (Mason, 2002).

Modern cod fishing methods also include angling with hooks and lines, particularly for recreational fishing (FAO, 2023; Ferter et al., 2013). Such traditional practices support the theory that cod were historically captured with variations on hooks and lines, as further evidenced by findings of hooks at archaeological sites with cod bones (Heinrich, 1986; Rogerson, 1976; Wheeler, 1979). Modern angling techniques are known to utilise an array of hook sizes for different species, with relatively large hooks assigned

to species with a large mouth gape such as cod (Hardy, 1974). When angling, the hook must puncture the mouth wall or be swallowed. Therefore, hook and line fishing selects against the catch of smaller fishes, as hooks must be smaller than the fish mouth size (Myers & Hoenig, 1997).

More detailed investigations on the relationship between fish size and gear type in modern fisheries have not been widely conducted. Of the few existing studies, even fewer offer conclusive results relating to relationships between hook size and fish size, demonstrating the need for more accurate gear-selection models (Millar, 1992; Myers & Hoenig, 1997; Ralston, 1990).

A rare study on the relationship between hook size, bait size and cod fish size, conducted in Iceland, demonstrated that body size increased with hook size when combined with smaller bait (Ingólfsson et al., 2017). An additional study on recreational black bream (*Acanthopagrus butcheri*) fisheries in Victoria, Australia, aimed to reduce deep-hooking and the number of under-size fish caught by assessing the relationship between fish TL and three different hook and bait sizes. The study demonstrated that the dominant fish TL was generally stable for all hook and bait sizes. While the use of large hooks significantly increased mean fish TL compared to small hooks, this increase was less than 1 cm (Grixti & Jones, 2007).

Archaeological gear evidence

Archaeological sources on past fishing gear and their corresponding strategies and environmental impact are rare, partially due to the decomposition of the organic materials from which such gear was often constructed, and excluding the few cases of gear survival such as nets in Dutch, Norwegian, Russian, and Polish sites which are colder and waterlogged (Herteig, 1975; Rulewicz & Zajdel-Szczyrska, 1970). Another contributing factor to the lack of fishing gear sources is the temporal stability of fishing methods developed in prehistoric periods that did not change typologically for millennia (Steane & Foreman, 1988; 1991), preventing exact chronological characterization by blurring shifts in gear typology in different periods. Subsequently, no direct link has been observed between certain species and their size classes to specific archaeological gear types (Clark, 1952; Colley, 1987; Greenspan, 1998; Morales Muñiz, 2010; Steane & Foreman, 1991; 1988).

The existing evidence reveals that archaeological fishing gear in Northern Europe included, in general chronological order of development, pronged fishing spears, hooks, and gorges, weirs and traps, and line sinkers as the final and most commonly found type (Clark, 1952; Hamilton, 1968; Holdsworth, 1883; Kolchin, 1959; Steane & Foreman, 1988; 1991). Such gear types have been traced as far back as the Maglemosian culture between the 9th to 6th millennium BCE in Northern Europe (Clark, 1952, 42 - 48).

Fish hooks for line fishing have been recovered from various English sites dated back to at least the 8th cent.CE, revealing line fishing from early periods (Reynolds, 2015). Line fishing can include single or multiple bent hooks, as well as a sinker, and branch lines to carry the hooks (Steane & Foreman, 1988; 1991). The bent hooks were typically U-shaped and were usually made of bronze or iron in medieval Europe, including England, France, Austria and Switzerland (Clark, 1952). The hooks are still challenging to identify in the archaeological record, often appearing as obscure metal rods due to breakage at their weak points. Despite these challenges, bent metal fishing hooks were identified at several key English sites dated between the 8th – 13th cent.CE, including Coppergate, York (Hall, 1984); Fuller's Hill (Rogerson, 1976); Great Yarmouth; London; Hartlepool (Salzman, 1923; Steane & Foreman, 1988); Pevensey (Dulley, 1967); Bloodmoor Hill (Lucy et al., 2009); Flixborough (Wastling & Ottaway, 2009); Fishergate (Reynolds, 2015), Bishopstone (Thomas, 2010); Dover (Riddler & Trazaska-nartowski, 2009) and King's Lynn (Clarke, 2010, Figure.1.3.A,B). Medieval fish hooks from England are generally larger compared to contemporaneous European sites such as Wolin on the south Baltic (Rulewicz & Zajdel-Szczyrska, 1970), with the smaller hooks potentially utilised for freshwater and estuarine fishing (Steane & Foreman, 1988).

Line sinkers, an additional component of line fishing, have also been found in the archaeological record. Lead weights for angling with lines, rods and hooks, or for hand-line fishing solely with lines, became increasingly common throughout medieval periods. This is evidenced by the great variety of weight shapes found at the Thames foreshore (Steane & Foreman, 1988) and by a stone fishing weight decorated with Viking motifs from Clifford street, York (Fig.1.4.B; Waterman, 1959, 97).

Some of the medieval sites with preserved fishing gear contained fish bone assemblages dominated by marine fish, particularly cod and herring. Lyminge and the earlier periods of occupation at Bishopstone, England, contained large cod that were probably caught using hooks and lines (Reynolds, 2015).

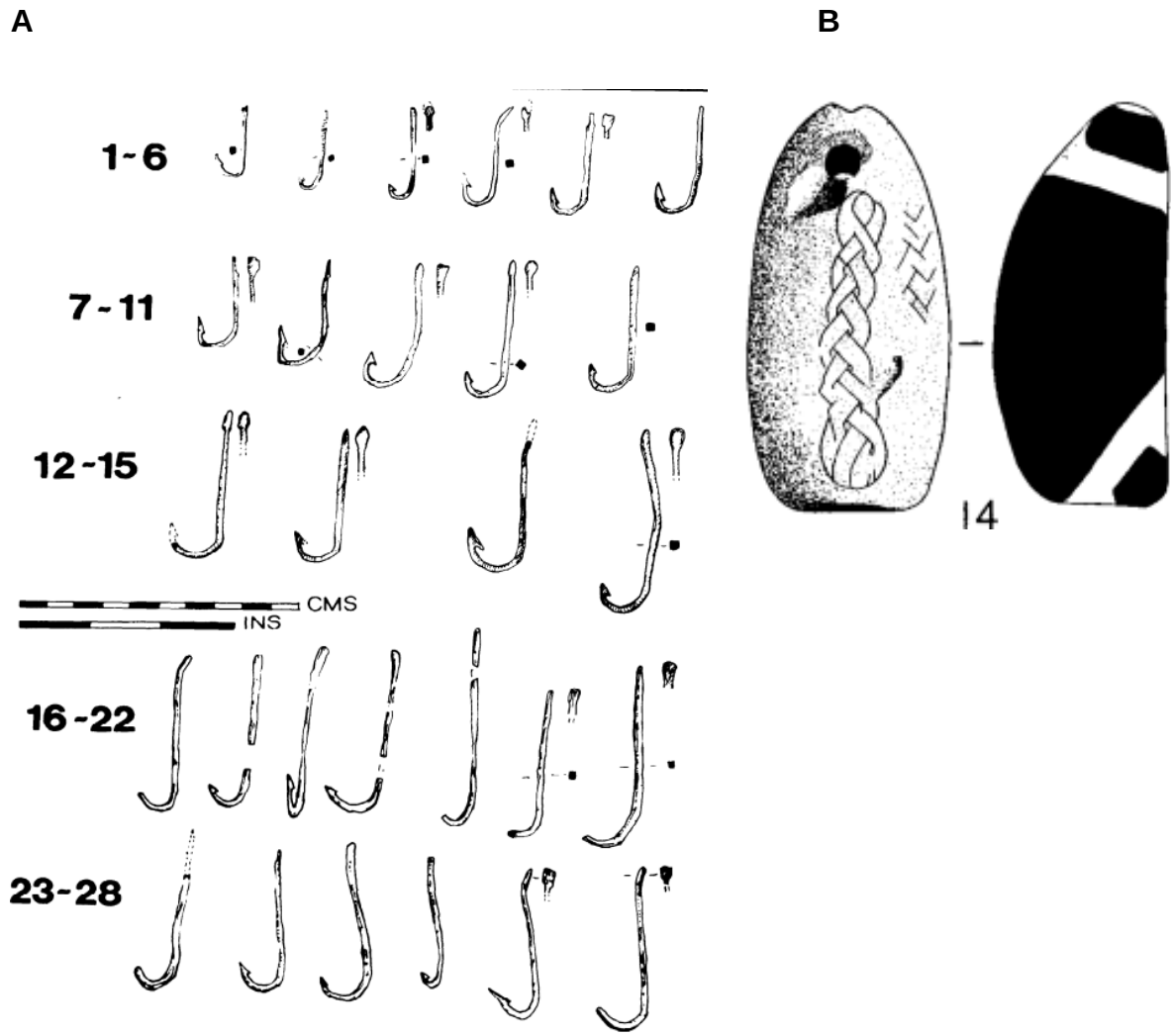


Figure.1.4. Archaeological examples of fishing gear from medieval England. A. Fish hooks made of iron from London (1 - 15) and Great Yarmouth (16 - 28) (Steane & Foreman, 1988, Fig.12.3); B. Stone net-sinker from Clifford Street with Viking motif (Waterman, 1959, 97, Fig.23).

Textual and Iconographic gear evidence

Early textual evidence of fishing gear includes the Domesday book from the 11th cent.CE, which mentions weirs several times (Galloway, 2017). A later legislative manuscript from the early 13th cent.CE attested to riverine fishing and ordered the removal of weirs from all waters except near the sea coast, suggesting that the shifting

of fisheries to more marine locations was encouraged by parliament (Bond, 2016; Hoffmann, 1996). Additional textual evidence includes the manuscripts of 14th cent.CE English writer Piers of Fulham, who described river fishing as a lucrative activity involving nets and hooks: "There eyll I fysche and take my fortune Wyth nettes and also with angle hokes". (Hazlitt, 1866).

Hooks are also mentioned in the early English book on angling from the late 14th cent.CE, the "Treatise on Angling in the Boke of St Albans" by Juliana Berners. The book includes instructions on the construction of fish hooks and fishing lines, as translated to English by Alfred Dension (Westwood & Satchell, 1883): "You must understand that the most difficult task in making your tackle is to make the hooks. To make them you need proper files, thin and sharp and beaten small; a semiclamp of iron; a bender; a pair of long and small tongs; a hard thick knife; an anvil and a little hammer." (Berners, 1881).

Iconographic descriptions of fishing gear have also been found in illuminated medieval manuscripts, such as the 15th cent.CE "The Hours of Catherine of Cleves" from the Netherlands. The manuscript includes the image of St. Lawrence holding the gridiron on which he was fried to death and is framed by eels and fish with bent metal hooks protruding from their mouths (Fig.1.5.A). The death of St. Lawrence is paralleled to that of the fish, who are similarly captured and cooked (Pierpont Morgan Library, MS M.917/945). Another 15th cent.CE illustration of fishing gear from the book of fables "Dialogus Creaturarum Optime Moralizatus", Sweden, depicts an angler using a float and line (Fig.1.5.B) (Nicolaus et al., 1482).

A



B

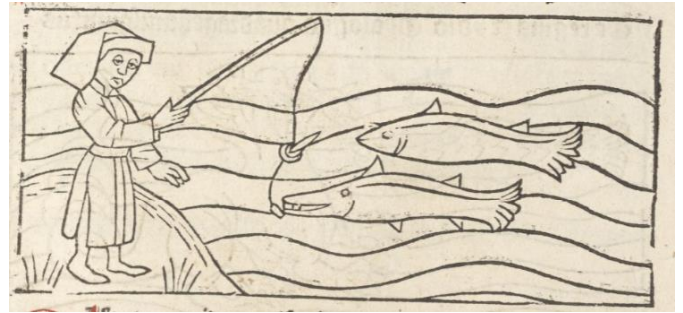


Figure.1.5. Images from Illustrated medieval manuscripts with scenes depicting fishing gear. A. Fish hooks from The Hours of Catherine of Cleves (Pierpont Morgan Library, MS M.917/945); B. An angler using a float and line (Nicolaus et al., 1482).

Selectivity of past gear on Atlantic cod TLs

The reviewed fishing gear types available both in modern times and in medieval Europe demonstrate that cod were likely captured with variations on hooks and lines, possibly with the use of gorges. This assertion is strengthened by the archaeological evidence consisting of hooks and cod bones from contemporaneous contexts in various European sites, i.e. England, Germany and Scotland (Heinrich, 1986; Rogerson, 1976; Wheeler, 1979).

For the purposes of examining the role of fishing gear selectivity on cod size classes at the study sites (i.e. Lyminge and Coppergate), a modified definition of selectivity as the ability to target and capture fish during fishing expeditions by one or a combination of the following criteria: species, size, or sex, has been adopted (Smith & Walsh, 1996). It should be noted that this definition does not account for natural selection processes,

nor for behavioural patterns within fish populations which do not involve human interference.

Beyond the above-noted scarcity of data on archaeological fishing gear, investigations on the relationship between fish size and fishing gear type in archaeological studies are also relatively uncommon, reflecting the similar lack of modern studies on the topic. This lack of information partially stems from the often poor preservation of both fishing gear and fish remains (Wheeler & Jones, 1989). Fishing gear can also be archaeologically invisible due to fishing methods such as hand catching and fish stunning.

A study on the relationship between archaeological fishing gear and fish size was conducted for snapper (*Pagrus auratus*) from the 1st cent.BCE to the 13th cent.CE in Southeast Australia to estimate the minimum fish size that could be caught with different hook sizes. The study assessed the relationship between hook and fish mouth sizes for 52 modern specimens, and found that the most effective fishing methods involved maximum hook widths smaller than minimum mouth width. These results indicate that while small hooks could be used for larger fish sizes, large hooks are limited to proportionally larger sizes. The study emphasised that the strength of both the material and design of the hook was not accounted for, but that these parameters are also known to significantly affect catches (Owen & Merrick, 1994).

Despite the challenges in directly linking fishing gear types to captured species and to their size classes, reconstructions of past fishing gear can still assist in understanding the distributions of fish sizes at archaeological sites, including at the study sites in this research. To assess the degree to which cod remains from Lyminge and from Coppergate represent baseline populations, it was critical to assess the potential fishing gears used to capture the fish, and to what degree the gear types might select for certain cod sizes. This section established that hook and line fishing was the most probable gear type used for cod fishing at the study sites and established the related selectivity pressures. The implications of the gear selectivity pressures on the fish bones and specifically on the cod size distributions from the study sites are detailed in Methods and materials Section 2.1.3, and in Discussion and conclusions Section 4.1.

1.6. Challenges in size estimations of archaeological Atlantic cod

Some key gaps still exist within the body of research on cod ecology and archaeology, particularly regarding the utilisation of archaeological cod bones for species identification and subsequent size estimations. Zooarchaeological morphological analysis has successfully identified certain cranial elements to species level (e.g. the articular, cleithrum, dentary, maxilla, parasphenoid, posttemporal, premaxilla, quadrate, and vomer), however, vertebrae elements have only been identified to species level in special cases (e.g. Gabriel et al., 2012, Harris et al., 2017; Lambrides & Weisler, 2015).

Gadid vertebrae are rarely identified to species and to location along the vertebral column due to minor morphological differences between taxa and vertebrae numbers, and frequently small sizes of vertebrae elements. Most vertebrae in the vertebral column subsequently remain under-utilised in archaeological analysis of species identifications and size estimations (rare exceptions include Dombrosky et al., 2022; Gabriel et al., 2012; Marrast & Béarez, 2019). Challenges in vertebrae identification are not specific to gadid fishes, but instead are a recognized difficulty in ichthyo-zooarchaeological research (Samper Carro et al., 2018; Moss & Cannon, 2011, 20 - 26). Despite the challenges in utilising vertebrae for species identifications, they are often abundant and well preserved within archaeological sites (Barrett, 1997; Dombrosky et al., 2022; Harland & Barrett, 2012; Lambrides & Weisler, 2015; Maltin, 2020; Orton et al., 2014; Walters, 1986).

For cod, identification of individual vertebrae also becomes more difficult along the vertebral column from anterior to posterior. Abdominal vertebrae are relatively easy to identify morphologically, while caudal vertebrae, diminishing in size and increasing in number, become increasingly less distinguishable (Fig.1.6). Specifically, cod reference specimens display a linear size decrease in caudal vertebrae measurements (discussed in Methods and materials Section 2.2.1).

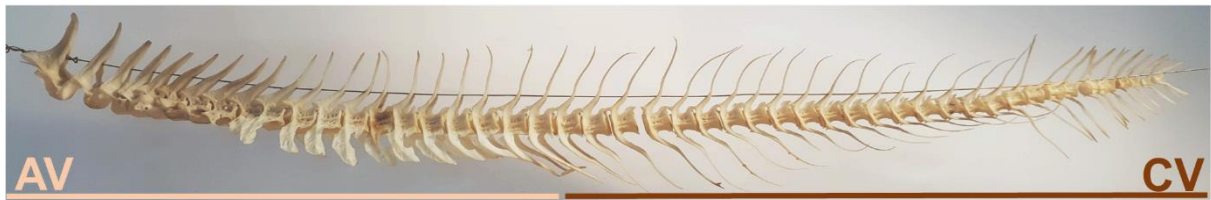


Figure.1.6. Vertebral column of a cod (*Gadus morhua*) reference specimen. Abdominal vertebrae marked as “AV”, caudal vertebrae marked as “CV”. The incremental size decrease in the CV is displayed from anterior to posterior.

In the past, studies have utilised global rachidian profiles (GRPs, graphs of the changing relationship between bone measurements and fish size along a vertebral column) to identify sections of the vertebral column containing vertebrae of similar size. GRPs can yield accurate estimates of fish TL if the vertebrae number is known in advance. However, individual vertebrae numbers are often hard to determine in the archaeological record due to the disarticulation and mixing of bones from fish of differing sizes (Desse et al., 1989; Jelu et al., 2021; Lambrides & Weisler, 2015; Lidour et al., 2018; Marrast & Béarez, 2019).

Regression analysis is another method utilised in past studies for estimations of fish size. Regression models are well established as a simple, accurate, and accessible tool for producing size estimations from archaeological bone measurements (Andrews et al., 2022; Dombrosky et al., 2022; Feltham & Marquiss, 1989; Russ & Jones, 2009; Turrero et al., 2014). For cod and for many additional taxa, cranial elements and selected, distinctively recognisable vertebrae have been the main elements measured to estimate fish TL with regression models (Enghoff, 1994; Gabriel et al., 2012; Jones, 1991; Limburg & Olsen, 2008; Rojo, 1988; Rurua et al., 2020; Watt et al., 1997).

At the study site of early medieval Lyminge, 356 cod vertebrae (292 of which were sufficiently intact to measure), as well as 115 cranial elements (38 of which were sufficiently intact to measure) were recovered from rubbish pits dated to the 8th – 9th cent.CE (Fig.1.1.A). The vertebrae and cranial elements were all recovered by sieving sediments with mesh (between 1 mm and 5 mm), minimising one of the main potential biases associated with archaeological reconstructions of animal size data (Zohar & Belmaker, 2005).

Based on the present challenges in cod archaeology and ecology, this research developed new regression models for the estimation of cod TLs based primarily on the most suitable vertebrae measurement variables and on additional cranial measurement variables. The vertebrae regression models were constructed from a uniquely large and diverse dataset of modern specimens sourced from several reference collections. The constructed models further involved a new methodology, where the vertebrae were divided into unique morphological groups. To date, archaeological cod vertebrae have not been identified to individual numbers along the column due to their indistinct morphological characteristics. This has limited estimations of archaeological cod TLs to select, morphologically distinct cranial and vertebrae elements, and subsequently limited analysis to assemblages containing these elements. The prototypical methodology in this thesis enables estimations of cod TL from all vertebrae elements, without the need to identify vertebrae numbers, as detailed in the Methods and materials Section.

To evaluate the body sizes of cod populations prior to the introduction of commercialised fishing endeavours in the North Sea and the English Channel, the constructed models were applied to bone measurements from the study sites of Lyminge and Coppergate (Harland et al., 2016), and the resulting TLs were compared with modern size data from ICES bottom trawl surveys (DATRAS Specification Document).

2. Methods and materials

The main method selected for this research comprised two consecutive steps. The first included the construction of regression models for cod size estimations from measurement variables of previously unutilised vertebrae and cranial elements. To improve the vertebrae regression models, vertebrae elements were classified into distinct groups based on their morphological characteristics.

The second methodological step included applications of the constructed regression models to measurements of vertebrae and cranial elements from the study site of Lyminge, and to the legacy dataset of measurements of cranial elements from the study site of Coppergate. To obtain measurements of cod elements from Lyminge, this research further included zooarchaeological analysis of a 2009-excavated fish bone assemblage, with emphasis placed on morphological identifications of cod bones to species level.

Regression models were chosen over other predictive methods, such as Geometric Morphometric (GMM) analysis, due to their specific ability to predict body size, and their simplicity, utilising traditional metrics instead of shape variables. The use of regression models for size predictions has been well-established in multiple zooarchaeological studies (Enghoff, 1994; Guillaud et al., 2016; Jones, 1991; Morales & Rosenlund, 1979; Samper Carro et al., 2018; Thieren et al., 2012; Watt et al., 1997).

Regression models were further selected based on their suitability to estimate past cod sizes from archaeological vertebrae. Vertebrae are often abundant in archaeological assemblages, but often remain unutilized in archaeological research due to their indistinct morphological characteristics, thus impeding identifications of individual vertebrae numbers (Barrett, 1997; Harland & Barrett, 2012; Maltin, 2020). Cranial elements are generally easier to identify morphologically in the archaeological record compared to vertebrae, and calculations of their MNI values (Minimum Number of Individuals) are more accessible. Consequently, past studies have constructed regression models for certain cranial elements (i.e. cleithrum, dentary, premaxilla), although most of these studies are not recent (Enghoff, 1994; Jones 1991; Morales & Rosenlund, 1979).

The newly constructed regression equations from both vertebrae and cranial elements (detailed in Methods and materials Section 2.1.5 - 2.1.6) enabled estimations of cod sizes from elements which are often ubiquitous but unutilised at many archaeological sites (Results Section 3.5). These regression models were thus expected to enhance the overall body of research on the ecology and economy of cod utilisation in both recent and distant periods.

Zooarchaeological methods were also selected for this research to better understand the nature of fishing and fish processing activities at the site, and to obtain cod vertebrae and cranial elements for the regression analysis (previously mentioned at the start of the section). These methods consisted of morphological identifications of skeletal elements and taxa to assess skeletal element representation and taxonomic composition; observations of taphonomic modifications on the skeletal elements; and size reconstructions of all available fish taxa identified (detailed in Methods and materials Section 2.5). This analysis, combined with cod size estimations from the constructed regression models, was conducted to reveal levels of processing and post-processing activities of cod and other identified fish taxa at Lyminge. Such activities can include size selections of fish made by fishermen and site inhabitants; the potential preparation and use of stockfish; the possible consumption of fresh fish; and the potential heating of fish by cooking or by burning domestic refuse (Harland & Barrett, 2012; Orton et al., 2014; Zohar et al., 2016). The extent of these activities at Lyminge are displayed in Results Section 3.9.

2.1. Research materials

2.1.1. Cod elements from the study sites of Lyminge and Coppergate

The archaeological cod bones analysed in this research originated from the two aforementioned study sites of Lyminge and Coppergate (Fig.1.1.A, Introduction Section).

The main site of Lyminge contributed cod bones (cranial and vertebrae elements) from numerous rubbish pits ($n \sim 100$) dated to the 8th – 9th cent.CE (Fig.2.1). This site produced abundant marine fish bone dating prior to commercialised fishing, and supplied archaeological cod remains reflecting early populations prior to human

impact. Size estimations of the archaeological cod vertebrae and cranial elements from Lyminge were obtained by employing the newly constructed regression models (detailed in Methods and materials Section 2.2 - 2.3). The size estimations, along with the zooarchaeological analysis, can partially reveal the exploited sizes of cod from the English Channel before the introduction of intensive marine exploitation. The estimated TLs of the Lyminge cod reflect 8th – 9th cent.CE populations. This sample population serves as a proxy for pristine, baseline populations since it is dated several centuries before the onset of widespread and ultimately industrialised fishing. As a proxy, it is limited by cultural and methodological factors such as fishing gear selectivity; cultural preferences by fishermen and by the site's inhabitants, and taphonomic processes such as fragmentation of measurable skeletal elements, sieving protocols, and the resulting sample sizes of the archaeological data. These factors are further discussed in Results Section 3.5 - 3.7, and in Discussion and conclusions Section 4.1.

Lyminge further supplied a fish bone assemblage sieved to 5 mm, with soil subsamples subjected to wet sieving and flotation to 1 mm. This assemblage was recorded and analysed with zooarchaeological methods (detailed in Methods and materials Section 2.5). The analysis of fish bone assemblages from near coastal sites such as Lyminge, where trade is known to have occurred, are still relatively underrepresented in archaeological surveys, and could improve our understanding of the transition from freshwater to marine fishing in medieval England (Reynolds, 2015; 2016). In particular, the combination of the presence of marine vs. freshwater taxa, the skeletal element representation, and the sizes of the archaeological cod specimens, can offer insights on the temporal fluctuations in the intensity of local and remote cod fishing and trade in Anglo-Saxon and medieval periods in England, and potentially in Northern Europe more generally.



Figure.2.1. Map of excavated areas at Lyminge. The studied fish bone assemblage from the rubbish pits of the 2009 excavation season is marked in the red square. From Thomas & Knox, 2017, Fig.3.2.

The site of Coppergate contributed a substantial legacy dataset of measured cod bones (cranial elements) from various medieval contexts dated between the 10th – 16th cent.CE (Harland, P.C). The Coppergate samples were wet sieved to 1 mm, then dry sieved to 2 mm, with the >2 mm fraction systematically analysed. The site, which has been extensively researched, represents periods in which marine fishing had gradually expanded and the commercialization of fishing had begun (Harland et al., 2016).

The Coppergate dataset served three main purposes. Firstly, it enabled comparisons of size estimations of cod remains from: a) the two archaeological sites (Fig.1.1.A);

and from b) the two types of skeletal elements, i.e. vertebrae and cranials from Lyminge and cranials from Coppergate. Secondly, the estimated dates of the Coppergate remains (Hall & Hunter-Mann, 2002; Harland et al., 2016) enabled the construction of a rough timeline of estimated cod sizes from earlier to later periods (Fig.1.1.B, Introduction Section). Lastly, the comparison of Coppergate to the earlier site of Lyminge contributed to reassessments of the start of the FEH in Medieval England, due to the fact that current definitions of the start of the FEH have been strongly influenced by the appearance of marine fishing from the 10th cent.CE at Coppergate (Harland et al., 2016).

Due to the established central role of the two study sites in supplying the materials for this thesis, their current state of research is discussed in greater detail below.

Lyminge

The monastic site of Lyminge, Kent, located 6 km inland from the coast of the English Channel (Fig.1.1.A), had been extensively excavated between 2008 and 2014, revealing occupation sequences rich in material finds and faunal remains. A sample of fish bones from the 2008 and 2010 excavations was analysed in Reynolds, 2015 (NISP = 3,859), and served as a comparison to the fish bones from the 2009 excavation analysed in this thesis.

The excavations revealed a high-status, Anglo-Saxon monastery that was active in the 8th – 9th cent.CE, possibly with the addition of a high-status household (Thomas & Knox, 2017). The site revealed an especially extensive and complete archaeological sequence reaching at least as far back as the 6th cent.CE, when the site functioned as a pre-Christian regional administrative centre. This early period was characterised by specialised crafts, including smelting and working of iron; the manufacture of copper-alloy items; and possibly the assembly of glass vessels. Craft specialisation continued into the 7th – 9th cent.CE, with prominent evidence of wool production at the site in the form of loom weights, wool combs and pin beaters, as well as the presence of older domesticated animals (Hamerow, 2004, 123; Thomas & Knox, 2017).

Based on the archaeological evidence and on the small size of the monastic church in particular, it is likely that the site housed a relatively small religious community in comparison to other monasteries in 7th – 8th cent.CE in Kent. The small community mainly comprised female aristocrats, possibly 20 - 30 residents. The elite character of

Lyminge in these periods is further supported by the particularly rich diversity and abundance of the archaeobotanical assemblages. The predominance of cereal crops such as wheat and barley in these assemblages reflects agricultural production. Monastic Lyminge was also characterised by the presence of fruits, vegetables, herbs and spices, all of which are generally absent in many contemporary sites of the 8th - 9th cent.CE (Thomas & Knox, 2017).

Lyminge is also mentioned in several historical documents, such as the charter from 732 CE describing a coastal area near Sandtun, Kent which was granted to the Lyminge settlement (Kelly, 2006, 109), possibly linking the minster of Lyminge to the fishing settlement of Sandtun. The text linking Sandtun to Lyminge, combined with the fact that toll privileges were granted to Kent ministers, implies that Lyminge could have procured fish from nearby Sandtun (Reynolds, 2015; 2016).

Animal remains from Lyminge

A large and well preserved animal bone assemblage was recovered from the buildings from the 5th – 7th cent.CE and from primary rubbish pits at the site from the 8th – 9th cent.CE. The assemblage was dominated by pigs in the earlier periods and by chickens and dogs, followed by cattle, sheep, horse, cat, deer, and corvids in the later periods.

Based on global ethnographic studies, the dominance of pigs in the earlier periods has been connected to feasting patterns. The elite nature of the site is further supported by the remains of cattle of prime meat-age and by the presence of birds of prey, suggesting the practice of falconry at the site (Thomas & Knox, 2017).

The pronounced shift in the represented taxa in later periods, with a decline in pigs and an increase in chickens, marine fish, cats, dogs, and deer, has been linked with the observed expansion of monastic culture across England. This shift has been accordingly interpreted as a reflection of intensified agricultural activity; decreased pastoralism, and intensified Christian practices. The Rule of St. Benedict had peaked in influence in northwest Europe in these periods, and included strict and extensive instructions on fasting periods where meat consumption from quadrupeds was not allowed. Fish may have been permitted for consumption during the fasts, and could have provided an important alternative source of protein (Ervynk, 1997), though it is unclear how many households followed this rule (Foot, 2006). The extent to which

certain fish were permitted as fasting foods is also unclear, as some argue that their luxury status would have made them unsuitable for that purpose (Dembinska, 1986; Frantzen, 2014).

A surviving historical document on fasting includes a set of laws by king Wihtred, which commanded fasting in both secular and monastic contexts in Kent in the 7th cent.CE. These laws may have resulted from the circulation of penitentials, i.e. handbooks of penance, by Irish missionaries in England. Penitentials often discussed the categories for allowing or denying the consumption of animals by humans, including fish (Frantzen, 2014). The combination of these laws with the fact that fish were a common symbol of the new Christian movement and that they were associated with humeral theory provides clear evidence that fish had an important role in the emerging monastic ideology (Sykes, 2014).

Fish remains from Lyminge

Notable quantities of marine fish remains were recovered from rubbish pits from the 8th – 9th cent.CE (Fig.2.1), despite the proximity of the site to freshwater sources such as the Nailbourne River. Consequently, Lyminge displays the exploitation of marine fish for elites before the currently defined start of marine fishing (the FEH) and well before industrialised fishing. Furthermore, cod remains from the site could reflect early baseline populations (Reynolds, 2015; 2016; Thomas & Knox, 2017). These theories have been reassessed in the present research through the zooarchaeological analysis of the fish remains and through reconstructions of size distributions using the newly constructed vertebrae and cranial regression models.

Although fish remains were rare in the early Anglo-Saxon period at Lyminge between the 5th – 7th cent.CE, evidence of ritualised feasting was found in the form of glassware; the analysed mammal bones; and the reconstructed feasting halls. Herring and flatfish were recovered in small amounts from these periods, possibly signifying the beginning of procurement of fish at the site. Small amounts of sturgeon were also recovered, possibly representing luxury food items (Thomas & Knox, 2017).

Contrastingly, a large fish bone assemblage was recovered from the 7th – 9th cent.CE period at the site, dominated by cod and followed by herring (*Clupea harengus*) and other marine fish, including whiting (*Merlangius merlangus*), horse mackerel (*Trachurus trachurus*), Atlantic mackerel (*Scomber scombrus*), and other gadids

(Gadidae) (Reynolds, 2016). The recovery of the fish bone assemblage from the site's rubbish pits indicates that they represent the dietary remains of several generations of residents and their guests (Thomas & Knox, 2017; Thomas, P.C).

The exploitation of marine fish for elites well before the FEH, as noted at Lyminge, illuminates the complexity of the temporal shift to marine fishing in more remote waters. Lyminge is also one of the few early to middle Anglo-Saxon sites (~ 7th – 9th cent.CE) with evidence of marine fish continuing into later periods, possibly reflecting an increasing taste for marine fish and the monastic diet of the site's inhabitants (Reynolds, 2015; 2016).

Coppergate

An additional dataset of measurements on the cranial elements of cod bones originated from the 10th – 16th cent.CE phases of medieval urban Coppergate. The site was extensively excavated between 1976 - 1981, revealing an urban settlement rich in finds indicating Viking influences. A sample of fish bones was analysed but unpublished by Andrew Jones, however the presence of large cod (80 cm - 100 cm TL) was determined from the comparison of archaeological specimens with reference specimens of known size (Barrett et al., 2008; Jones, 1988).

The excavation of the Coppergate settlement revealed an Anglo-Scandinavian population who constructed the site's medieval streets in the 10th cent.CE. Parishes were developed at the site before the Norman conquest (1066 CE) as two churches: All Saints and St Mary (Fig.2.2). These churches held both ecclesiastical and governmental roles. An urban settlement gradually developed at the site to house local mercantile elites in the 14th – 15th cent.CE. Population density seemed to increase in post-conquest periods, with more evidence of tenement residencies. Poorer sectors of society are rarely visible in the historical and archaeological materials from Coppergate, but some evidence is present in estate records from the site. These records describe cottages and multiple-occupancy residences from the 14th cent.CE.



Figure.2.2. Map of the Coppergate area. Urban features are from later medieval periods while the extents of the rivers Ouse and Foss reflect 11th cent.CE water defence systems constructed around York Castle. From Hall & Hunter-Mann, 2002, Fig.395.

Material and textual evidence of site residents before the 14th cent.CE is rare. An exception is the cartulary of St.Leonard's Hospital from the early 13th cent.CE. The cartulary describes the land extending from Coppergate to Ousegate and its free tenants, which included some of York's leading members of society. Records also mentioned that in the 13th – 14th cent.CE tenancies close to the settlement market were occupied by artisans, including butchers, millers, blacksmiths, blanket makers, and weavers.

Textual evidence begins to appear in records from the 14th cent.CE onward, mainly from parish records, and document the ruling of the land around the marketplace by the mercantile elite population.

The settlement developed considerably in the 12th – 14th cent.CE, with higher food production and consumption, better living standards and improved building

construction. This pattern was observed at additional settlements across England. The prosperity and urbanisation of the site was accompanied by challenges, such as overcrowded living conditions and water pollution as evidenced in the King's Pool (expanded below).

The settlement has been described by excavators as a city based on its diversified economy, its importance as an administrative, religious and social centre and its intense importation and exportation of goods. The paucity of archaeological evidence of craft and industrial activity at the site in later medieval periods has been linked to the emerging prominence of rich and influential mercantile residents in the 14th – 15th cent.CE, which may have shifted economic focus to trade rather than craft activities.

The development of trade at the site throughout medieval periods is also reflected in the naming of areas within the site as Pavement and Marketshire from the 14th cent.CE onwards. These names describe official marketplaces, and could reflect increasingly regulated and organised trade in later medieval periods. Site records mentioning market goods in Pavement included references to vegetables, grain, herbs and cloth, as well as salted and fresh fish from the Fossgate and Ousegate markets.

The Pavement market was also used to show plays that emphasised the connection between the nourishment of the body and of the soul, suggesting that food staples such as fish had important roles in religious and ritualistic aspects of the settlement (Hall & Hunter-Mann, 2002).

Animal remains from Coppergate

Medieval urban Coppergate was clearly linked to the surrounding countryside through animal husbandry. The animal bone assemblage from the site mainly consisted of cattle, followed by sheep, pig, fowl, and goose. The dominance of cattle was likely due to demand, and to their suitability to the heavier soils found in Yorkshire. The high numbers of adult cows and sheep in the assemblage suggested that they were used for primary products such as meat, as well as for secondary products such as milk, leather, and traction in farming. Refuse deposits at the site contained high levels of stable waste, suggesting that animals were kept in the tenements for food. Overall the urban settlement seemed to be involved in all aspects of food production, from raising

the animals to converting them into food products to victualize the town (Hall & Hunter-Mann, 2002).

Fish remains from Coppergate

The construction of the York Castle in 1068 CE heavily altered the nearby Foss river (Fig.2.2). Alterations to the river included the construction of a dam to create an artificial lake, the “King’s Pool”, which served as a royal fishery throughout the medieval period. The dam was frequently exposed to high tides and floods on the rivers Ouse and Foss, and was completely washed away by a flood in 1315 CE. The river Foss was so frequently flooded that site structures were purposefully built less durably and were renewed often, and ground levels were raised. Floodings were attributed to shifting climatic conditions across England in the 13th – 14th cent.CE (e.g. The Little Ice Age following the preceding Medieval Warm Period), which resulted in heavy rain and rising sea levels (Schofield & Vince, 1994).

Records of declining fish stocks in the King’s Pool appeared regularly from the 15th – 16th cent.CE; a result of waste dumping into the pool, and of leat construction to power water mills and supply defensive ditches around the town. The pool was out of use by the 18th cent.CE (Hall & Hunter-Mann, 2002).

Assemblages of fish bones from Coppergate were mainly recovered from floors of buildings and houses and pit fills such as rubbish and latrine pits with a 2 mm size mesh. Most of the recovered bones exhibited low levels of breakage or burning. Herring was the most abundant marine taxon present, followed by eel, gadids (haddock, cod and whiting), cyprinids, flatfish, pike, smelt, and salmonids. The marine taxa are detailed further in the following subsection.

The assemblages present an example of the shift to more marine fishing during the 10th – 11th cent.CE, where the presence of freshwater and migratory species, e.g. eel (*Anguilla anguilla*), cyprinids (Cyprinidae) and pike (Esox) decreased, while the presence of marine species, e.g. cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*) and herrings (Clupeidae) increased. Most of the fish remains (herring, cod and haddock) seemed to reflect local North Sea catches.

The shift from freshwater to marine fish at the site, combined with the diversity and amount of fish taxa, reflect a growing demand for fish products in early medieval periods from as early as the 10th cent.CE. This demand may have had a negative impact on freshwater and migratory species well into the 14th cent.CE, possibly accompanied by monopolisation by elite groups and the initiation of new marine fisheries (Harland et al., 2016).

Freshwater fish from the 12th cent.CE onwards (pike, cyprinids, perch) could have originated in man-made ponds, as seen at the King's Pool. Fish from the King's Pool, however, are probably not present in this assemblage as it would have been gifted to rural magnates rather than to the urban craftspeople of Coppergate (McDonnell, 1981; Jones & Daniell, 2002; Steane, 1988).

The marine taxa from Coppergate

Herring is the most abundant taxon at Coppergate (NISP = 8,829). The presence of appendicular elements which are usually removed for curing purposes, point to local catches (Cutting, 1955; Unger, 1978). Large and well established medieval English fisheries between Scarborough to Yarmouth were developed by the 12th cent.CE (Holm et al., 1996). The herring trade continued to expand from the 14th cent.CE, with imports of Baltic herring into England.

Whole eel skeletons were also dominant in the assemblages between the 7th – 9th cent.CE (NISP = 2,931), decreasing gradually in number and in size into the 14th cent.CE, due to either overfishing or to changing fashions.

Gadids, the third most abundant taxon at Coppergate (NISP = 612), increased from the 10th cent.CE onwards, becoming numerous from the 11th cent.CE. Medieval England imported air-dried stockfish from Northern Scandinavia from around 1100 CE (Nedkvitne, 2014), later shifting to salted and dried cod fish from local and distant waters (Candow, 2009; Childs, 1995; Jones, 2000; Kowaleski, 2003). Both of the aforementioned preservation methods began with decapitating the fish, with or without the inclusion of the appendicular elements and some anterior vertebrae (Barrett, 1997; Betts et al., 2014).

The cod remains from Coppergate are interpreted as local catches, with a small amount from more distant waters which might have been imported as a salted and/or

dried stockfish product. This interpretation is based on several analyses, including skeletal element representation, size reconstruction data, stable isotope analysis, and butchery patterns. Each of these methods is expanded below, as several of them are later compared with the zooarchaeological analysis of the Lyminge and Coppergate cod in this research (in Discussion and conclusions Section 4.4).

Firstly, cod cleithra are clearly present at Coppergate in the 10th – 11th cent.CE and in the 13th cent.CE, despite their relative fragility. An additional relative abundance of vertebrae and in these periods suggests that cod were imported to the site in a decapitated state, as was the usual practice for the production of stockfish (Harland et al., 2016; Fig.15.8).

Secondly, the relatively large reconstructed cod TLs from the 13th cent.CE (TL > 80 cm) matched those of several known stockfish varieties, further suggesting that cod were imported to the site in a preserved state. These reconstructed cod TLs were based on comparisons with reference specimens of fish of known total lengths (cf. Perdikaris & McGovern, 2009).

Thirdly, stable isotope analysis of cod bones from the 10th – 11th cent.CE (n = 21) revealed that four were of non-local origin. The non-local bones could have originated from Arctic Norway or from the northeastern North Atlantic, indicating that preserved cod may have been imported to Coppergate from afar (Barret et al., 2011; Harland et al., 2016).

Lastly, the pattern of butchery marks on several cod bones (e.g. vertebrae, cleithra) are indicative of preparation for salting and/or drying the cod as done for stockfish preparation (Barrett, 1997; Barrett et al., 1999; Harland et al., 2016).

In sum, the zooarchaeological evidence suggests the 10th cent.CE as the date of establishment of the east-coast cod fisheries. This date is earlier than the suggested 14th cent.CE date from historical texts, where the establishment of east-coast English cod fisheries is mentioned as a compensation strategy for the increased competition with herring fisheries from Sweden and from the Netherlands (Childs & Kowaleski, 2000).

Haddock remains are the next abundant taxon after cod (NISP = 476), and are interpreted as local, coastal catches, due to the relatively even distributions of skeletal

elements and the lack of patterning in their reconstructed size distributions (Harland et al., 2016).

The following abundant taxon, pike (NISP = 275), showed a clear decrease in size from the 11th cent.CE onwards, possibly reflecting increased fishing pressures and shifts from river fishing to artificial fish ponds (Hoffmann, 2009; Jonsson, 1986).

In addition to the identified fish taxa, weights associated with hook and line and net fishing were recovered from Coppergate (Fig.2.3). Stone weights were also found at Fishergate, York (Rogers, 1993), and at Bishopstone, East Sussex (Reynolds, 2015), further suggesting that fishing was locally practised during these periods.

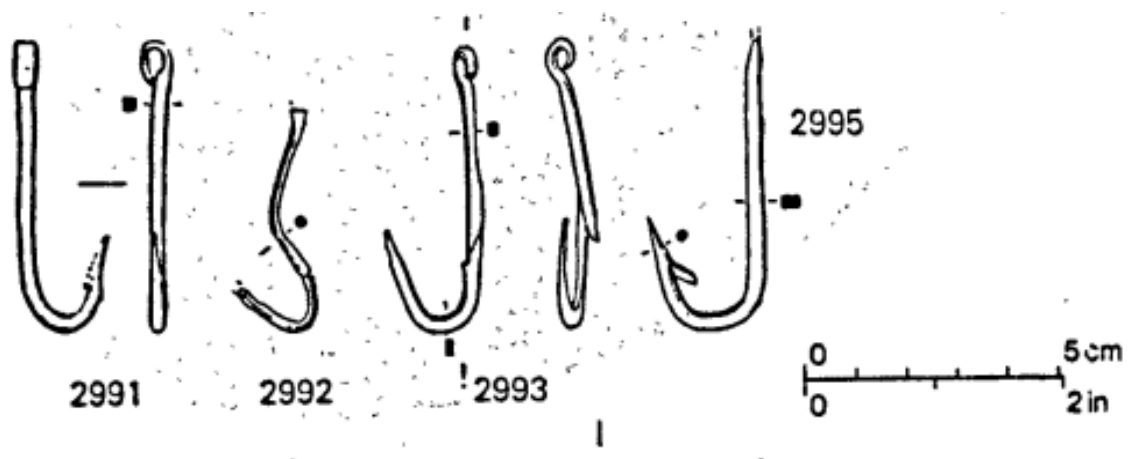


Figure.2.3. Bent fish hooks from Coppergate. From Ottaway 1989, Fig. 21, p.1088.

2.1.2. Measurements of modern cod TLs

TLs of modern specimens were obtained from bottom trawl surveys conducted by the International Council for the Exploration of the Sea (ICES), (DATRAS Specification Document) to assess natural TL distributions of modern populations. Recent studies on the cranial elements and otoliths of Australasian snapper (*Pagrus auratus*); Pacific cod (*Gadus macrocephalus*); and Atlantic cod have similarly utilized modern trawl data to estimate past levels of fishing pressures (Pedersen et al., 2022, Plank et al., 2018; West et al., 2022).

For the purpose of this research, the selected survey data were collected between 2018 - 2022 from the North Sea regions proximate to the archaeological sites

(Fig.1.1.A, Introduction Section). Bottom trawl survey data were chosen for this research over data from other gear due to the non-selective nature of trawls, therefore taken to represent the complete range of cod TLs (DATRAS Specification Document).

2.1.3. Fishing gear and other size-based selectivity

To further assess the degree to which the archaeological cod remains represented natural baseline populations, the type of gear (e.g. hook size) and its influence on the size of fish caught was evaluated from several sources (in Introduction Section 1.5.3). The chosen sources included historical texts, archaeological reports and studies on relationships between fish size, gear size and gear type (Berners, 1881; Hall, 1984; Heinrich, 1986; Ingólfsson et al., 2017; Lucy et al., 2009; Myers & Hoenig, 1997; Ottaway, 1992; Reynolds, 2015; Rogers, 1993; Rogerson, 1976; Wheeler, 1979).

The estimated TL distributions from Lyminge and Coppergate were also evaluated to infer the minimum TL of cod retained for consumption, be this through gear selectivity, cultural preferences or remaining recovery bias (if some bones passed through the mesh employed). Based on the lower-end point of the 95% highest-density region (calculated with the *hdr()* function in R), this minimum TL was 50 cm for Lyminge and 60 cm for Coppergate. The distributions of the archaeological and modern cod TL densities were truncated at these lower-end points of the calculated highest-density region to take into account the aforementioned gear selectivity, as hook and line can select against cod with mouth sizes smaller than the utilised hook sizes; cultural preferences, if fishermen selected larger fish; and recovery bias when comparing past and present fish sizes (Ingólfsson et al., 2017; Myers & Hoenig, 1997; Wouters et al., 2021). To analyse the most reliable data, TL values below the truncation, or 'cutoff' points (i.e. the values most affected by the biases) were excluded from the analysis.

2.1.4. Modern reference specimens for vertebrae analysis

The vertebrae of 36 modern cod reference specimens with complete or nearly complete vertebral columns were used to establish the regression models in this research (Appendix.2.1). The reference specimens came from collections housed at The Norwegian University of Science and Technology, the Grahame Clark Laboratory for Zooarchaeology at University of Cambridge, the University of Bergen, the University

of Southampton and the University of York. All reference specimens were identified to species level and had recorded TLs. The vertebrae of most of the reference specimens were not articulated ($n = 25$). Vertebrae numbers were determined by conducting morphological comparisons with the vertebrae of four newly prepared articulated specimens possessing known vertebrae numbers (Appendix.2.1).

Cod vertebrae were classified into distinct morphological groups FV, AV1 – AV3, CV1 – CV3 (after Barrett, 1997, refined in this research), before constructing corresponding regression models for estimating TL (Appendix.2.2). The AV1 group was ultimately divided into individual vertebrae numbers 2 – 5, due to the improved accuracy of the resulting regression models and to the distinct morphological characteristics of the individual vertebrae which enables their identification to specific vertebrae number using archaeological material, which often includes disarticulated vertebrae.

2.1.5. Vertebrae measurements of reference specimens for size estimations

Four variables- posterior Centrum Width (CW), posterior Centrum Height (CH), Lateral Length (LL) and left lateral minimum height (LH) were measured for the vertebra of modern reference specimens (mentioned in the previous section) by a single researcher with a digital calliper (Mitutoyo 500 Series Digital Caliper ABSOLUTE CD-15AX), with an absolute error range of 0.02 mm (Fig.2.4). The CW, CH and LL measurements were taken on the centrum of all vertebrae (Watt et al., 1997, 134 - 135). The LH measurement variable was taken solely for the caudal vertebrae to assist in more accurate estimations of TL through the estimation of vertebrae number (as explained in subsection 2.2.1) (Fig.2.4).

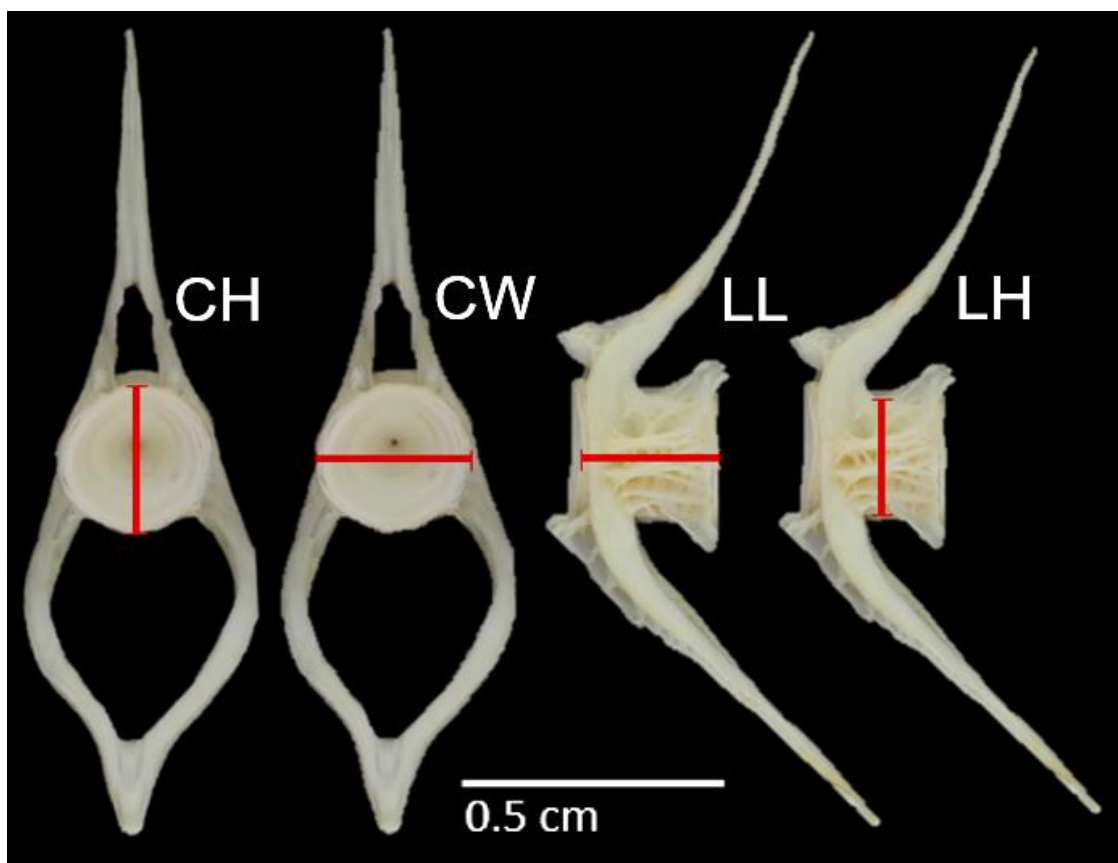


Figure.2.4. Measurement variables for the cod (*Gadus morhua*) vertebrae. From left to right: Posterior Centrum Height (CH); posterior Centrum Width (CW); Lateral Length (LL); and Left Lateral Minimum Height (LH).

2.1.6. Cranial measurements of reference specimens for size estimations

Additional regression models were constructed in this research from a legacy dataset of cranial measurements (D.2.3) on file from the modern reference collections at the Department of Archaeology, University of York and at the University of Cambridge. This legacy dataset included some reference specimens ($n = 17$) that were also utilised for the new vertebrae measurements discussed in the previous section 2.1.6 (Craig & Orton, University of York, P.C). These data included the following elements: dentary, supracleithrum, quadrate and premaxilla (sample size between 74 and 91 specimens for the different elements). The measurements (defined as M1 for each skeletal element) follow Enghoff, 1994; Jones, 1991 and Morales & Rosenlund, 1979 (Fig.2.5). A previously undefined M1 measurement for the supracleithrum is illustrated in Fig.2.5 (Craig & Orton, University of York, P.C). Of the four analysed elements, the quadrate and supracleithrum did not have pre-existing regression models from the published literature (Fig.2.5).

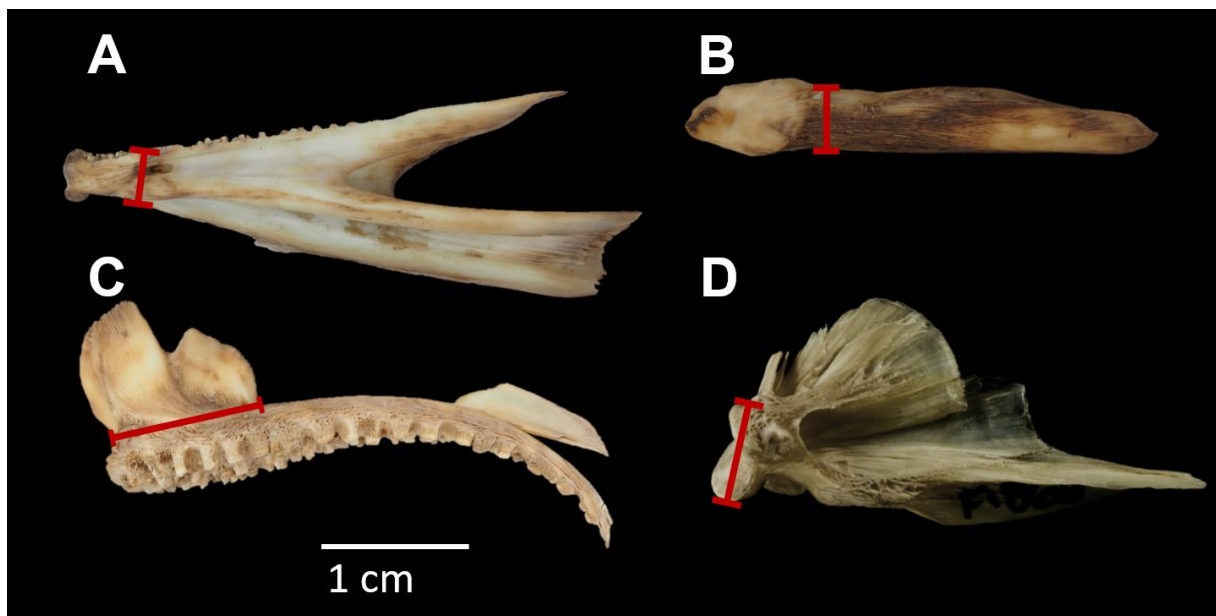


Figure.2.5. Measurement variable M1 for the cod (*Gadus morhua*) cranial elements. The elements are: A. dentary, B. supracleithrum, C. premaxilla and D. quadrate. Measurements are displayed on the left lateral side of each element. Quadrate image from Archaeological Fish Resource, 2020.

2.2. Regression models for cod size estimations

Regression models were constructed for the estimation of cod TLs based on the best vertebrae measurement variables and on the M1 measurement variable for cranial elements (Fig.2.4; 2.5). The construction of the regression models for the various cod elements is detailed in the following subsections 2.2.1 and 2.2.2.

2.2.1. Size estimations from vertebrae measurements

Raw measurement data from the modern reference specimens (Appendix.2.1) were log10 transformed and used as predictive measurement variables to construct 15 equations. The corresponding 15 regression models were used to estimate TL values for each of the morphological groups and for vertebrae 1 to 5 individually (Fig.2.4; Appendix.2.2). The models were based on known ecological equations (Fryxell et al., 2014; McClanahan et al., 2007), and included multiple regressions with and without interaction terms.

Vertebrae number was initially added as a predictive variable in the suite of models, however these equations were ultimately omitted. This was done due to the fact that,

with the exception of the first vertebrae and the AV1 group, (Appendix.2.2), it is not possible to consistently and accurately identify individual vertebrae numbers from archaeological materials. Geometric Morphometric analysis (GMM) was considered as a method for the estimation of vertebra number, but excluded in the interest of creating a time-efficient and accessible methodology, and due to the paucity of research on the utility of the method for this purpose (Dombrosky et al., 2022; Guillaud et al., 2016; Morales Muniz et al., 2021; Samper Carro et al., 2018).

The variables CW, CH, and LL were used as predictive variables for all of the morphological groups, while LH was added solely to the CV groups (as a ratio with the other variables) to further improve the accuracy of their regression models, as explained at the end of the section. Calculations were performed on the averaged measurement variables for the AV2 and AV3 groups due to minimal size variation between vertebrae within the group and to avoid an artificial inflation of sample sizes (Appendix.2.3; S.2.1). For caudal vertebrae, all individual measurements were included in the regression models for reasons explained below.

The suites of regression models were compared using AICc (Akaike information criterion for small sample sizes) to identify the model with the best trade-off between goodness-of-fit and number of parameters in estimating TL (Appendix.2.4). The use of AICc thus provides a systematic method to select the models that best fit the training data. The AICc formula was defined with the *model.sel()* function in R, as $AICc = n \cdot \log P(m) + n \cdot (1 + m/n) / (1 - (m + 2)/n)$, where n is the sample size; m is the dimension of the candidate model; and P(m) is the white noise variance fitted to the data by maximum likelihood (Hurvich & Tsai, 1989).

The highest-ranked equations in the AICc selections were chosen as the final regression models for each of the morphological vertebrae groups and for vertebrae 1 (FV) to 5 (V2 – V5). The highest ranked models are those with the lowest AICc values relative to the other models, providing a relative measure of out-of-sample predictive power. The goodness of fit of the selected models was assessed by observing the R² values and the residual standard error ranges of the models. The predicted TLs from the regression models were also compared to the original TL data (Appendix.2.5).

The vertebrae in the CV groups display an incremental size decrease with increasing vertebrae number (Appendix.2.3), which lowered the initial accuracy of their regression models and made it necessary to include individual measurements per vertebra rather than means per variable (inflating artificially the sample size, as multiple observations from the same individual were included in the regression analyses). To improve their predictive accuracy, equations were constructed through a two-step process. Firstly, ratios of the measurement variable LH and the three measurement variables CW, CH, and LL (none being log10 transformed for this purpose) were ranked by their accuracy in estimating vertebrae number via AICc. The ratios of CW/LH and LL/LH ranked highest for the CV1 and CV2 groups, respectively. Secondly, the highest ranked ratios of measurement variables were incorporated into the regression equations as interaction terms or as multiple regression coefficients to estimate TL. The final suite of models was then put through an AICc selection to determine the most accurate equations for the CV groups.

The AICc-selected models were subsequently used to generate estimates of TLs (via the *predict()* function in R) using measurements of archaeological cod vertebrae from Lyminge (S.2.2). For added validation, the TL estimates generated from the *predict()* function were compared with TL estimates calculated from manual equations (Appendix.2.4; S.2.2; S.2.4; S.2.5).

2.2.2. Size estimations from cranial measurements

The legacy dataset of cranial measurements of modern reference specimens was used to construct additional regression models for cod TL estimates from the M1 measurement variable (Results Section 3.3; Fig.2.5).

The studied cranial elements are all paired and (in cod) exhibit negligible variation between sides. Regression calculations were thus performed on the averaged measurements of the left and right side to avoid artificial inflation of sample size.

For each element a suite of three regression models was constructed with and without log10 transformation of the raw data (Appendix.2.4; S.2.3). The suite of models was put through an AICc selection process to determine the most accurate model for each element and implemented (with the *predict()* function in R) for the new cranial measurements of cod from Lyminge taken by the author R.Blevis, and also for

previously collected measurements from Coppergate taken by J.Harland (S.2.4; S.2.5). Note that vertebrae measurements were not available from Coppergate due to limited access to the assemblage. For added validation, the TL estimates generated from the *predict()* function were verified through comparisons with TL estimates calculated from manual equations (Appendix.2.4; S.2.2; S.2.4; S.2.5).

2.3. Retrieval and identification of archaeological cod elements

The vertebrae and cranial elements of cod from Lyminge were recovered from both 5 mm sieved material and from 1 mm flotation subsamples (S.2.5; S.2.6). The archaeological elements were morphologically identified with the aid of osteological reference collections (specified in Methods and materials Section 2.1.3). The morphological identifications of *Gadus morhua* were verified with aDNA analysis (n = 37) at the Centre for Ecological and Evolutionary Synthesis (CEES), University of Oslo. The skeletal elements selected for aDNA analysis were photographed with the OM-D E-M5 Mark III digital camera with focus stacking options, and Olympus M.Zuiko Digital ED 60 mm f2.8 Macro Lens. Morphological identifications of *Gadus morhua* were also compared to data available in atlases (Archaeological Fish Resource, 2020; Cannon, 1987; Gravendeel et al., 2002; Harland et al., 2003).

2.4. Estimations of cod biomass and fecundity

The estimated TLs of the archaeological cod remains were converted into biomass with the following equation: $Biomass(g) = 0.00730 \times TL(cm)^{3.052}$ (S.2.7). The equation was constructed from a sample of 5,346 specimens from the North Sea with a TL range of 7.5 cm – 126.5 cm (Wilhelms, 2013).

The estimated TLs were also converted into fecundity values with the following equation: $Fecundity = 0.123 \times (TL(cm)^{3.760})$ (S.2.7). The equation was constructed from a sample of 50 specimens from the Barents Sea with a TL range of 55 cm – 135 cm. Fecundity is defined per unit of body weight, i.e. relative fecundity (Marshall et al., 1998). An equation based on Barents Sea data was selected because North Sea cod of sizes comparable to the archaeological specimens from Lyminge and Coppergate are no longer available.

2.5. Zooarchaeological analysis of additional taxa

The fish bone assemblage from the 2009 excavation of Lyminge was subject to several zooarchaeological procedures to obtain cod elements for size estimations through regression analysis, and to better understand the nature of fishing and fish processing activities at the sites. These procedures are described in the following sections.

2.5.1. Quantification

All fish remains, i.e. each bone from the Lyminge assemblage, were recorded individually with morphological skeletal element identifications and taxa identifications (i.e. family, genus and species). These recordings were performed with Excel and Access spreadsheet and database software.

Various frequency calculations were based on the number of identified (skeletal) specimens (NISP), following Klein & Cruz-Urbe, 1984. NISP are widely utilised in zooarchaeological research due to several advantages: NISP values are easily calculated; they highlight taxa diversity; they contain numeric data for quantitative analysis; and they highlight relative abundances of fish vs. other taxa such as mammals, birds, and molluscs (Klein & Cruz-Urbe, 1984, 24 - 25; Lyman, 1994; Reitz & Wing, 1999).

Despite these advantages, NISP values do not correct for interdependence of individuals, due to taphonomic disarticulation of the skeletal elements, nor of skeletal elements, due to taphonomic fragmentation. NISP counts can thus lead to multiple counting of the same individual and/or the same element and can falsely inflate sample sizes of skeletal elements and taxa. To address the issue of interdependence in this research, identifications of skeletal elements to element type, anatomic region and to taxa were recorded when elements were preserved $\geq 50\%$, decreasing the probability of inflating element sample sizes.

Furthermore, the mechanism producing this multiplicity is expected to be common to all taxa within the Lyminge assemblage, thus further addressing the interdependence of individuals and facilitating comparisons of relative quantifications of NISP counts from the identified taxa. Comparisons of relative frequencies of NISP counts is further enabled by the similar number of individual bones within fish skeletons of multiple species (Cannon, 1987). The contexts containing the fish bone assemblages further

negate interdependence issues at Lyminge, as the multiplicity of both rubbish pits ($n \sim 100$, Fig.2.1) and deposition episodes within them (as witnessed in several pits) lower the probability of multiple skeletal elements originating from the same individual. Interdependence of individuals can also be addressed through counts of Minimum Number of Individuals (MNI). MNI counts are calculated by tallying the skeletal elements of the right and left sides of a taxon, and using the higher number as the final estimate (Lyman, 2008). MNI counts are well established in analysis of archaeological mammal remains, but are less common in the analysis of fish remains. Implementations of MNI counts for fish bones is complicated by both the relative lack of studies on archaeological fish remains compared to mammals (Wheeler & Jones, 1989), and by the higher numbers of unique skeletal elements in most fish taxa. Estimates of unique elements in fish approach 250 elements, many of which are difficult to identify morphologically, compared to estimates of 40 elements in mammals (Colley, 1990; Warren, 2023). MNI counts were completed on the fish bone assemblage from Lyminge despite these constraints, as they could address the overinflation associated with NISP counts (Results Section 3.9.1).

2.5.2. Skeletal representation

Skeletal representation was calculated by tallying each bone identified to element and side (left, right, midline) and grouping them by cranial and post-cranial regions and by more specific anatomic location (Cannon, 1987; Harland et al., 2003; Wheeler & Jones, 1989). Skeletal representation analysis was done to determine if whole fresh fish or processed products, such as stockfish, were present at the study sites (Barrett, 2004; Harland & Barrett, 2012; Orton et al., 2014; 2017).

2.5.3. Taxonomic composition

Identification of fish taxa was based on a predetermined list of diagnostic cranial and post-cranial bones (Harland et al., 2003; Leach, 1986; Wheeler & Jones, 1986). The list of diagnostic bones was determined by examining both the skeletons in the reference collections and the data available in atlases (Archaeological Fish Resource, 2020; Cannon, 1987; Gravendeel et al., 2002; Harland et al., 2003). Identifications of the archaeological taxa aids in reconstructing the exploited fishing grounds and the dietary preferences of the site's inhabitants.

Previously unutilized cranial elements and vertebrae (n = 37, see section 2.3) of cod underwent morphological analysis for identification to species level and subsequent aDNA analysis (n = 9) to determine if they were successfully identified morphologically (Atmore, 2023). The three chosen cranial elements for this analysis included the branchiostegal ray, palatine, and the symplectic (Fig.2.6). These chosen elements were compared with other gadid species to check for morphologically unique characteristics. The additional gadid species included bib (*Trisopterus luscus*) haddock (*Melanogrammus aeglefinus*), ling (*Molva molva*), pollock (*Pollachius pollachius*), poor cod (*Trisopterus minutus*), saithe (*Pollachius virens*), and whiting (*Merlangius merlangus*).

Certain skeletal elements are morphologically similar to a high degree in cod and close species, challenging taxonomic identifications of archaeological bones. Close species to cod include pollack (*Pollachius pollachius*), pouting (*Trisopterus luscus*), saithe (*Pollachius virens*) and whiting (*Merlangius merlangus*). The similarities observed in these species have prompted explorations of unique morphological traits to assist in species identifications. A key study by Watt, Pierce and Boyle (1997) has detected the unique morphological traits of premaxilla and vertebrae elements in cod and close species (Appendix.2.6). This study has greatly assisted in the process of identifying the aforementioned species in the present research.



Figure.2.6. Previously unutilized cod (*Gadus morhua*) cranial elements selected for morphological identifications to species. From top to bottom: branchiostegal ray, palatine, symplectic. The right lateral view is displayed for all elements.

2.5.4. Taphonomic surface modifications

Fish bones identified to skeletal elements were examined with the naked eye and under a stereoscopic microscope for fragmentation patterns indicative of cut marks; state of fragmentation (i.e. the percentage of preserved bone); potential pathologies and signs of burning (Harland et al., 2003; Shipman et al., 1984; Stiner et al., 1995; Zohar, 2004; Zohar et al., 2016).

The identification and interpretation of the cut marks from the Lyminge assemblage was based on previously studied medieval fish bone assemblages in the region, following Barrett, 1997; Harland, 2006, and Jones, 1991.

For the purpose of this research, cut marks were defined as straightened grooves on the bone's surface containing straight, sharp edges along each side of the groove. Identified cut marks were photographed with a Dino-Lite Edge digital microscope.

Cut marks are less visible on fish bones compared to mammal bones (Willis & Boehm, 2014; Willis et al., 2008). Nonetheless, they are often indicative of different preservation methods and can appear as a result of the following butchery activities: decapitation, gutting, filleting, and splitting (Barrett, 1997; Cerón-Carrasco, 1998; Hamilton-Dyer, 2001; Harland, 2006; Harland & Barrett, 2012; Willis & Boehm, 2014).

The interpretation of the identified cut marks was based on their categorization into six unique butchery processes defined in Barrett, 1997. The categories include the following: tongue or hook removal (1); gut, tongue or cheek removal (2); decapitation along the transverse plane (3); gutting along the sagittal plane (4); splitting the vertebral column along the sagittal plane (5); and severing the vertebral column along the transverse plane (6). The construction of these categories followed observations of correlations between the type of performed butchery process and the type of skeletal element containing the cut mark.

The state of fragmentation (i.e. the level of bone preservation) was determined for each skeletal element by comparing it both to the complete, modern element from the reference collection, and to the skeletal element "zones" defined in Harland et al., 2003. Next, the state of fragmentation for each recorded element was defined as a percentage of completeness between 10% to 100%. The assessment of the state of fragmentation is important in evaluating and countering biases from destructive taphonomic processes.

Burnt bones were determined by colour (Shipman et al., 1984; Stiner et al., 1995; Zohar et al., 2016). Exceptionally white and grey bone colourings were defined as burnt, as experimental studies showed that fire temperatures over 500 °C resulted in white or grey coloured bones (Nicholson, 1996; Shipman et al., 1984, 312 - 314). Identification of signs of burning on the bones may suggest domestic cooking activities or burning of domestic refuse.

2.5.5. Taphonomic and methodological biases

The relative taxonomic abundances present in fish bone assemblages (detailed in Methods and materials Section 2.5.3) are usually affected by several taphonomic and methodological processes. These processes must be accounted for when interpreting such assemblages. To guide the interpretation of the Lyminge fish bone assemblage, the four main processes responsible for affecting relative taxa abundances have been summarised below.

1. Sieve size- large sieve sizes employed to retrieve assemblages can bias against the recovery of small bones, and can lead to false inflation of mean archaeological TL values, and to false underrepresentation of smaller sized taxa (Zohar & Belmaker, 2005).
2. Skeletal element preservation- varying sizes and fragility of different skeletal elements often leads to increased preservation of more robust bones and increased fragmentation of fragile bones. This overrepresentation of robust skeletal elements can skew interpretations of fish processing activities at study sites. Such activities include determining if whole fish were transported to the site, and determining if fish were decapitated and butchered for preservation and trade purposes.
3. Skeletal element size and intricacy- the complexity of identifying fish taxa and their skeletal elements in the archaeological record varies by the size of the element and its number of unique morphological characteristics. This complexity leads to false underrepresentation of taxa possessing smaller skeletal elements with ambiguous morphological features. Different taxa possessing morphologically similar skeletal elements further complicate taxonomic identifications (Wheeler & Jones, 1989).

4. Sample size and interdependence- smaller sample sizes of fish bones may inaccurately reflect the compositions of both skeletal elements and species in the assemblages. There is also a potential risk of falsely inflating sample sizes due to a lack of sample independence. As previously mentioned in Methods and materials Section 2.5.1, multiple samples can originate from the same individual, which could lead to falsely inflated sample sizes. Such sample sizes can lead to false relative quantifications of the identified taxa (Harland et al., 2016). The implications of this interdependence on interpretations of relative taxonomic quantifications at Lyminge were discussed in Methods Section 2.5.1, and are expanded further in Discussion and conclusions Section 4.5.

2.5.6. Size estimations of additional taxa

Regression models from the published literature were applied to the cranial and vertebral elements of the identified fish species available from Lyminge (S.2.8). The cranial regression models follow Enghoff, 1994; Jones, 1991; Klippel & Sichler, 2004; and Watt et al., 1997. Vertebrae models follow Klippel & Sichler, 2004, and Watt et al., 1997. The elements available for size estimations from each taxon at Lyminge are summarised in Table.2.1.

The resulting graphs of the estimated TLs of the available fish species are plotted separately for cranial and vertebrae elements due to differences in accuracy. Specifically, the vertebrae regression equations are constructed for the most anterior caudal vertebrae for all the species in Table.2.1 (Watt et al., 1997). The morphological characteristics of such vertebrae are usually unidentifiable in the archaeological record. To utilise the vertebrae regression models from the literature and obtain additional fish size estimations, all identified caudal vertebrae (CV) are used in lieu of the most anterior caudal vertebrae. The interpretations of the estimated sizes of the discussed taxa subsequently focus more on the cranial regression models which are more accurate.

The regression models from the existing literature are also applied to the cod elements from Lyminge. The use of cod elements in new cranial regression models is detailed in Methods and materials Section 2.2, while their use in vertebrae regression models is shown in Table.2.1. This analysis enables comparisons between the estimated cod

TLs from the newly constructed models in this research and from the preexisting models in the literature.

Table.2.1. Skeletal elements of the Lyminge species used in regression models from the existing literature for TL estimates

Common Name	Species	Element	Reference
Eel	<i>Anguilla anguilla</i>	Cleithrum	Enghoff, 1994
Flounder	<i>Platichthys flesus</i>	First anal pterygiophore	Enghoff, 1994
Flounder	<i>Platichthys flesus</i>	Premaxilla	Watt et al., 1997
Flounder	<i>Platichthys flesus</i>	CV	Watt et al., 1997
Pollack	<i>Pollachius pollachius</i>	Dentary	Jones, 1991
Pollack	<i>Pollachius pollachius</i>	CV	Watt et al., 1997
Haddock	<i>Melanogrammus aeglefinus</i>	Cleithrum	Jones, 1991
Haddock	<i>Melanogrammus aeglefinus</i>	CV	Watt et al., 1997
Whiting	<i>Merlangius merlangus</i>	Premaxilla	Watt et al., 1997
Whiting	<i>Merlangius merlangus</i>	CV	Watt et al., 1997
Plaice	<i>Pleuronectes platessa</i>	Premaxilla	Watt et al., 1997
Plaice	<i>Pleuronectes platessa</i>	CV	Watt et al., 1997
Herring	<i>Clupea harengus</i>	CV	Watt et al., 1997
Cod	<i>Gadus morhua</i>	FV	Enghoff, 1994
Cod	<i>Gadus morhua</i>	CV1	Watt et al., 1997

2.6. Data storage and code

Raw data was recorded in Excel and in Access software and stored as CSV files (D.2.1-D.2.5). Graphical representations, regression models and calculations were executed in R (R Core Team, 2023) with the following libraries:

car, coin, dplyr, forcats, ggdist, ggplot2, ggpubr, here, hdrclde, ImpactEffectsize, muMIn, patchwork, plyr, readxl, rstatix, scales, tidyverse, writexl. Pertinent code is also included as supplementary material (S.2.1-S.2.8)

2.6. Scripts and datasets

Scripts

- S.2.1. AIC.SelectionsG.morhuaMean.R
- S.2.2. CodSizeLymByVertGroup1.R
- S.2.3. AIC.SelectionsG.morhuaMeanCran.R
- S.2.4. MartynModelsLymingeApplied.R
- S.2.5. LymCoppModCompare.R
- S.2.6. MartynBlevisSieveCompMEAN.R
- S.2.7. FecundityBiomassLymingeModern.R
- S.2.8. LymOtherSpeciesSizeReg2.R

Datasets

- D.2.1. AllVert36Spec17.2.22.CSV
- D.2.2. LymingeDatasetZooarch.CSV
- D.2.3. YorkMeasurementsMartyn.CSV
- D.2.4. CoppergateTLcodMartynReg.CSV
- D.2.5. CPUEarea4.5.10.2018.2022.CSV

3. Research results

Results of this research pertain to two main topics: Sections 3.1 - 3.8 concern the construction of regression models from cod skeletal elements for TL estimations (as a proxy for fish size) and their application to archaeological cod bones from the two archaeological study sites of Lyminge and Coppergate. Sections 3.9.1 - 3.9.6 include results from the zooarchaeological analysis of the fish bone assemblage from the 2009 Lyminge excavation (see Methods and materials Section 2.1.1). This zooarchaeological analysis served to obtain cod elements for the above-noted regression models, but also for the assessment of fishing and fish processing activities at Lyminge.

3.1. Subdivision of the vertebral column into morphological groups

Modern vertebrae were placed with confidence into the morphological groups V1 – V5, AV2 – 3, CV1 – 2 (Fig.3.1), following Methods and materials Section 2.1.4 and Appendix.2.2. As noted in the Methods and materials Section, FV and V2 – V5 were treated as single elements with individual regression equations. Within the groups AV2 and AV3, the vertebrae measurements display minimal variation in the CW, CH and LL measurements (Appendix.2.3). The minimal variation of the measurement variables within these groups support the use of pooled regression equations for each group, rather than analysis by individual vertebra number which cannot be inferred with confidence from archaeological material in any case. For CV1 and CV2 there is incremental change in size along the vertebral column, but attribution to individual vertebra number is not possible for disarticulated archaeological material. Thus pooled regression equations are also employed for these groups, with the addition of a variable that partly controls for position within the vertebral column (the ratio of CW/LH for CV1 and of LL/LH for CV2), as discussed above and in Methods and materials Section 2.2.1.

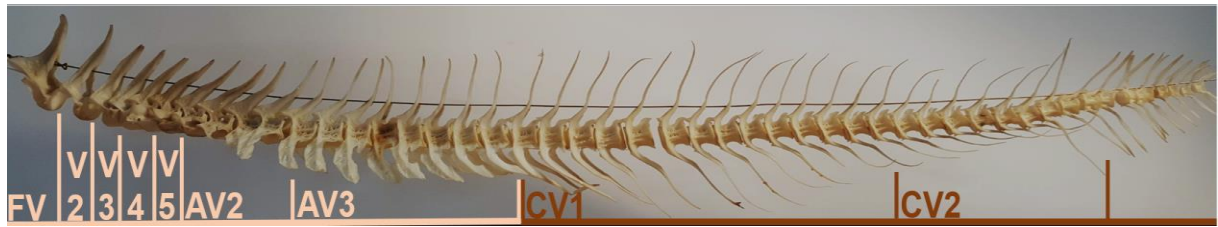


Figure.3.1. Division of the cod vertebral column into the morphological subgroups FV, V2 – V5; AV2; AV3; CV1; CV2.

3.2. Regression model construction from vertebrae for TL estimations

The modern vertebrae dataset ($n = 36$) represents a range of TLs between 15.5 cm and 150 cm, with an average of 74.95 cm and a standard deviation of 31.26 cm (Appendix.2.1).

The chosen regression equations result from the application of AICc selections to suites of potential models (Appendix.2.4; Methods and materials Section 2.2.1).

For most abdominal vertebrae groups, the selected regression models that best estimate TLs consist mostly of multiple regression equations without interactions (V1, V3, AV2, AV3). For the remaining groups, V2, V4, and V5, simple regressions were selected based on only a single measurement (Appendix.2.4, Table.A.2.4.a,b).

For the CV groups, the ratios of CW/LH (CV1) and LL/LH (CV2) rank highest in the AICc selections for estimations of vertebrae number. The regression models that best estimate TLs incorporate the CW/LH ratio and the LL/LH ratio as interactive terms for the CV1 and CV2 groups, respectively (Appendix.2.4, Table.A.2.4.a,b).

The regression equations for all the vertebrae groups have high R^2 values (0.97 – 0.99) and low residual standard error values (0.03 cm – 0.04 cm) when compared to the pooled vertebrae where groupings are not taken into account (Appendix.2.4, Table.A.2.4.b). The highest ranking models from the AICc selections for the AV and CV groups have error values < 0.05 ; R^2 values > 0.95 and display the best fits to the measured dataset (Appendix.2.4, Table.A.2.4.b). The fits of the selected models can be observed visually by comparing the estimated TLs from the regression models to the original cod TLs for all of the vertebrae groups (Fig.3.2). Distributions of predicted TLs based on the above-described regression models (Appendix.2.4) display similar patterns for all vertebrae groups (Appendix.2.5.A).

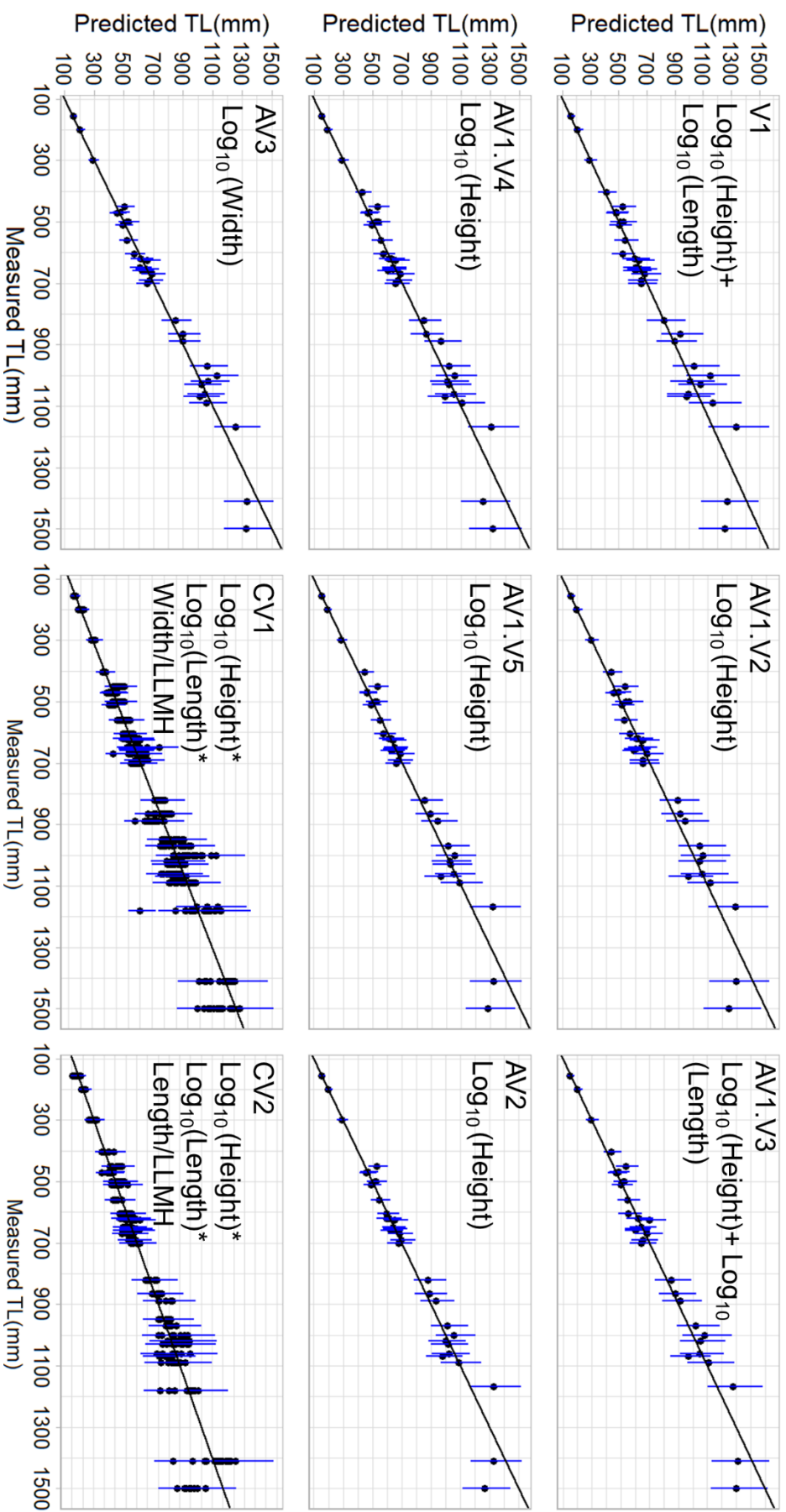


Figure 3.2. Predicted cod TLs based on nine vertebrae regression models vs. true TLs for vertebrae groups FV, V2 – V5, AV2, AV3, CV1, CV2, displayed left to right, top to bottom (Appendix 2.5; S.2.1). Vertical lines represent 95 % prediction intervals. LLMH = Left Lateral Minimum Height. Sample sizes for the regression models noted in Appendix 2.4, Table A.2.4.b.

3.3. Regression model construction from cranial elements for TL estimations

The modern cranial dataset consisted of several elements (Fig.2.5) with sample sizes between 74 and 91, and presents a range of TLs between 20 cm and 150 cm, with an average of 68.04 cm and a standard deviation of 24.15 cm.

The selected regression parameters result from the application of AICc selections to suites of potential models (Appendix.2.4, Table.A.2.4.c,d; Methods and materials Section 2.2.2). The regression models that best estimate TLs utilise response variables proportional to the log10 of the independent variables. The models that rank highest in the AICc selections have residual standard errors of ≤ 0.06 ; R^2 values > 0.85 and display the best fits to the measured dataset (Appendix.2.4, Table.A.2.4.d). The fits of the selected models can be observed visually by comparing the predicted TLs from the regression models to the original cod TLs from the cranial elements (Fig.3.3). Distributions of predicted TLs based on the above-described regression models (Appendix.2.4) display similar patterns for all cranial elements (Appendix.2.5.B).

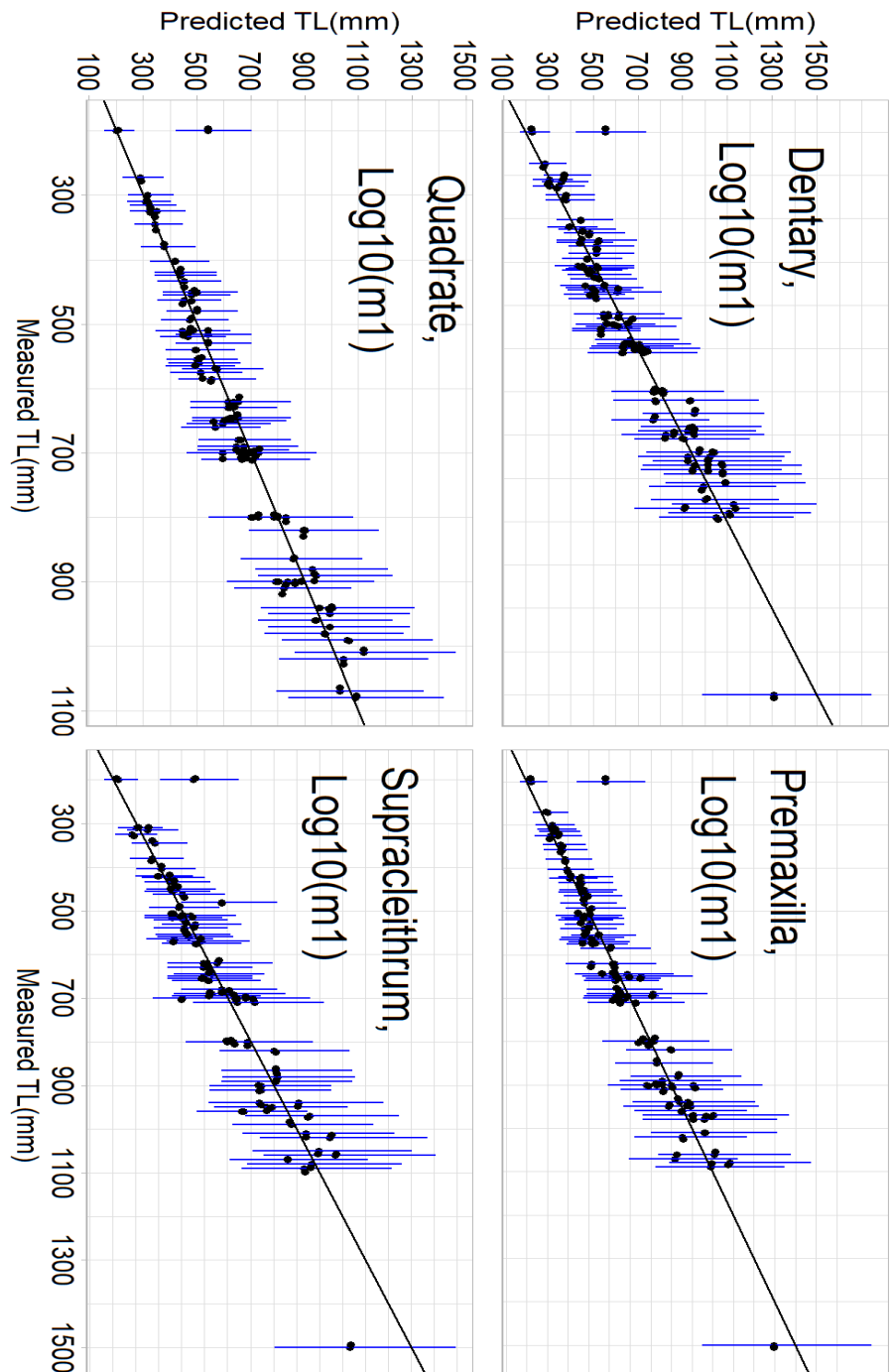


Figure.3.3. Predicted cod TLs based on four cranial regression models vs. true TLs for cranial elements, from top left corner, clockwise: dentary, premaxilla, supracleithrum, quadrate (Appendix.2.5; S.2.3). Vertical lines represent 95 % prediction intervals, sample sizes between 74 and 91.

3.4. Identification of cod elements from Lyminge

The morphological identifications of the cod bones to species level in this research (using reference specimens and atlases described in Methods and materials Section 2.3, see also Appendix.2.6) were verified through aDNA analysis ($n = 37$) at the Centre for Ecological and Evolutionary Synthesis (CEES), University of Oslo (Martinez-Garcia, P.C;D.3.1).

Cod vertebrae, most of which had not been used for species identification prior to this research (Introduction Section 1.6), were first classified into morphological groups (see Methods and materials Section 2.1.4 and Appendix.2.2) that were then used for species identification.

A sample of 37 morphologically identified cod bones were then genetically verified as *Gadus morhua*. These samples include previously unutilized skeletal elements, including the following: branchiostegal ray, palatine, symplectic, FV, and vertebrae from the morphological groups AV2, AV3 and CV1 (Fig.3.4).

The results of the aDNA analysis indicate that the morphological identifications of the Lyminge cod bones to species level are reliable and reflect the true nature of the fish bone assemblage. These results also reveal the potential use of new skeletal elements for species identifications. This is exemplified by the addition of several skeletal elements that can be reliably utilised to identify remains of *Gadus morhua*, as seen in this study (Fig.3.4).

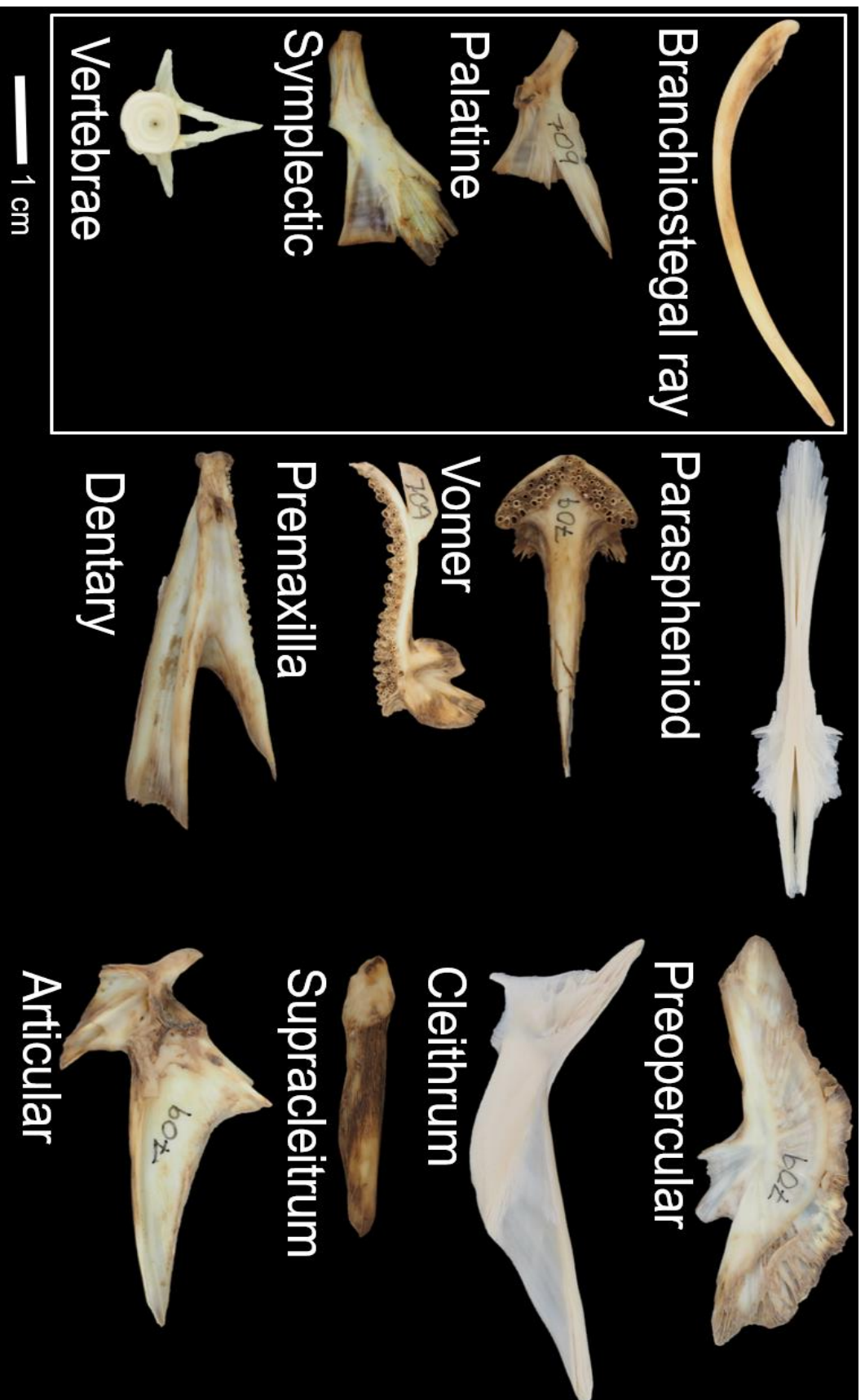


Figure.3.4. Cod skeletal elements morphologically and genetically identified as *Gadus morhua*. Previously unutilized skeletal elements are marked in the white box in the leftmost column (D.3.1).

3.5. Estimations of TL from archaeological cod remains

Measurements of the archaeological cod vertebrae ($n = 292$) and cranial elements from the Lyminge fish bone assemblage ($n = 38$) were incorporated into the selected regression models constructed in this research (Appendix.2.4). Predictions were calculated using the *predict()* function in R (v.4.0.2, R Core Team, 2023) (S.2.2; S.2.4). As previously mentioned, the cod elements from Lyminge were recovered from both 5 mm sieved material and from 1 mm wet sieving and flotation subsamples. The 1 mm flotation samples (56 vertebrae and 3 cranial elements) are omitted from cod size estimation analysis in this research due to volume differences (S.2.6). Specifically, the sample sizes sieved to 1 mm are significantly smaller than those sieved to 5 mm (detailed in Results Section 3.6). Assessment of potential recovery biases from the different sieve sizes in the next section reveals that most of the cod remains originated from the 5 mm material for both cranial and vertebral elements.

The legacy dataset from Coppergate yielded an assemblage of 206 cod cranial elements, recovered from bulk samples subjected to wet sieving to 1 mm followed by dry sieving to 2 mm, with the >2 mm fraction systematically analysed (Harland, 2016; P.C). However, only 38 elements had the M1 measurement available for the constructed regression models (Appendix.2.4). Estimated cod TLs from Lyminge ($n = 378$) are compared to those from the later site of Coppergate ($n = 38$) and to measured TLs from ICES bottom trawl survey data ($n = 118$) (Fig.3.5; S.2.5). The TLs from Coppergate were estimated using the *predict()* function in R with regression models constructed in this study (Appendix.2.4; S.2.5). The 95 % prediction intervals ($\pm 2\sigma$) are shown in Appendix.3.1 for the individual samples from Lyminge and from Coppergate (S.2.4; S.2.5).

TL data of modern cod from ICES bottom trawl surveys (hereby referenced as IBTS) originates from areas proximate to the archaeological sites to best mimic past fishing practices (Fig.1.1.A, Introduction Section; S.2.4; DATRAS Specification Document).

Summary statistics for the changes in TL estimations over time from the datasets are provided using mean, median, and interquartile values (Fig.3.5; Table.3.1; S.2.5). The TL distribution of the Lyminge dataset has a mode of 93 cm, with a range of 34 cm – 147 cm and an interquartile range of 33.72 cm. The corresponding modern dataset (areas 5 and 10 in Fig.1.1.A) has a mode of 20 cm with a range of 8 cm – 96 cm and an interquartile range of 25.75 cm.

The Coppergate distribution has a mode of 105 cm, with a range of 38 cm – 133 cm and an interquartile range of 25.75 cm. The corresponding modern dataset (area 5 and 4 in Fig.1.1.A) has a mode of 25 cm with a range of 5 cm – 87 cm and an interquartile range of 15.75 cm (Fig.3.5; Table.3.1; S.2.5).

Comparison of the cod TLs from Lyminge, Coppergate and from modern trawl survey data display a temporal decrease in size between the medieval sites and the present, with the differences between the archaeological and modern datasets being greatest and (given the small sample size of Coppergate) most meaningful for Lyminge (Fig.3.5; Table.3.1; S.2.5). The significant differences resulted from application of a Mann-Whitney-Wilcoxon test (with the *wilcox.test()* function in R) comparing the archaeological samples ($n = 378$ for Lyminge and $n = 38$ for Coppergate) and their corresponding modern samples ($n = 118$ for Lyminge-proximate area, and $n = 422$ for Coppergate-proximate area), both of which had $p\text{-value} < 0.001$ (S.5) and non-parametric effect sizes > 2.72 (with the *Impact()* function and *ImpactEffectsize* package in R) (Lötsch & Ultsch, 2020).

The archaeological and modern datasets were compared after the data was cut off at the first occurring high density point (Table.3.2) to account for size selectivity based on the criteria in Methods and materials Section 2.7 (at 50 cm TL for Lyminge and at 60 cm TL for Coppergate). The differences between the datasets were then compared with a Mann-Whitney-Wilcoxon test. The archaeological samples ($n = 367$ for Lyminge and $n = 35$ for Coppergate) and their corresponding modern samples ($n = 22$ for Lyminge-proximate area and $n = 16$ for Coppergate-proximate area) were significantly different, with $p\text{-value} < 0.001$ and non-parametric effect sizes > 1.77 for Lyminge and for Coppergate (S.2.5) (Lötsch & Ultsch, 2020).

The estimated TL distributions of the archaeological cod have a slightly wider range compared to the modern distributions from the bottom trawl surveys (Fig.3.5). As will be elaborated further in Discussion and conclusions Section 4.1, this wider archaeological TL distribution may suggest that these are closer to natural ecological ranges and subsequently to baseline TLs compared to modern distributions.

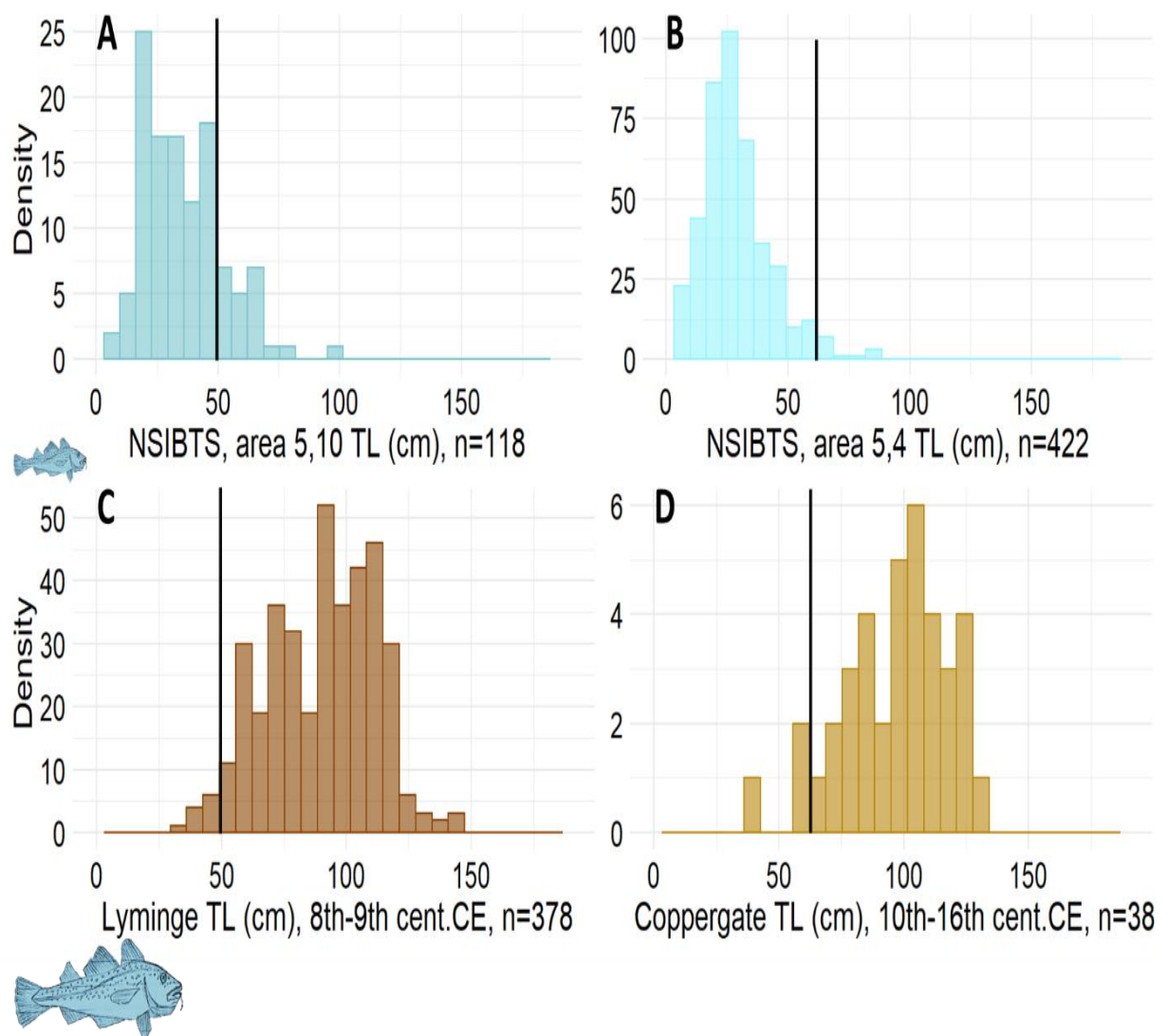


Figure.3.5. Histograms showing frequencies of cod TL (cm) ranges from: A. ICES bottom trawl survey data (NS-IBTS) between 2018–2022 (DATRAS Specification Document) for Lyminge-proximate area; B. ICES bottom trawl survey data for Coppergate-proximate area; C. archaeological Lyminge and C. archaeological Coppergate. Black lines mark the estimated TL threshold of gear and other (e.g. cultural, recovery) fish-size selectivity; bones of smaller fish did not routinely enter the archaeological record of the studied sites (S.2.5).

Table.3.1. Statistical measures of the estimated cod TLs from the archaeological and modern datasets before first occurring high density point cutoff. Modern.L and Modern.C mark the modern datasets compared to Lyminge and to Coppergate respectively. TL values are in cm (S.2.5).

Dataset	Mean TL	Median TL	Interquartile range TL	Standard Deviation	n
Lyminge	89.93	92.30	33.72	21.53	378
Modern.L	35.51	32.00	25.75	16.70	118
Coppergate	97.14	100.60	27.89	21.44	38
Modern.C	28.64	26.00	15.75	14.02	422

Table.3.2. Statistical measures of the estimated cod TLs from the archaeological and modern datasets after first occurring high density point cutoff. Modern.L and Modern.C mark the modern datasets compared to Lyminge and to Coppergate respectively. TL values are in cm (S.2.5).

Dataset after cutoff	Mean TL	Median TL	Interquartile range TL	Standard Deviation	n
Lyminge	91.59	93.24	32.93	20.16	367
Modern.L	61.54	60.00	13.30	10.79	22
Coppergate	100.99	102.81	24.19	17.26	35
Modern.C	68.94	66.00	10.00	9.04	16

For Lyminge only, it is possible to compare the TL estimates derived from cranial bones (n = 88) and vertebrae (n = 290). The estimated distribution of TLs from the vertebrae models have a higher mean and median value and a narrower range compared to the cranial models (Fig.3.6; S.2.6). The difference between the two models is significant based on a Mann-Whitney-Wilcoxon test (p-value < 0.001) and a non-parametric effect size of 0.64 (Lötsch & Ultsch, 2020), an observation that emphasises the value of using vertebrae for size estimates. This observation also suggests that the largest cod may have been decapitated for stockfish production (expanded in Discussion and conclusions Section 4.3).

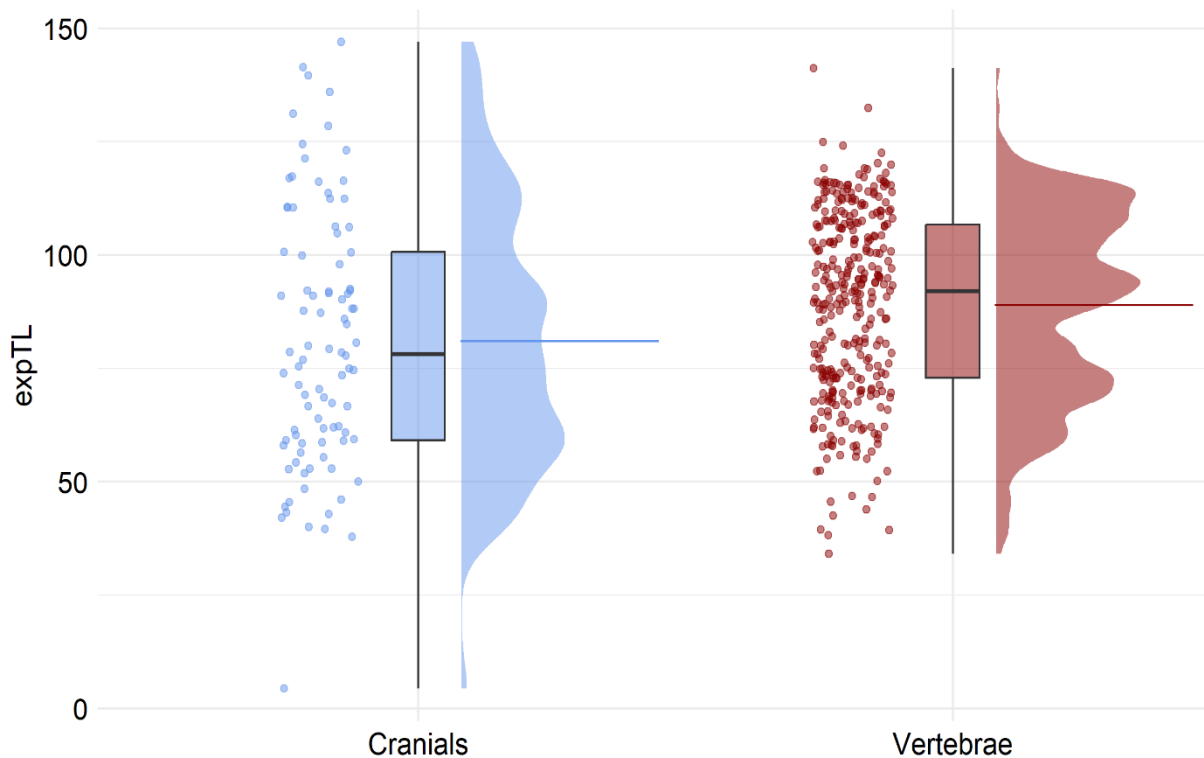


Figure.3.6. Estimated cod TLs (cm) from Lyminge presented as density, box and scatter plots. Vertebrae plots marked in red, cranial plots marked in blue (S.2.6).

The vertebrae TL distributions may include a positive bias from the CV regression models (Appendix.2.4), which were constructed with all values of multiple vertebrae from individual reference specimens without averaging, contrary to the averaged AV groups (Methods Section 2.2.2; Appendix.2.4, Table.A.2.4.a,b). This bias is likely insignificant, as the Lyminge vertebrae sample consisted mostly of abdominal vertebrae ($n = 191$) with only a smaller sample of the caudal vertebrae ($n = 99$) (S.2.6). Furthermore, the cranial and vertebrae TL distributions from Lyminge have similar values in the upper tails, indicating that a bias from the CV models is unlikely.

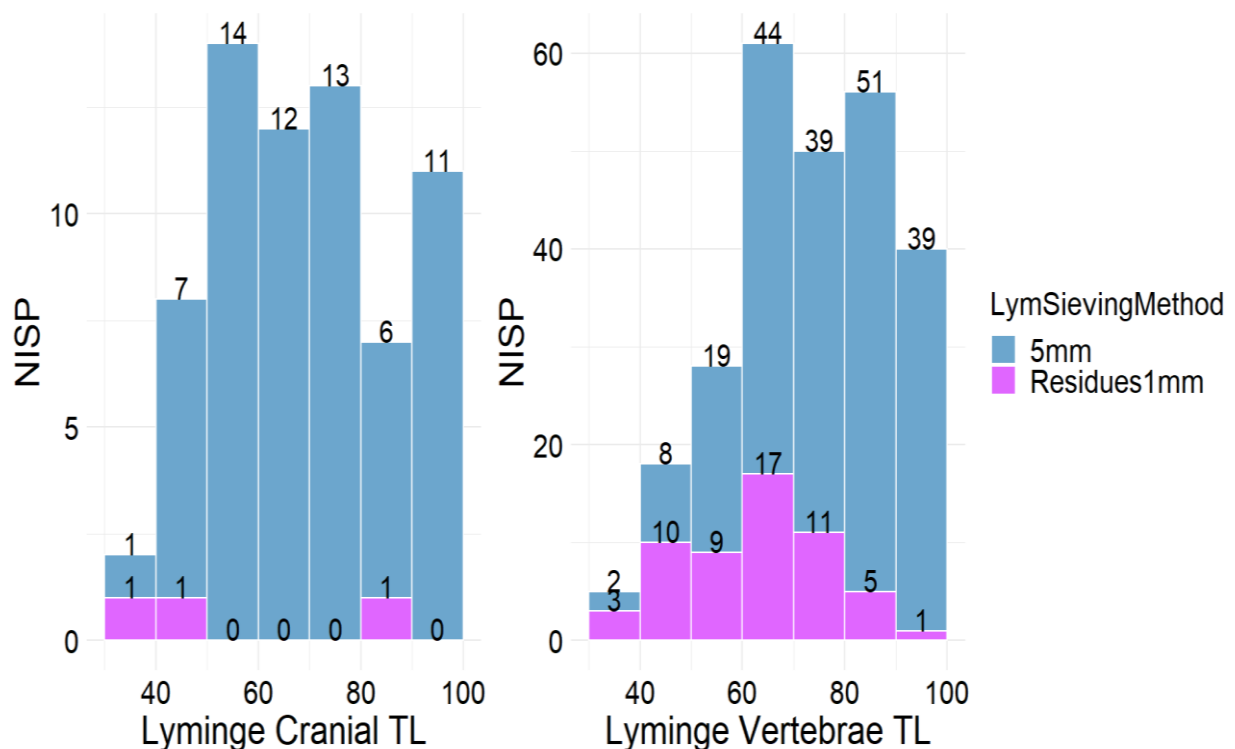
Inter-analyst variation; variation in the modern datasets utilised for cranial and vertebrae measurements; non-independence of the vertebrae measurements, and the prediction errors may also influence the TL distributions from the datasets and are expanded in Discussion and conclusions Section 4.3 - 4.4, however future research is needed to know the extent of influence. A similar comparison is not possible for Coppergate because vertebrae measurements are not part of the relevant legacy dataset (Harland et al., 2016).

3.6. Potential sieve size influences on TL estimations of Lyminge cod

The effects of sieve size on the frequencies of the estimated cod TLs from Lyminge are assessed in Fig.3.7.A;B. Both vertebrae and cranial elements of cod occur mainly in the 5 mm sieved material. The range of estimated cod TLs from the vertebrae elements is similar in the 1 mm flotation samples and 5 mm sieved material. The distribution does differ between the two, however, with the 5 mm assemblage having the same mode but a higher median and mean. The cod TL range from the cranial elements is larger in the 5 mm sieved material, but the number of cranial bones from the 1 mm samples is too small for this comparison to be meaningful.

Overall, the 5 mm dataset may show some bias against the smallest cod represented in the 2009 Lyminge assemblage. This bias is taken into account throughout the thesis by applying minimum estimated TL thresholds that reflect a combination of archaeological recovery, fishing gear and other (e.g. cultural) fish-size selectivity (see above).

A



B

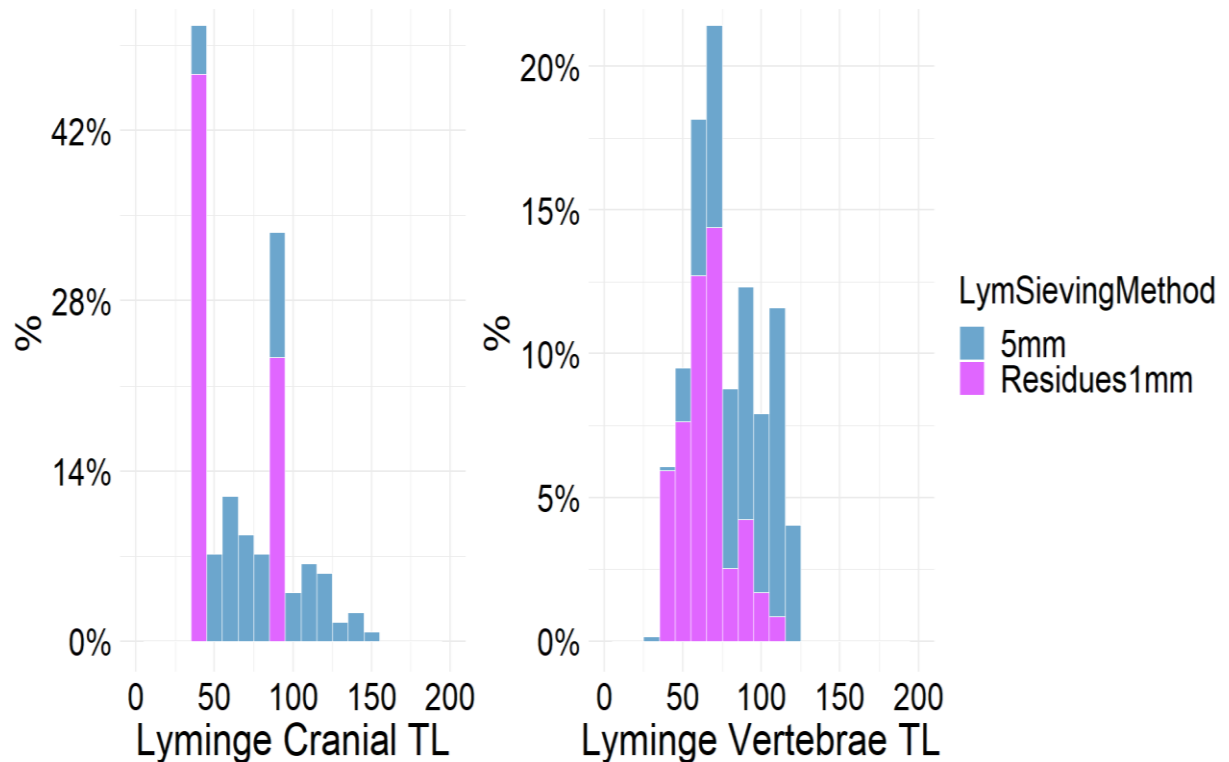


Figure.3.7. Histograms of estimated cod TLs (cm) from Lyminge, calculated for two main anatomic regions, cranials (left) and vertebrae (right): A. NISPs; B. Relative frequencies. Plots are coloured by sieving method. Relative frequencies marked as % of total NISP (S.2.6).

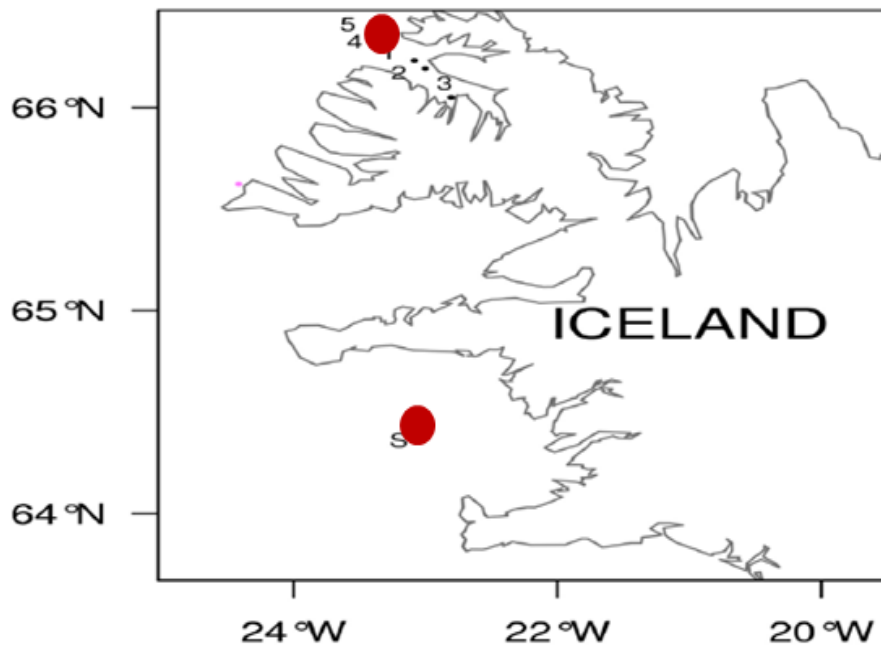
3.7. Gear selectivity influences on TL estimations of archaeological cod

As mentioned in Introduction Section 1.5.3, studies on the selectivity of different hook sizes on captured fish sizes (Grixti & Jones, 2007; Hardy, 1974; Owen & Merrick, 1994) have revealed that hook and line fishing occasionally selects against smaller fish, as the hooks must be smaller than the mouth size of the fish, but not against larger fish, as the range of selected hook sizes successfully captures larger fish (Owen & Merrick, 1994, Fig.3.7.A).

A previous case study on Atlantic cod assessing the selectivity of hook size on catch and body size was carried out on two geographically separated Icelandic cod populations (Fig.3.8.A;B). The southern cod population did not display any correlations between body size and hook size, while the northern population displayed a positive correlation when combined with smaller baits. A negative correlation between hook size and cod catches was observed for both populations, with smaller hooks selecting

for larger catches of cod. The study indicates that while a relationship between hook size and fish body size might exist, it likely only selects against smaller fish (lower TLs) (Ingólfsson et al., 2017).

A



B

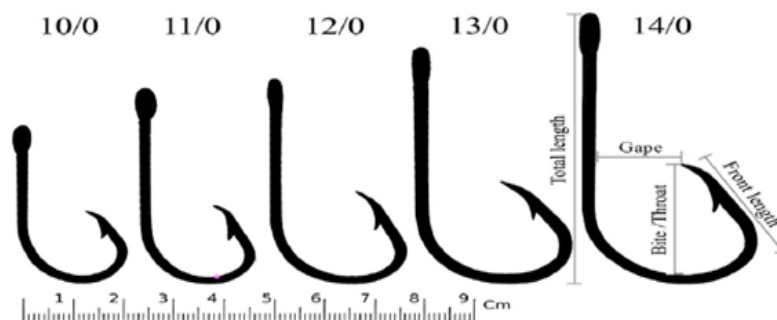


Figure.3.8. Gear selectivity study on cod: A. Map with the two studied cod populations marked in red circles; B. Hook sizes utilised in the study. From Ingólfsson et al., 2017, Fig.1, 2.

Hook and line was the likely gear type chosen to capture cod at Lyminge and Coppergate (Introduction Section 1.5.3). Considering the relatively large estimated sizes of cod from these sites, as compared with modern data (Fig.3.5), and based on the above studies of gear selectivity, a bias stemming from hook sizes is unlikely to affect the estimated upper cod TL ranges from the archaeological sites of Lyminge and

Coppergate. The lower ranges of the TL distributions may be slightly affected, however, as considered in the Discussion and conclusions Section 4.1.

To summarise Results subsections 3.6 and 3.7, estimated TL distributions from the archaeological sites of Lyminge and Coppergate are likely only slightly affected by gear type and recovery methods (i.e. hook and sieve size). These biases are accounted for when applying minimum estimated TL thresholds that reflect a combination of archaeological recovery, fishing gear and other (e.g. cultural) fish-size selectivity. In this way the archaeological TL distributions can be meaningfully and directly compared to modern TL distributions, after applying the same minimum TL thresholds.

3.8. Implications of TL estimations for biomass and fecundity

Conversions of the estimated TLs to relative fecundity (Fig.3.9; S.2.7) and to biomass (Fig.3.10; S.2.7) respectively, show the magnitude of shifts between the archaeological data from the study sites and modern distributions. Only Lyminge and the corresponding modern IBTS data are considered in this comparison, given the need to standardise for sample size and the much smaller number of measurements from Coppergate. The Lyminge data were randomly sampled (without replacement) to produce a smaller dataset of 118 measurements, matching the available IBTS data from ICES areas 5 and 10. Based on medians of the datasets ($n = 118$), the subsampled archaeological Lyminge assemblage displays a 1.4 fold higher fecundity (median = 6.50) and 27 fold higher biomass (median = 7614.64 g) vis-a-vis the modern IBTS data. Note that the scales of Fig.3.9 are in log₁₀ units. The modern and archaeological datasets were also significantly different based on a Mann-Whitney-Wilcoxon test ($p\text{-value} < 0.001$), with non-parametric effect sizes of 2.38 for fecundity and 1.81 for biomass (using the *Impact()* function and *ImpactEffectsize* package in R) (Lötsch & Ultsch, 2020). Applying the minimum fish-size thresholds noted above ($n = 43$), the differences remain striking for both fecundity (Lyminge being 1.4 fold higher than modern, with a median of 6.57) and biomass (Lyminge being 8 fold higher than modern, median = 9542.24 g) (Appendix.3.2; S.2.7). The differences were significant based on a Mann-Whitney-Wilcoxon test ($p\text{-value} < 0.001$), with non-parametric effect sizes of 2.48 for fecundity and 1.78 for biomass.

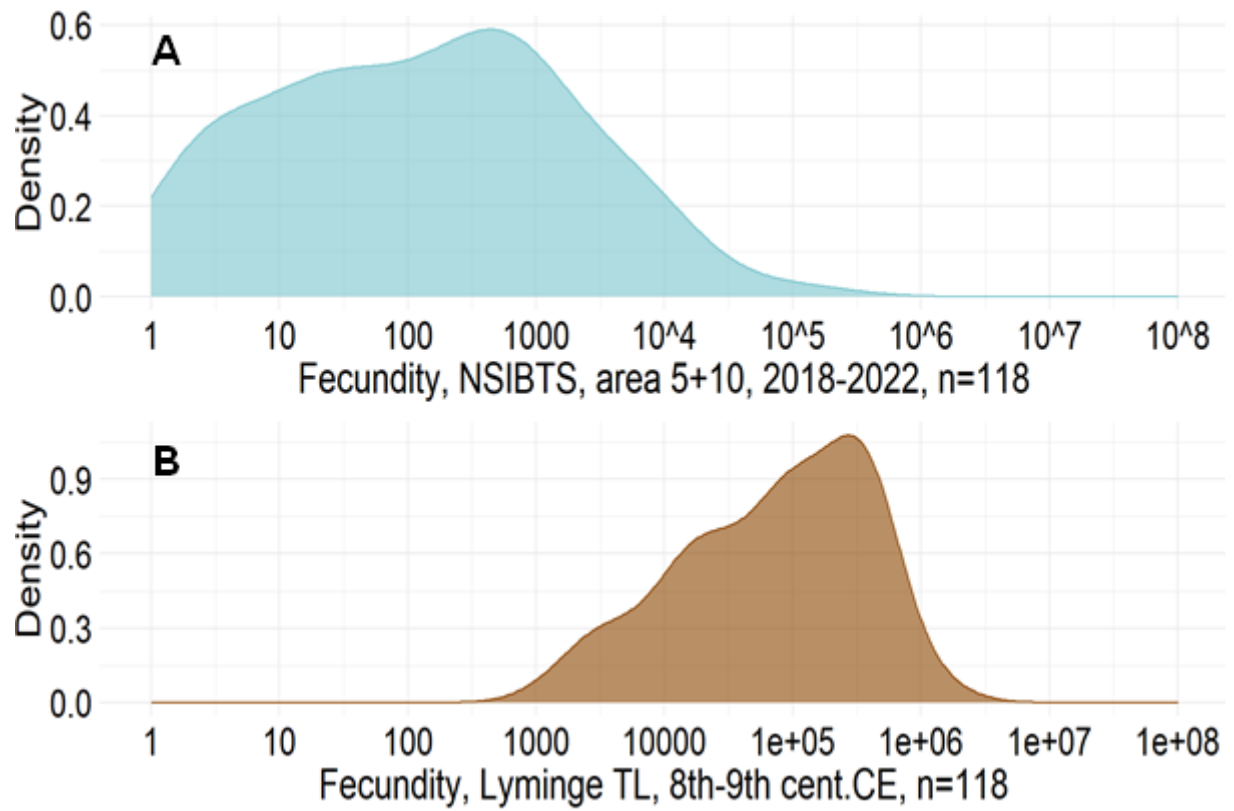


Figure.3.9. Density plots of potential fecundity estimates, based on cod TL (cm) estimates (as log10 data), for the Lyminge study areas: A. modern Lyminge-proximate area; B. Lyminge area (S.2.7).

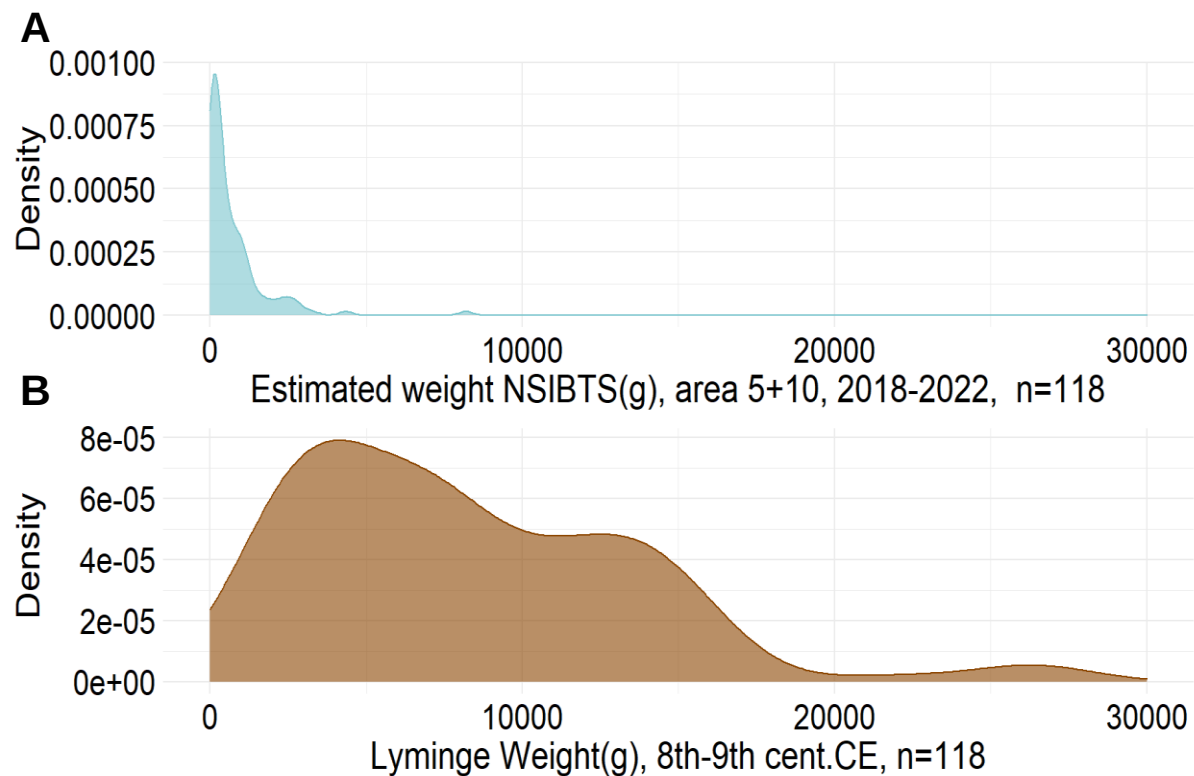


Figure.3.10. Density plots of potential biomass estimates, based on cod TL (cm) estimates: A. modern Lyminge-proximate area; B. Lyminge area (S.2.7).

3.9. Zooarchaeological analysis and size reconstructions of additional fish taxa from Lyminge

The following subsections (3.9.1 - 3.9.6) detail results from the analysis of zooarchaeological recordings and fish bone assemblage from the rubbish pits of the 2009 Lyminge excavation season (D.3.2). These results include taxonomic composition of the assemblage; skeletal element representation and aquatic habitats of the identified taxa; taphonomic modifications of the skeletal elements, and size estimations of identified species from Lyminge.

3.9.1. Quantification and taxonomic composition

A total of 4,296 fish bones from Lyminge were successfully identified to family level, with over 90 % further identified to genus and species (Table.3.3; S.3.1).

Table.3.3. NISP and relative frequencies of fish bones identified to taxonomic levels from Lyminge, from the combined 5 mm sieved material and 1 mm flotation samples. Relative frequencies marked as % of total NISP (S.3.1). A complete list of identified species is in Appendix.3.3.

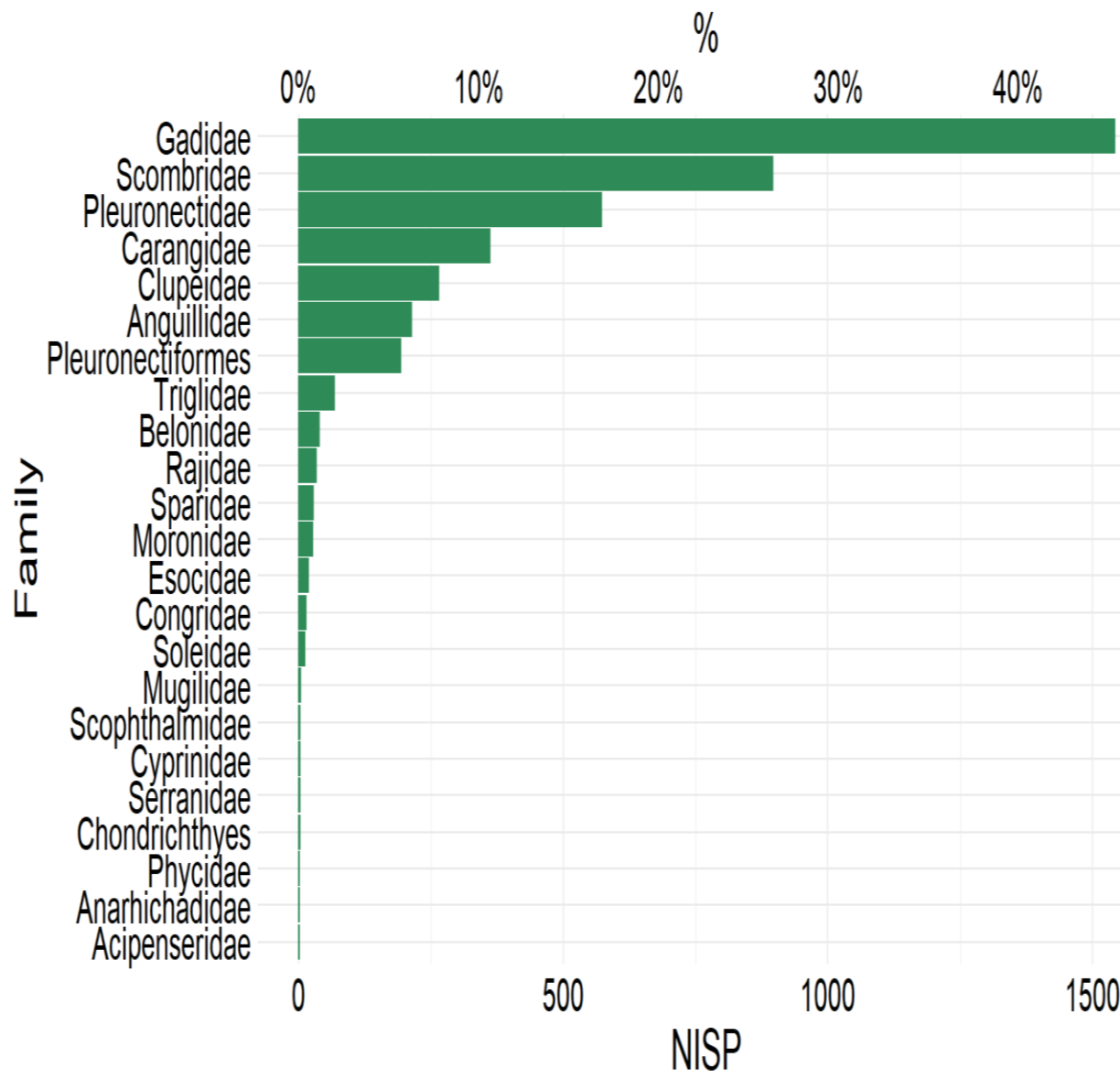
Lyminge fish bones	NISP	% NISP from Total
Identified Species	3,906	90.92
Identified Genus	3,911	91.06
Identified Family (Total)	4,295	100

The identified fish bones were classified into twenty-two individual families (Fig.3.11.A; S.3.1) according to the diagnostic skeletal elements available in the existing literature (Methods and materials Section 3.6.3). The assemblage is dominated by Gadidae (> 45 %), followed by Scombridae (> 25 %) and Pleuronectidae (> 23 %). Most of the identified bones are classified further into thirty-four individual species (Fig.3.11.B; S.3.1). The most common species (by % NISP) is Atlantic cod (*Gadus morhua*, > 26 %), followed by Atlantic mackerel (*Scomber scombrus*, > 20 %) and Atlantic Horse Mackerel (*Trachurus trachurus*, > 9 %) (see also Appendix 3.3).

The taxa identified at Lyminge were quantified through two counting methods, NISP and MNI (Table.3.4). The relative species abundances in both the NISP and MNI counts were compatible, i.e. the same species dominated the assemblage (Fig. 3.11.B; Table.3.4). The resulting MNI counts were consistently lower compared to NISP counts (Table.3.4). This result is unsurprising, as the two methods quantify taxa frequencies differently - NISP counts the number of identified (skeletal) specimens, while MNI counts the Minimum Number of Individuals (Methods and materials Section 2.5.1). Furthermore, elements that often inflate NISP values (e.g. vertebrae, fin spines, fin rays, and dermal denticles) were abundant within the Lyminge assemblage (further detailed in Results Section 3.9.3). For interpretations of taxa abundances (Discussion and conclusions Section 4.4) both measures could be used, and NISP was chosen due to its smaller relative error. The interpretations of NISP counts from Lyminge are further based on relative frequencies, which removes the aforementioned factor of inflation (see Methods and materials Section 2.5.1) .2454-2458

A sample of herring bones identified morphologically to species level, *Clupea harengus* (n = 9), utilising the following skeletal elements: dentary, maxilla, AV and CV (D.3.3), was subject to aDNA analysis at the Centre for Ecological and Evolutionary Synthesis (CEES), University of Oslo (Atmore, 2023; D.3.3). All nine sampled bones were genetically verified as Atlantic herring (*Clupea harengus*).

A



B

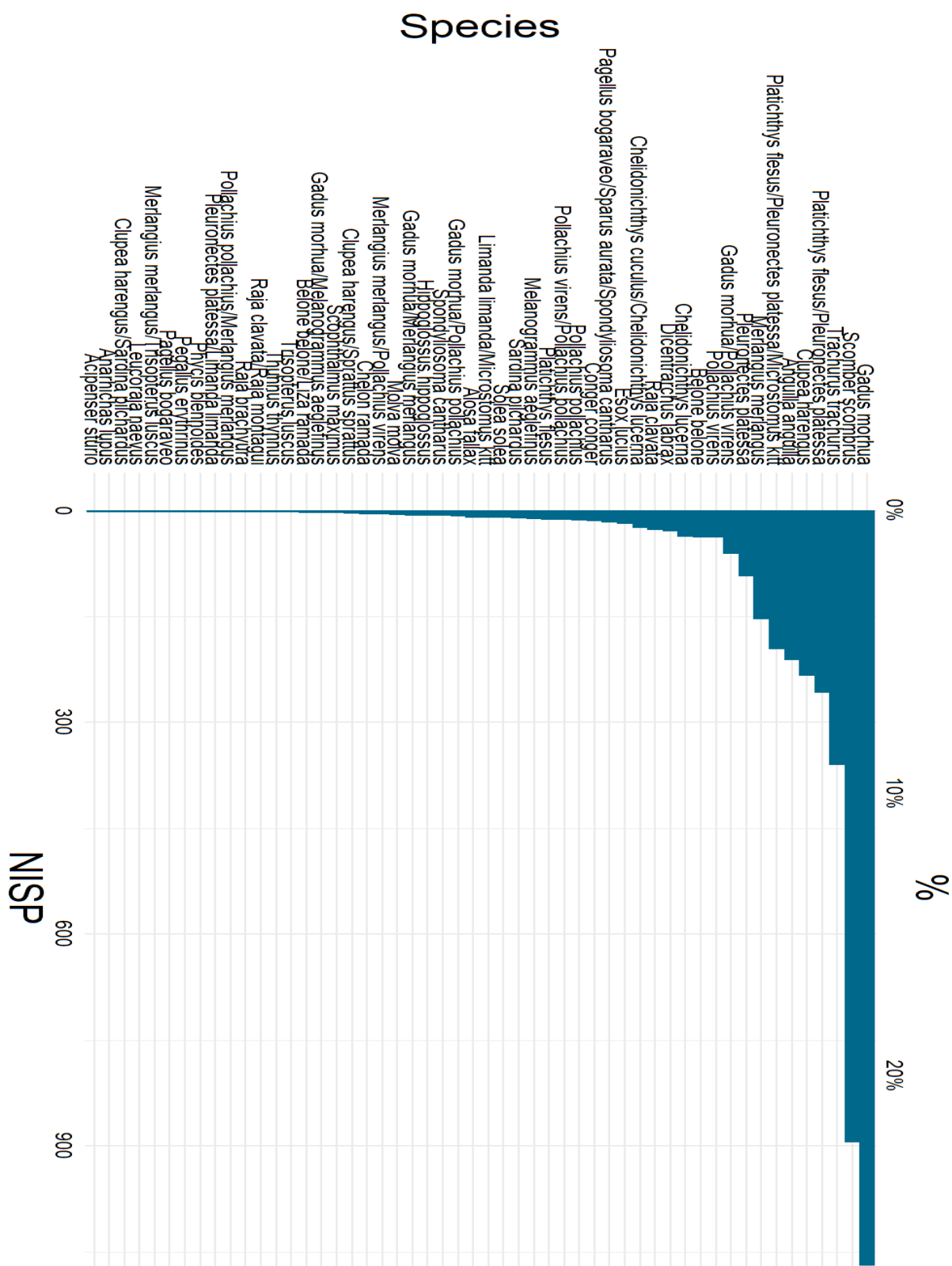


Figure.3.11. Bar charts of NISPs and relative frequencies of fish bones identified to taxonomic levels from Lyminge: A. Family; B. Species. Relative frequencies marked as % of total NISP. Plots displayed in ordered frequency counts (S.3.1).

Table.3.4. NISP and MNI values of the fish bones identified to species from Lyminge, listed alphabetically

Species	NISP	%	MNI	MNI Element
		NISP		
<i>Alosa fallax</i>	9	0.34	1	Cleithrum
<i>Anguilla anguilla</i>	195	7.47	1	Cleithrum
<i>Belone belone</i>	25	0.96	2	Articular
<i>Chelidonichthys lucerna</i>	13	0.50	2	Dentary
<i>Clupea harengus</i>	221	8.47	6	Dentary
<i>Conger conger</i>	8	0.31	4	Ceratohyal
<i>Dicentrarchus labrax</i>	25	0.96	4	Hyomandibular
<i>Gadus morhua</i>	643	24.64	23	Articular
<i>Hippoglossus hippoglossus</i>	6	0.23	2	Quadrate
<i>Melanogrammus aeglefinus</i>	9	0.34	2	Supracleithrum
<i>Merlangius merlangus</i>	153	5.86	5	Dentary
<i>Pagellus bogaraveo</i>	1	0.04	1	Premaxilla
<i>Platichthys flesus</i>	10	0.38	2	Premaxilla
<i>Pleuronectes platessa</i>	85	3.26	23	First anal pterygiophore
<i>Pollachius pollachius</i>	12	0.46	1	Dentary
<i>Pollachius virens</i>	35	1.34	1	Articular
<i>Sander lucioperca</i>	1	0.04	1	Quadrate
<i>Sardina pilchardus</i>	9	0.34	2	Opercular
<i>Scomber scombrus</i>	876	33.56	15	Hyomandibular
<i>Scophthalmus maximus</i>	2	0.08	1	Maxilla
<i>Solea solea</i>	7	0.27	1	Premaxilla
<i>Spondyliosoma cantharus</i>	6	0.23	1	Dentary
<i>Trachurus trachurus</i>	259	9.92	11	Dentary
Total	2610	100	112	

3.9.2. Sieving effects on additional identified taxa

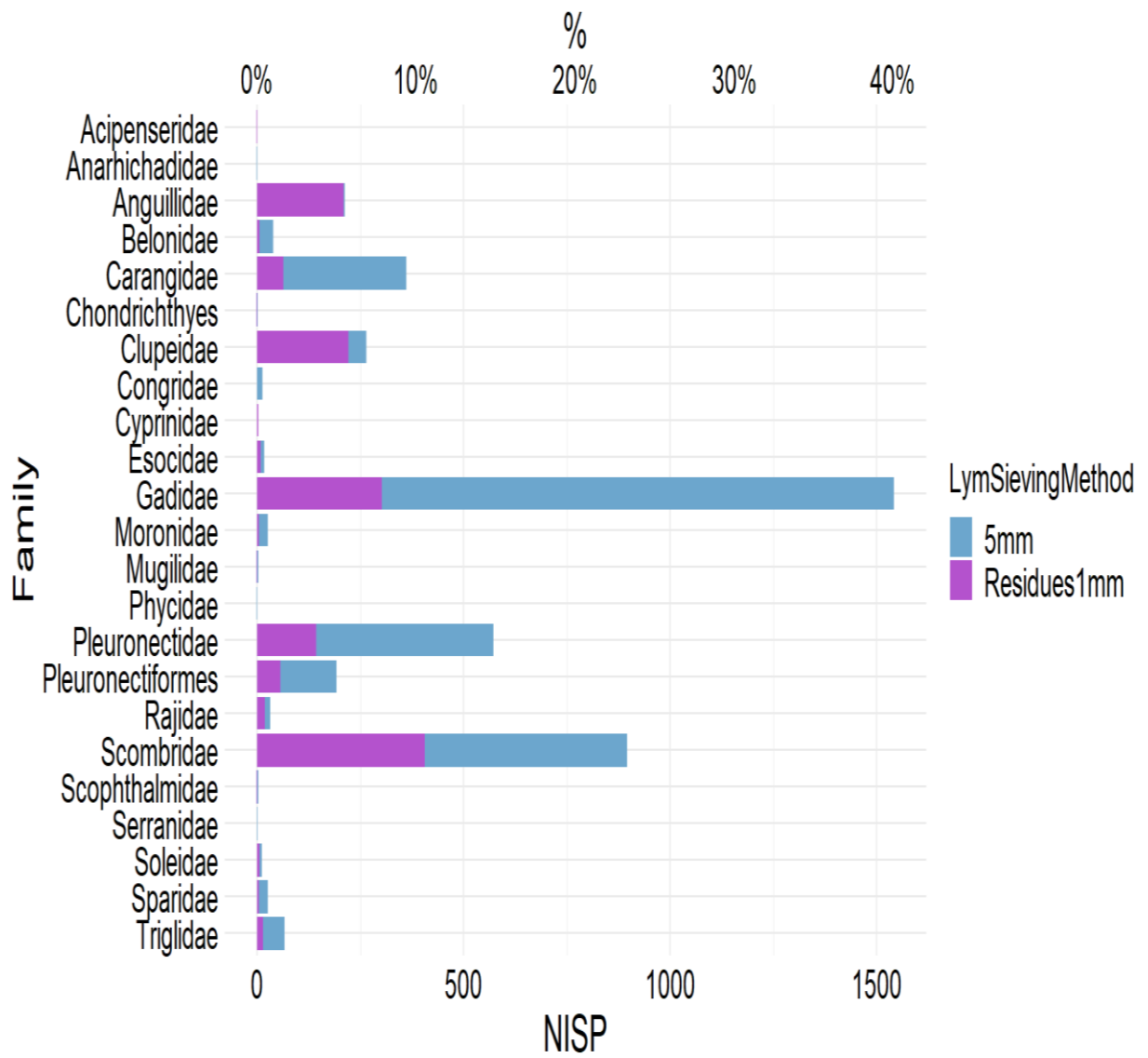
Identified taxa from Lyminge were mainly present in the 5 mm sieved material (65 %), with a smaller proportion present in the 1 mm flotation samples (34 %). This pattern is observed for all taxonomic levels: family, genus, and species (Table.3.5; S.3.1) and is visualised in Fig.3.12.A, B for families and species. This pattern is also observed, in

more detail, for cod elements, as reported in Results Section 3.6. All identified families and species from the two sieving protocols are listed in table form in Appendix.3.4.

Table.3.5. NISP and relative frequencies of fish bones identified to taxonomic levels from Lyminge from the 5 mm sieved material and 1 mm flotation samples (S.3.1). Relative frequencies marked as % of total NISP. A complete list of identified species is included in Appendix.3.4.

Lyminge fish bones	Identified Family	Identified Genus	Identified Species
NISP 5 mm	2,817	2,542	2,539
% 5 mm	65.60	65.00	65.02
NISP 1 mm	1,478	1,369	1,366
% 1 mm	34.40	35.00	34.98
NISP Total	4,295	3,911	3,906
% NISP from Total	100.00	100.00	100.00

A



B

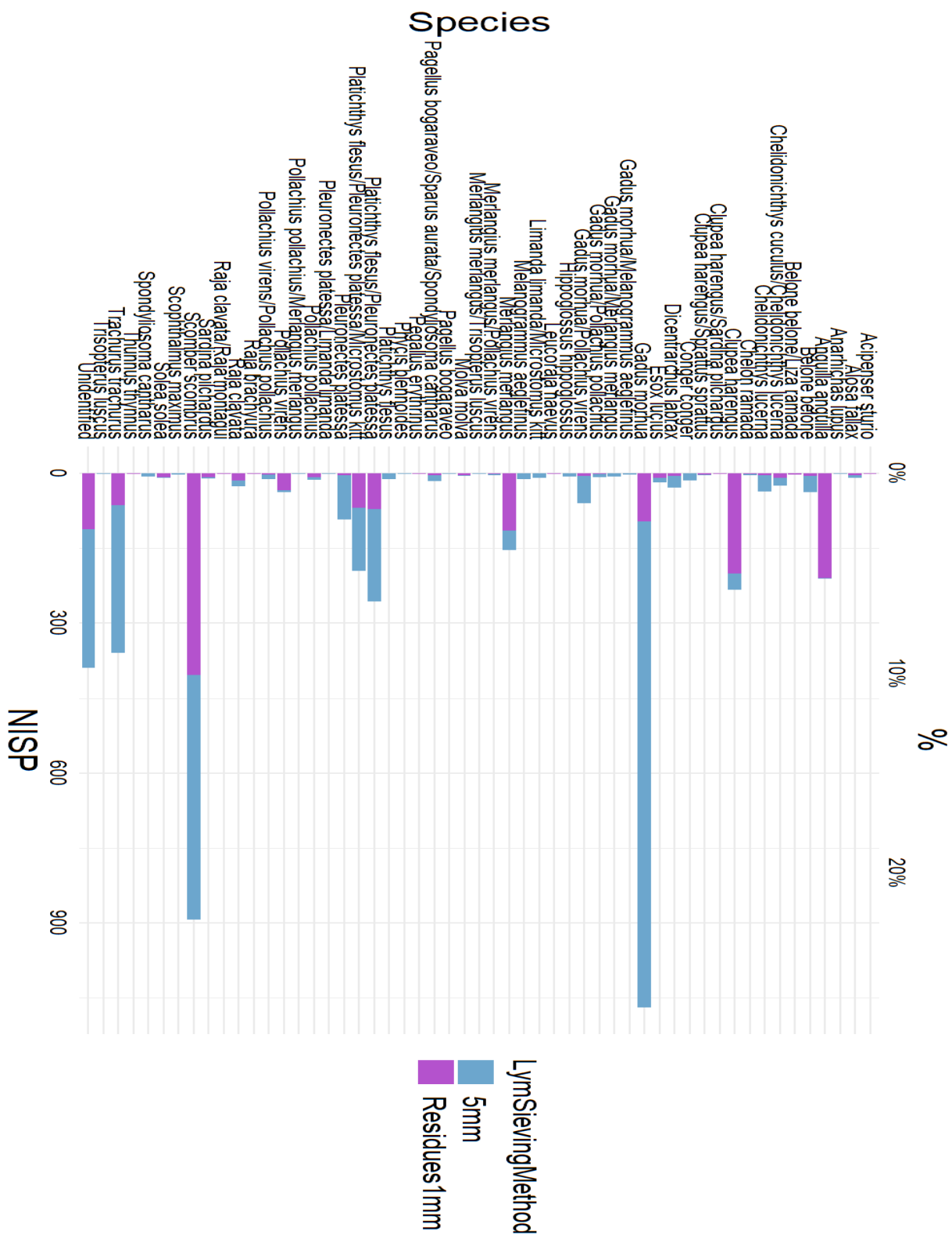


Figure.3.12. Bar charts of NISPs and relative frequencies of the identified fish bones from the 5 mm sieved material and 1 mm flotation samples from Lyminge, according to taxonomic levels: A. Family; B. Species. Plots are coloured by sieving procedure. Relative frequencies marked as % of total NISP (S.3.1).

The much higher representation (by NISP) of most of the select species in the 5 mm material (Fig.3.12) suggests that the employed sieving protocols strongly affect the observed taxonomic compositions in only a few cases, e.g. *Anguilla anguilla* (European eel), *Clupea harengus* (Atlantic herring), *Merlangius merlangus* (Whiting), and, to a lesser degree, *Scomber scombrus* (Atlantic mackerel).

The total weight (in grams) of fish bones recovered from the two employed sieve sizes was tallied for five identified species: *Anguilla anguilla* (European eel); *Clupea harengus* (Atlantic herring); *Gadus morhua* (Atlantic cod); *Scomber scombrus* (Atlantic mackerel) and *Trachurus trachurus* (Atlantic horse mackerel) (Fig.3.13). These species were chosen for weight analysis due to their relative dominance in the Lyminge assemblage (NISP counts between 211 and 1,080, see Fig.3.11) and their high ecological and economic significance (Introduction Section 1.5.1). Of these taxa, only eels and herring had higher weights in the 1 mm material than in the 5 mm assemblage. A complete list of the weights of all identified species from Lyminge is included in Appendix.3.5.

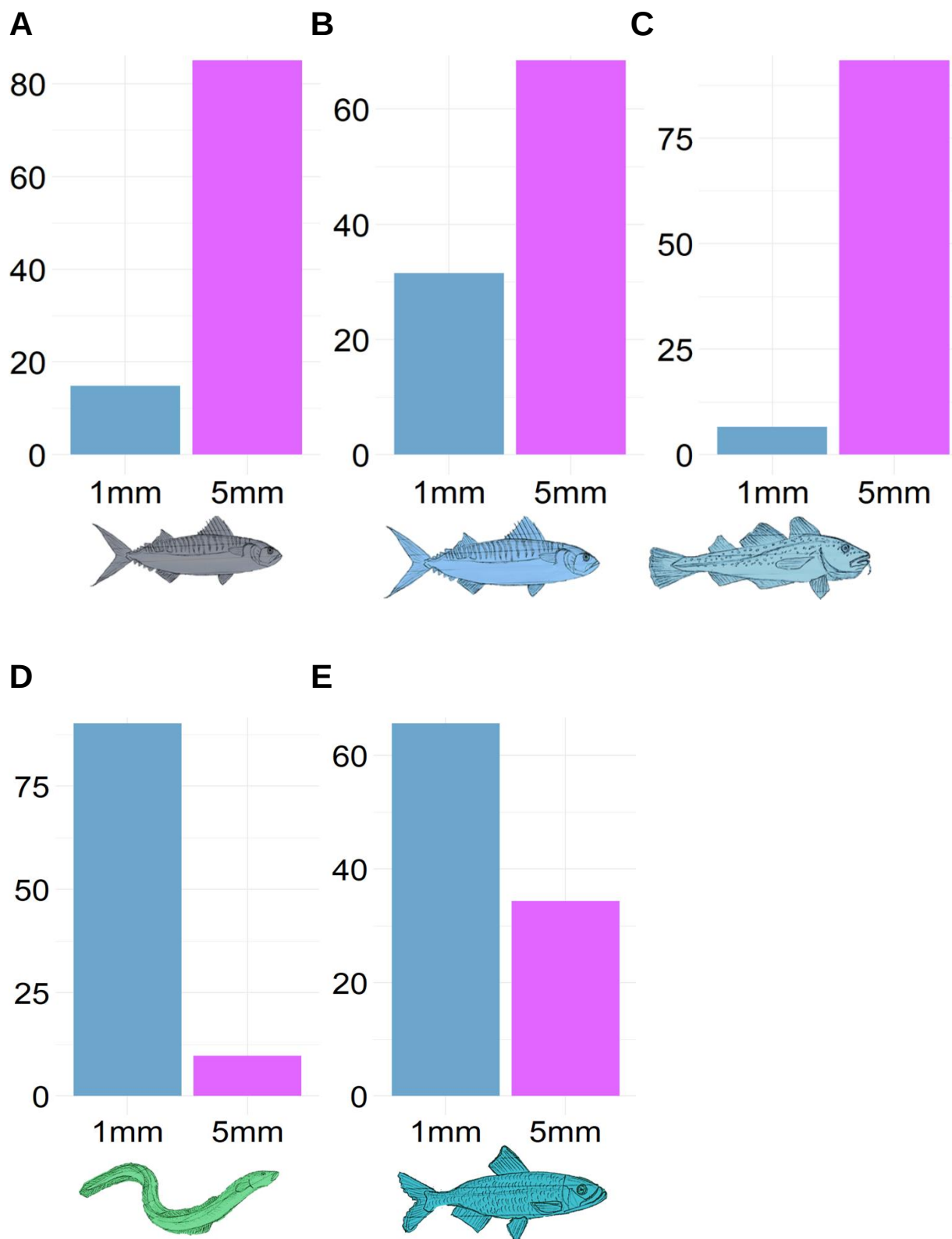


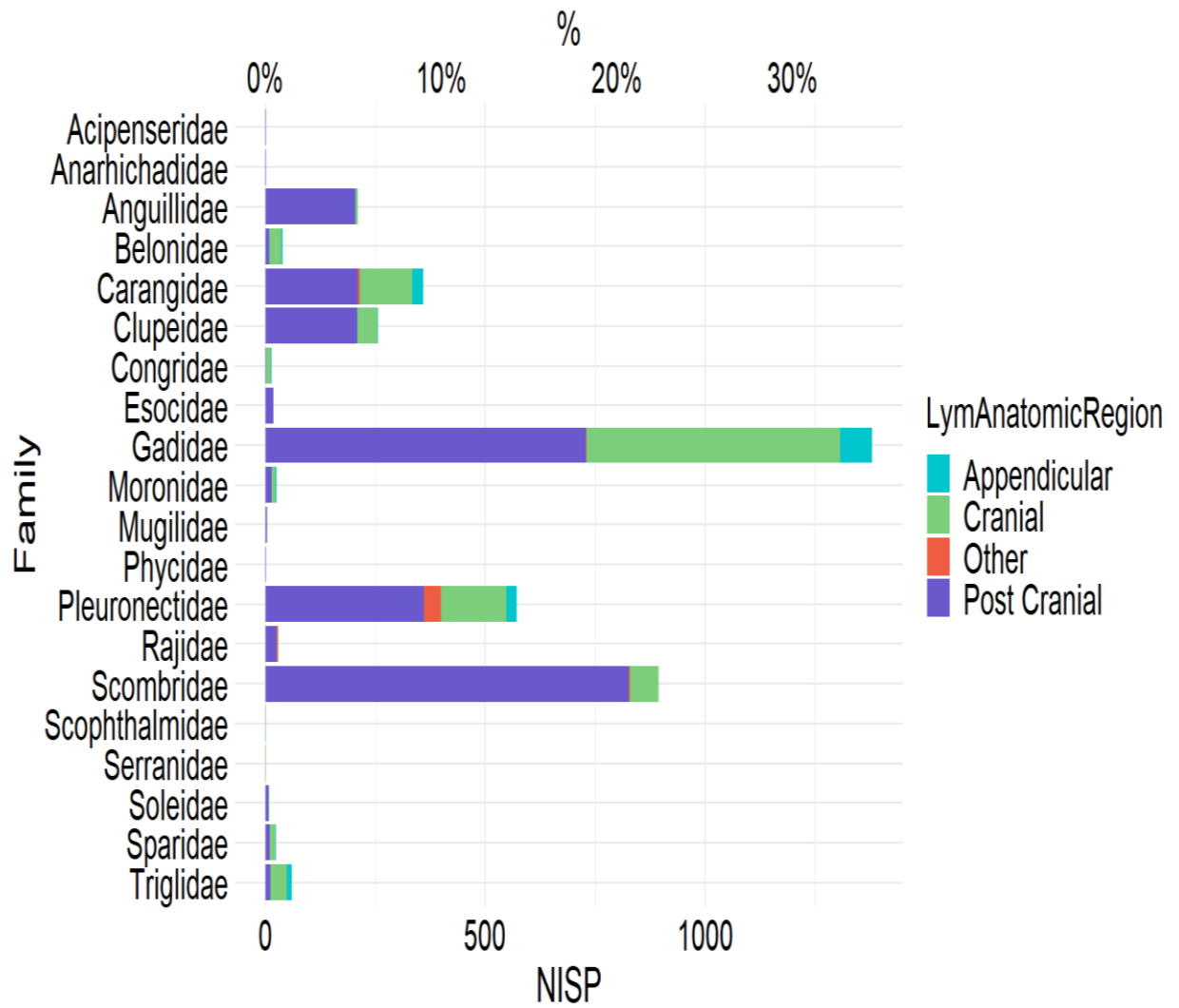
Figure.3.13. Bar charts of relative weights of the selected species vs. sieving method from Lyminge: A. Atlantic horse mackerel (*Scomber scombrus*); B. Atlantic mackerel (*Trachurus trachurus*); C. Atlantic cod (*Gadus morhua*); D. European eel (*Anguilla anguilla*); E. Herring (*Clupea harengus*) (S.3.1). Plots are coloured by sieving procedure. Relative weights marked as % of total weight.

3.9.3. Skeletal element representation

All three of the main anatomic regions of the fish skeleton: cranial, appendicular, and post cranial, are represented in the Lyminge assemblage to varying degrees (Fig.3.14). Six of the twenty-two total identified families (with NISP counts > 150) are represented by two or three anatomic regions: Anguillidae, Carangidae, Clupeidae, Gadidae, Pleuronectidae, and Scombridae. Five of the thirty-four total identified species (with NISP counts > 150) are similarly represented: *Clupea harengus* (Atlantic herring); *Gadus morhua* (Atlantic cod); *Merlangius merlangus* (Whiting); *Scomber scombrus* (Atlantic mackerel) and *Trachurus trachurus* (Atlantic horse mackerel). The identification of most anatomic regions from several families and species suggests the presence of whole fish of various taxa at Lyminge. Individual skeletal elements of all identified taxa from Lyminge are detailed in Appendix.3.6.

As further expanded on in Discussion and conclusions Section 4.3, the presence of both vertebrae and cranial cod elements (Fig.3.14.b) may indicate that cured fish products such as stockfish were produced for consumption and for trade at Lyminge.

A



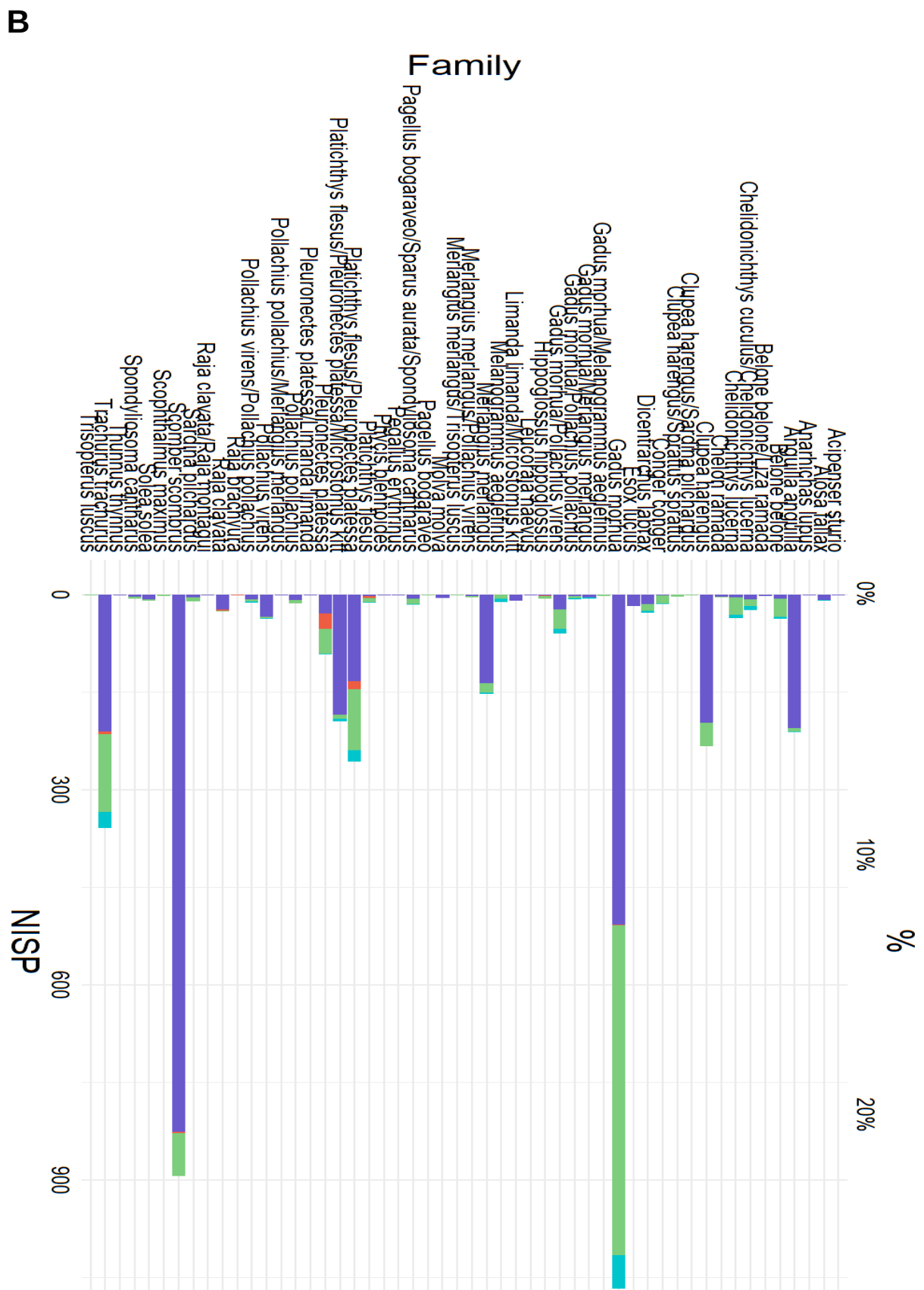


Figure.3.14. Bar charts of NISP counts and relative frequencies of identified taxonomic levels from Lyminge by anatomic region: A. identified families; B. identified species. Plots coloured by anatomic regions. Relative frequencies marked as % of total NISP (S.3.1).

3.9.4. Estimated aquatic habitats and fishing grounds

In the absence of published data on fishing grounds from the studied periods, published geographic distributions of modern species (Appendix.1) were used as proxies for the aquatic habitats of the Lyminge identified species, and as a first approximation for potential fishing grounds (Methods and materials Section 2.5.3; Froese & Pauly, 2023).

The identified taxa were estimated to have mainly originated from habitats in marine areas (Table.3.6; Fig.3.15.A). A smaller proportion were estimated to have originated from habitats in both marine and freshwater areas (i.e. euryhaline fish that tolerate a wide range of salinities). Fish from habitats in freshwater areas were the least represented (Table.3.6; Fig.3.15.A).

Marine habitats were mainly represented by the Gadidae family, followed by Scombridae and Carangidae, with NISP counts > 300 per family (Fig.3.15.B). Within these families, *Gadus morhua* (Atlantic cod) was the main species represented, followed by *Scomber scombrus* (Atlantic mackerel), and *Trachurus trachurus* (Atlantic horse mackerel), with NISP counts > 300 per species.

The closest marine habitat to Lyminge is the North Sea, containing 87 native families of fishes and comprising 195 species (Froese & Pauly, 1992). The identified marine taxa from Lyminge match families and species native to the North Sea (Fig.15.B;C). These taxa represent both littoral (e.g. Clupeidae, Pleuronectidae) and deep-sea (e.g. Gadidae) fishing areas.

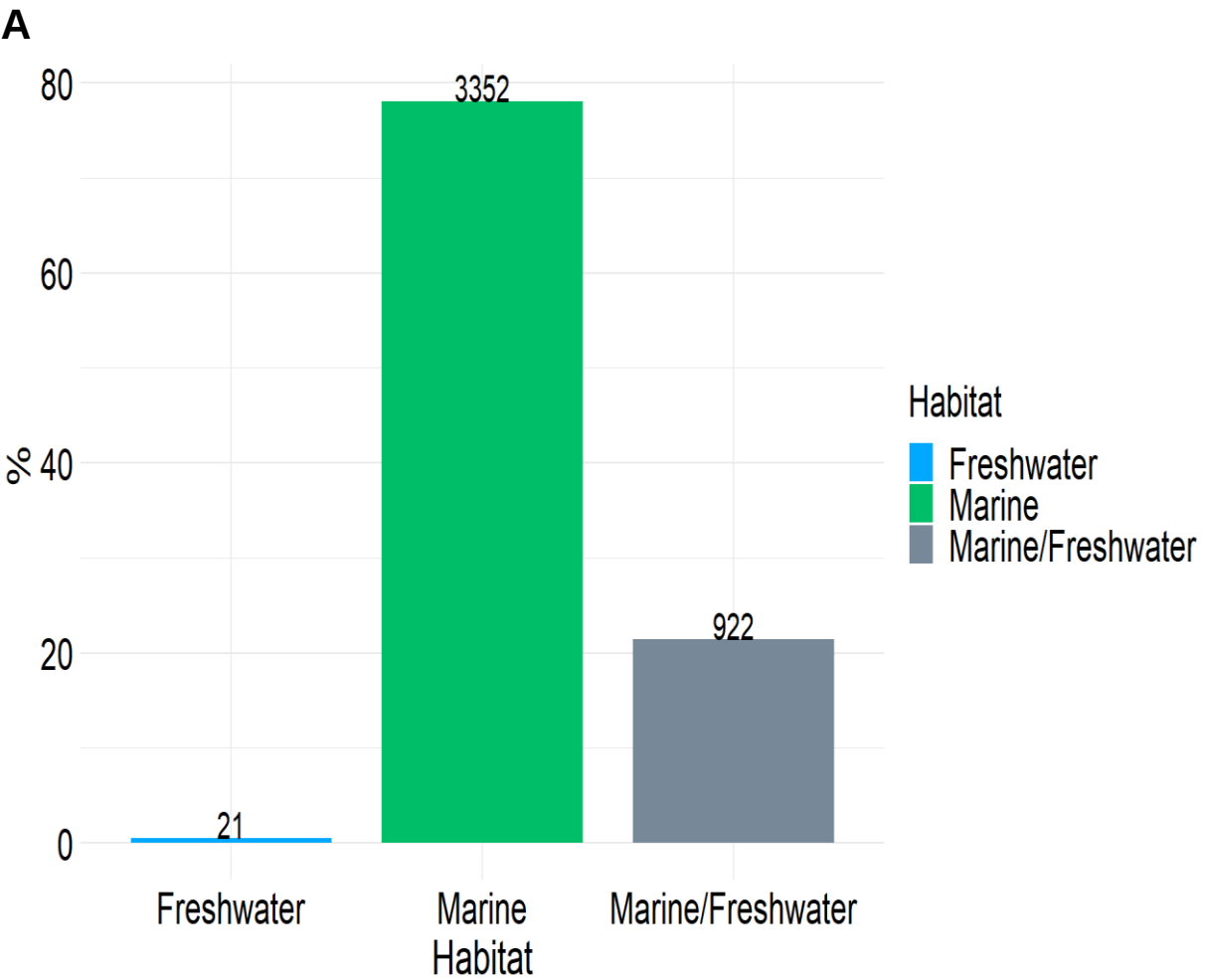
Marine/Freshwater habitats were mainly represented by the Pleuronectidae family, followed by Anguillidae, with NISP counts > 125 per family. The main genus/ species represented included *Pleuronectes*, *Platichthys* and/or *Microstomus* (of which only *Platichthys* is really marine/freshwater, the other two being marine), followed by *Anguilla anguilla* (European eel), with NISP counts > 200 per genus/ species.

Freshwater habitats were mainly represented by the Esocidae family, followed by Cyprinidae, with NISP counts < 20 per family. The main species represented included *Esox lucius* (Pike), with Cyprinidae unidentified to genus/ species.

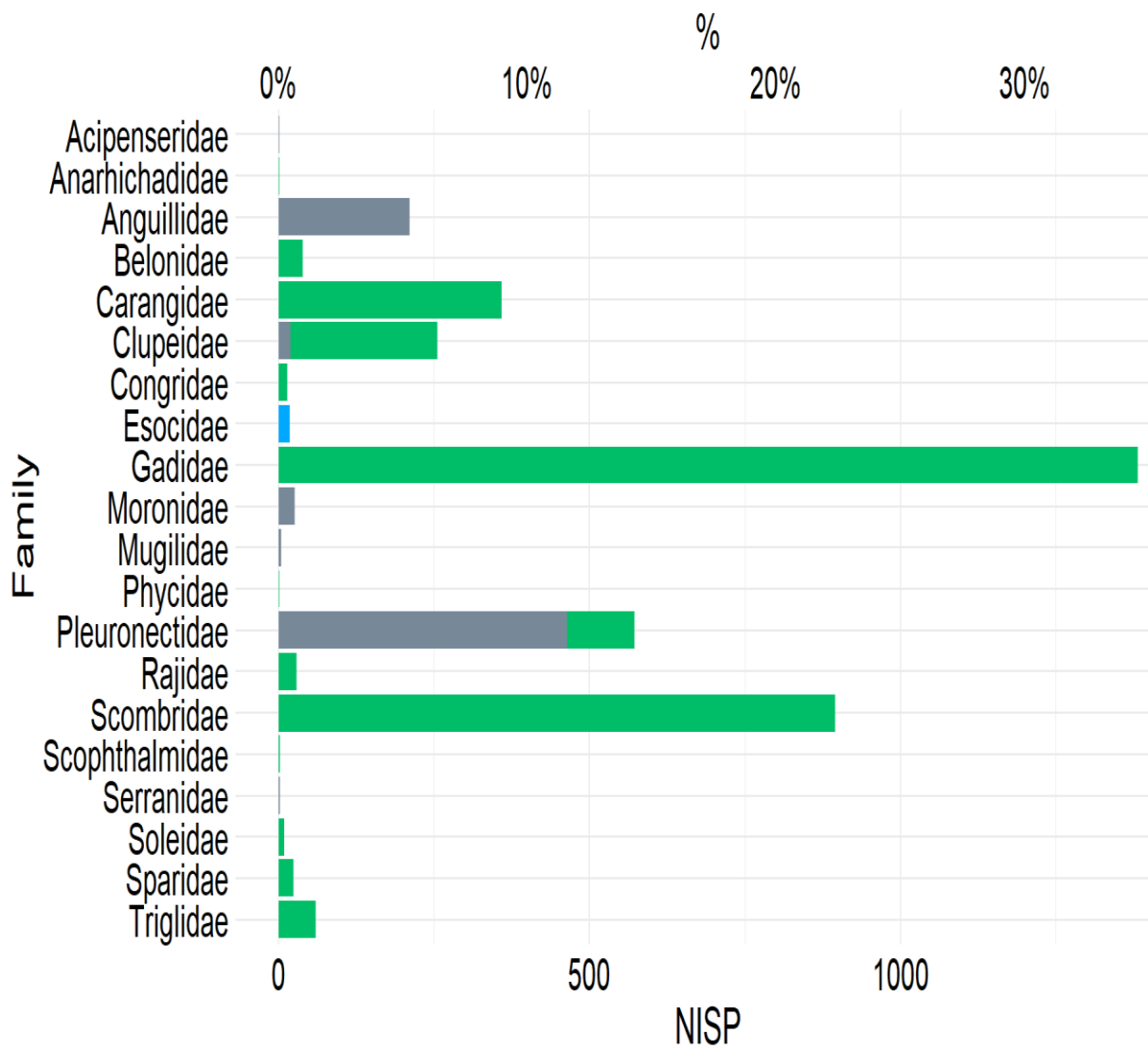
The presence of both marine and freshwater taxa at Lyminge reflects a range of aquatic habitats surrounding the site, including local streams and rivers (i.e. the Nailbourne stream), that were likely utilised for fishing activities, either by the site’s inhabitants or by their close contacts.

Table.3.6. Habitats represented at Lyminge by NISPS and relative frequencies. Relative frequencies marked as % of total NISP.

Habitat	NISP	% of NISP from Total
Marine	3352	81.76
Marine/Freshwater	922	17.73
Freshwater	21	0.51
Total	4295	100



B



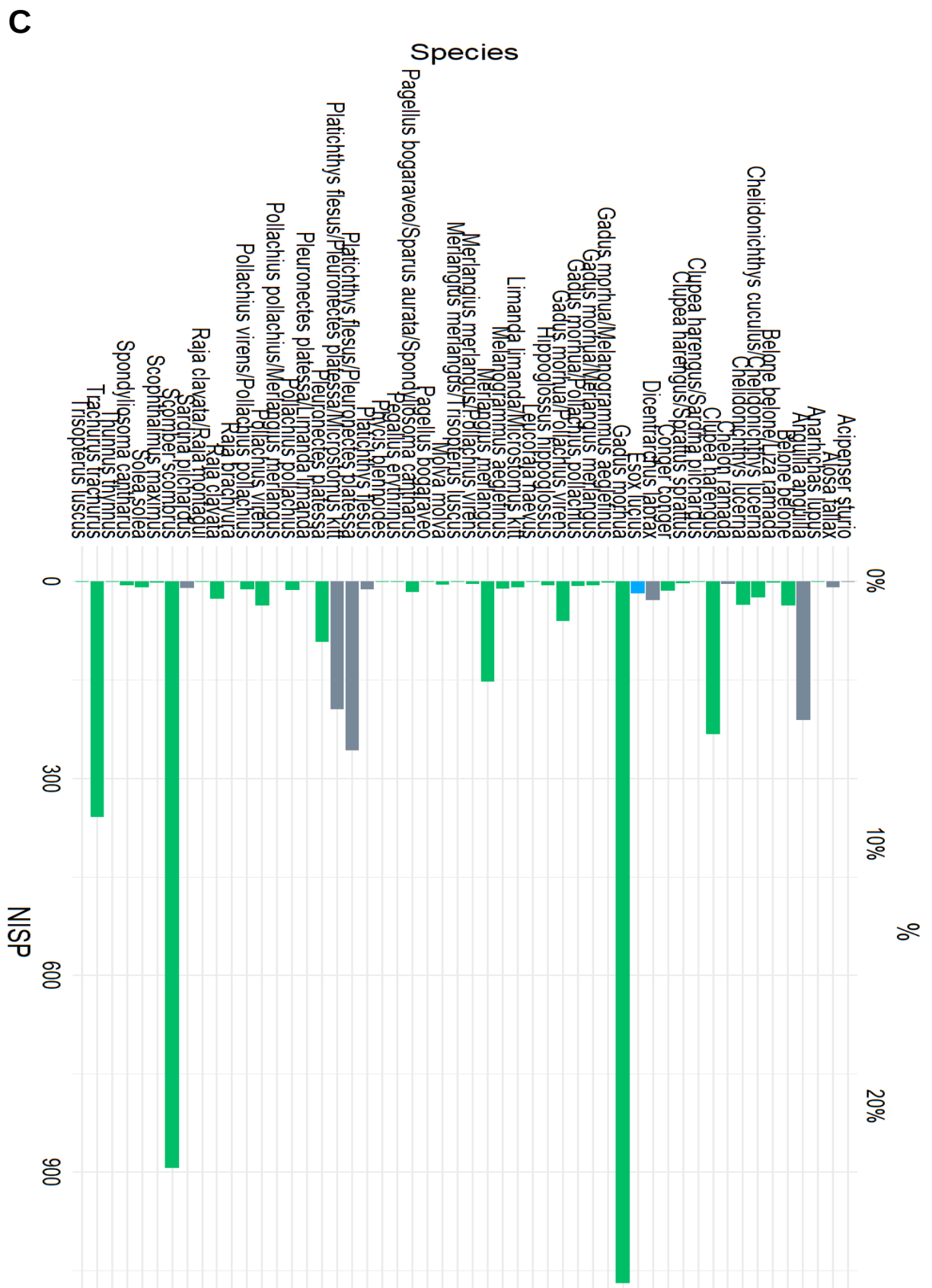


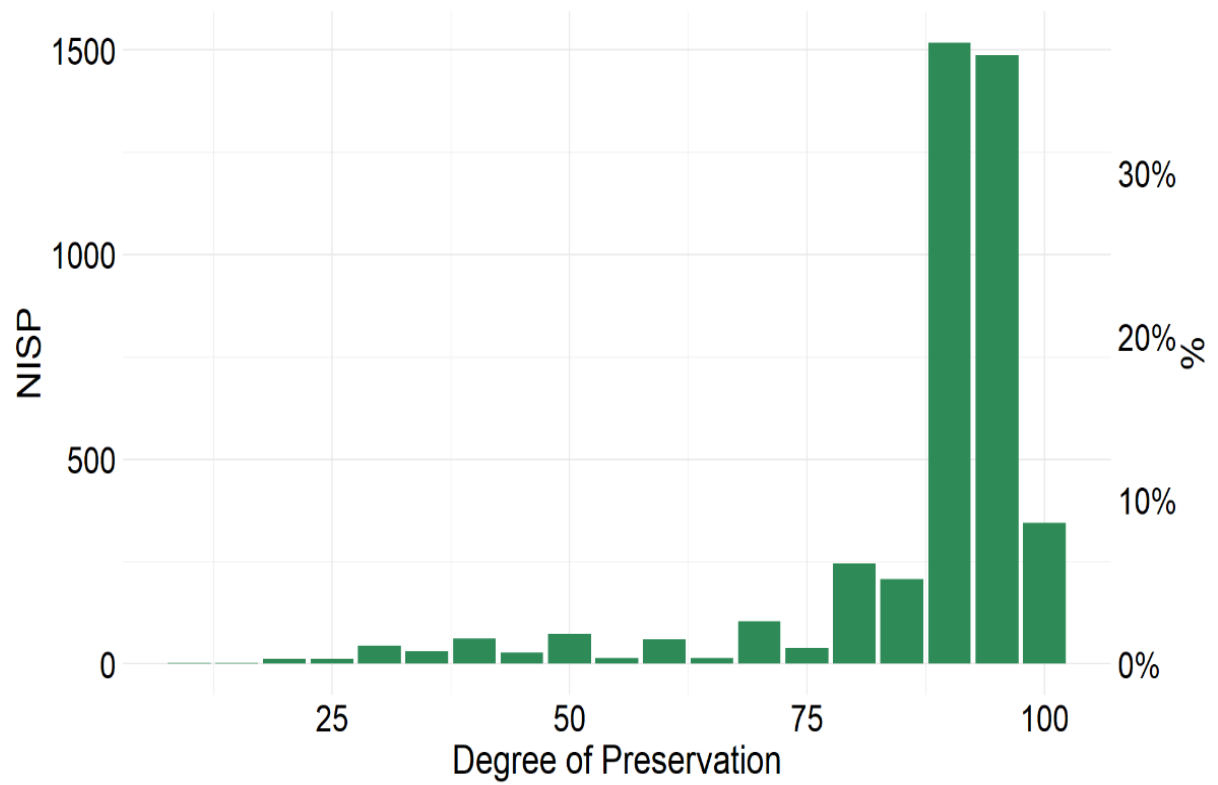
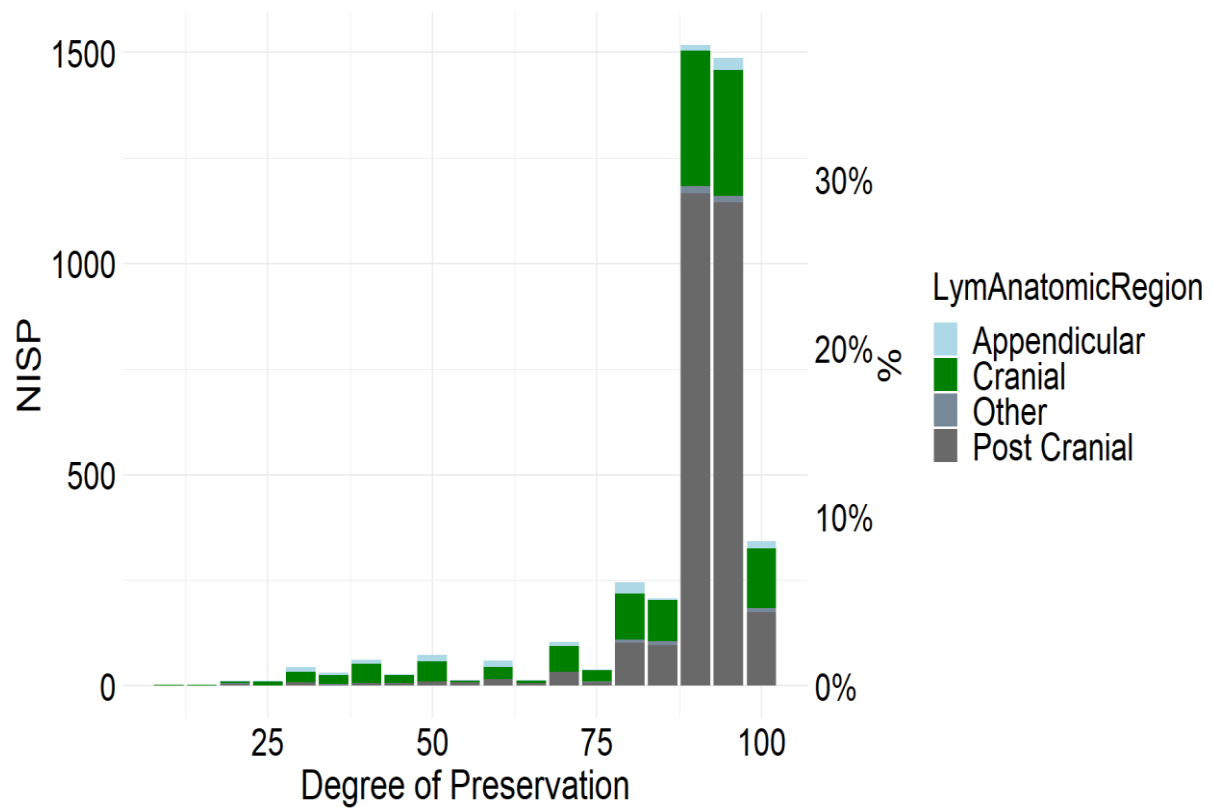
Figure.3.15. Bar charts of NISPs and relative frequencies of identified taxonomic levels of Lyminge fish bones by habitat: A. Total fish bone assemblage; B. Families; C. Species. Plots coloured by habitat. Relative frequencies marked as % of total NISP (S.3.1).

3.9.5. Taphonomic surface modifications

Preservation Levels

Preservation level measurements in this study (see Methods and materials Section 2.5.4) demonstrated that most of the recorded fish bones were complete (preservation between 85 % – 100 %), with highly fragmented bones (preservation < 50 %) present in low frequencies (Fig.3.16.A). This indicates that the assemblage was well preserved overall and that taphonomic processes were limited. The high preservation levels and low taphonomic modifications of the Lyminge fish bones indicate that the additional analyses of the Lyminge fish bones in this research are little biased by taphonomic processes.

Most of the complete bones represent post-cranial anatomic regions, followed by cranial and appendicular regions (Fig.3.16.B), strengthening the practicability of cod size estimations based on measurements of vertebrae and cranial elements (Results Section 3.5). Furthermore, most of the bones identified to species are complete (preservation > 75 %), which strengthens the reliability of the fish bone identifications to the highest taxonomic level (Fig.3.16.C).

A**B**

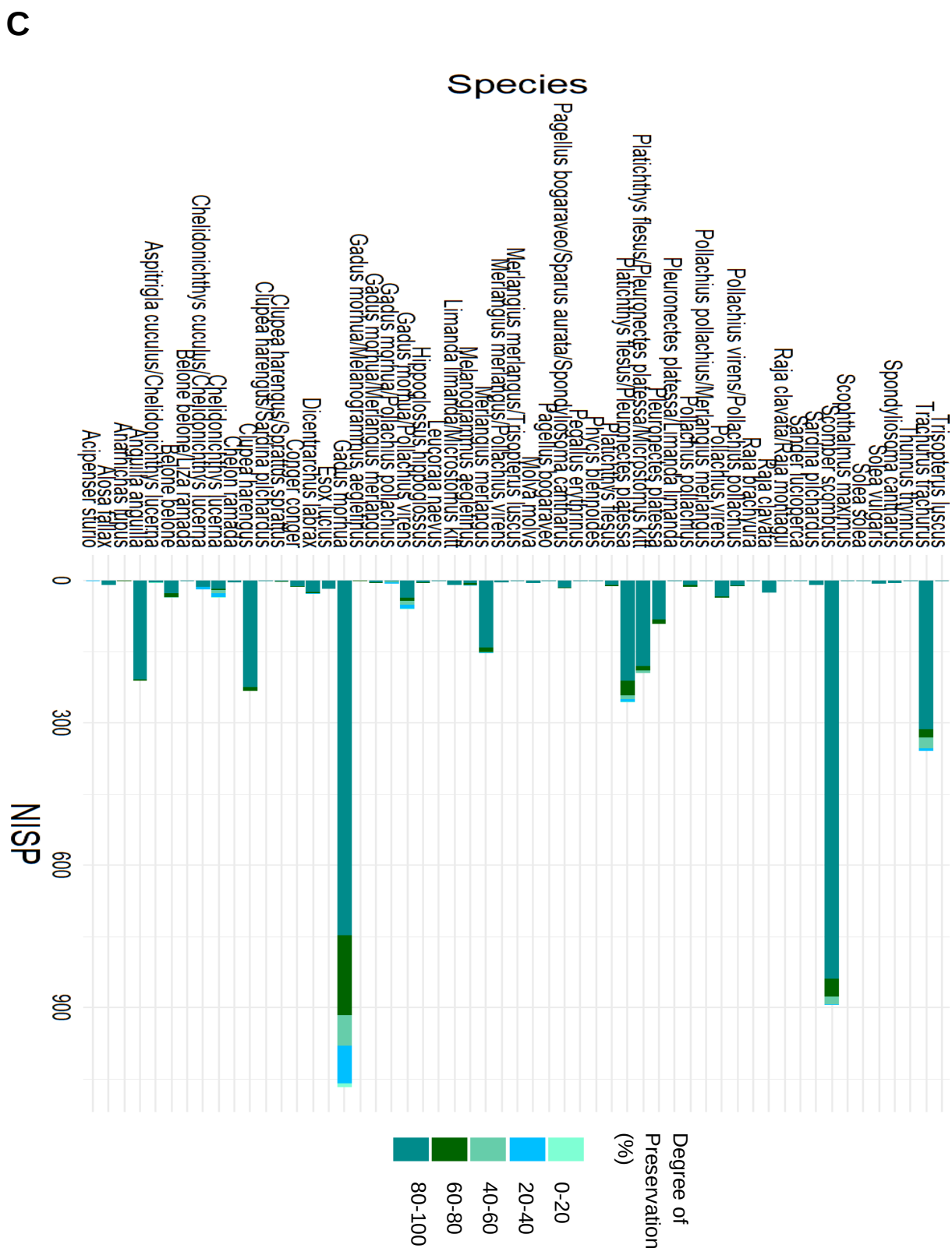


Figure.3.16. Bar charts of NISPs (top) and relative frequencies (bottom) of Lydinge fish bones, including their degree of preservation: A. Total fish bone assemblage; B. Anatomic regions; C. Species. Plots coloured by anatomic region in B, and by degree of preservation in C. Relative frequencies marked as % of total NISP (S.3.1).

Butchery marks

Man-made butchery marks were observed and identified on five types of skeletal elements of *Gadus morhua* from Lyminge, and on a total of thirteen skeletal elements, following Methods and materials Section 3.6.4 (Table.3.7; Fig.3.17). Photographs and illustrations of the butchery marks (following Cannon, 1987) are included in Appendix.3.7. The elements were fragmented to various degrees (35 % – 95 % preservation) and were unburnt. The identified butchery marks were classified into three of six categories of fish processing activities described in Barrett, 1997 (Table.3.7). These categories include: gut, tongue or cheek removal (2); decapitation along the transverse plane (3) and severing the vertebral column along the transverse plane (6) (Fig.3.17).

The presence of butchery marks that match several fish processing activities points to on-site processing of fresh cod fish. The reconstruction of fish processing activities at Lyminge is further supported by the in-situ location of the butchered bones within the rubbish pits at the site. The possibility that the butchered cod bones from Lyminge constitute the remains of stockfish production, either for local consumption or for trading purposes, is further explored in Discussion and conclusions Section 4.3.

Table.3.7. Butchery marks observed on cod elements from Lyminge. The categorization of the butchery marks into potential fish processing activities follows Barrett, 1997. N marks sample size. Relative frequencies marked as % of N.

Skeletal Element	N Elements	% Elements	N Butchery marks	% Butchery marks	Category
Cleithrum	3	42.86	7	53.85	3
Hyomandibular	1	14.29	1	7.69	2
Preopercular	1	14.29	1	7.69	2
Supracleithrum	1	14.29	2	15.38	3
Vertebrae (AV3)	1	14.29	2	15.38	6

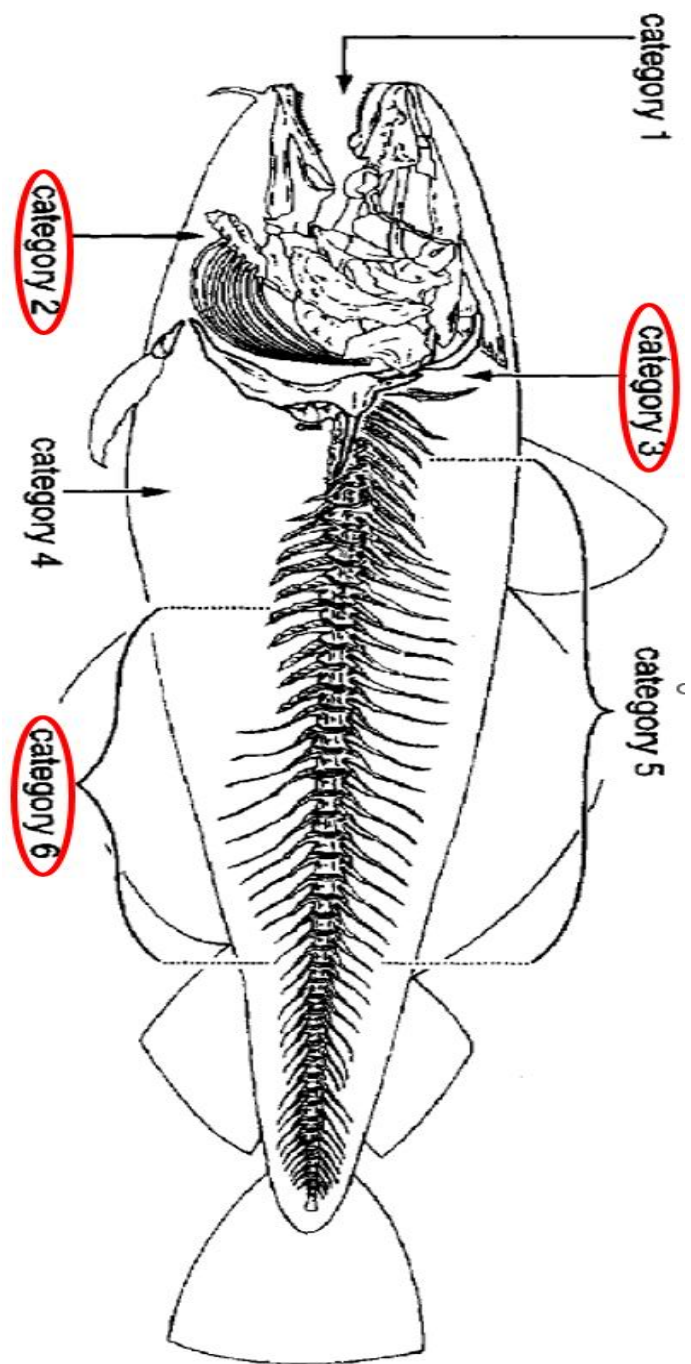


Figure.3.17. Illustration of a gadid skeleton with the locations of the butchery mark categories from Barrett, 1997, Fig.7. Categories observed at Lyminge are marked in red circles.

Signs of burning

Most of the identified bones from Lyminge do not display signs of burning based on bone colour. The colour of 97.37 % of the bones is beige or brown, while 2.63 % displayed colours consistent with burning: white, grey, and black (Table.3.8; Fig.3.18.A;B).

A relatively high frequency of burnt bones are identified as Atlantic horse mackerel (*Trachurus trachurus*, n = 31), followed by Plaice/Flounder (*Pleuronectes*

platessa/Platichthys flesus, n = 18) and Atlantic cod (*Gadus morhua*, n = 15) (Appendix.3.8; S.3.1).

Most signs of burning occur on post cranial elements, particularly vertebrae, followed by cranial and appendicular elements (Fig.3.18.C;D).

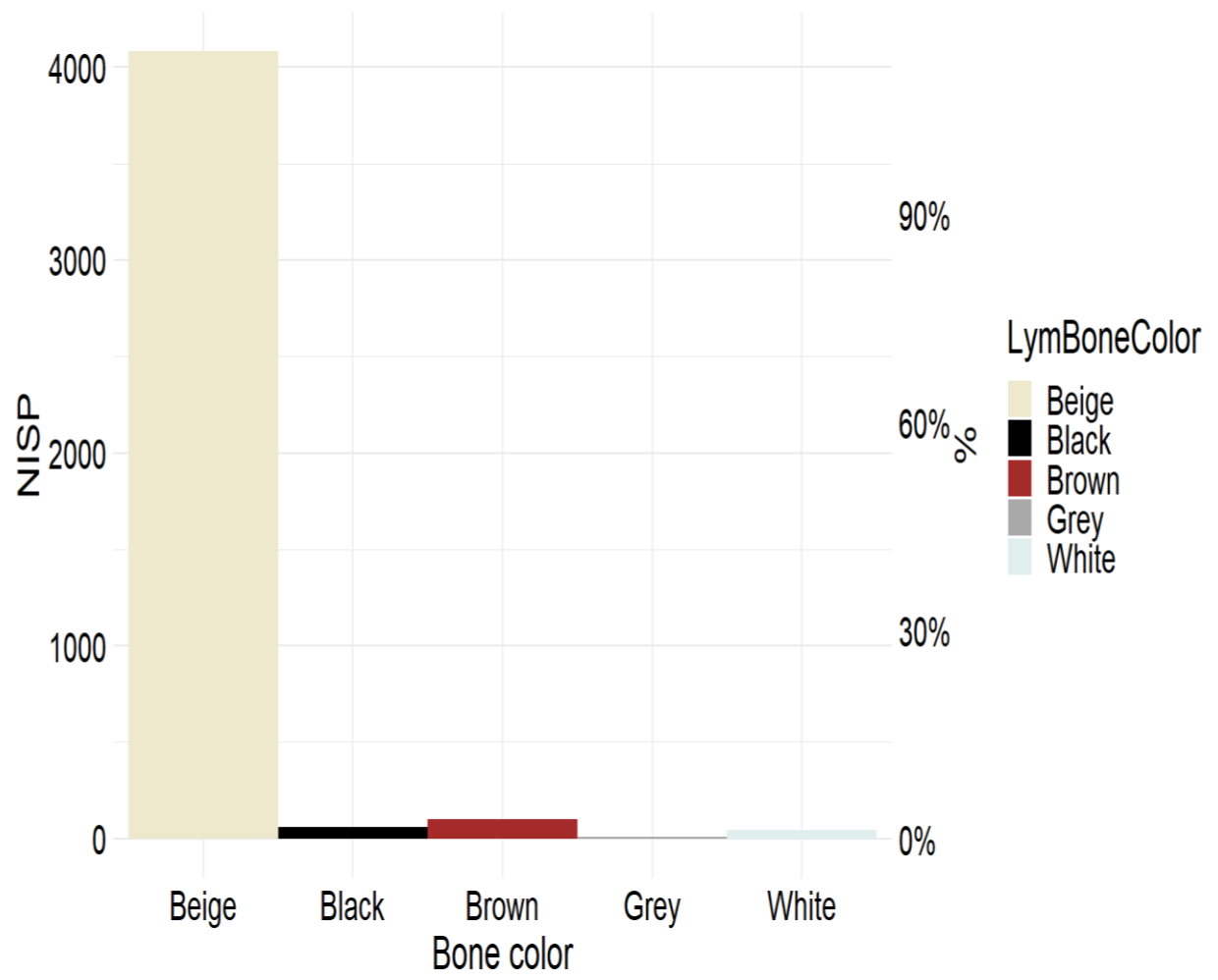
The relatively low frequencies of burnt bones challenge the reconstruction of burning activities of fish at Lyminge. It is possible that the burnt bones represent refuse that was periodically burnt in the rubbish pits for reduction purposes. Alternatively, the fish bones may have been burnt in smaller kitchen fires before their transportation to the rubbish pits. Furthermore, fish bones could have remained unburnt when the fish was heated for cooking purposes (Zohar et al., 2016).

The higher frequencies of burnt vertebrae elements (compared to cranial elements) may correlate to their higher survival rates. Cranial elements may become more fragmented under high temperatures due to their relatively complex morphologies and to their higher surface-to-volume ratios. Cranial elements may subsequently survive to a lesser extent in the archaeological record (Wheeler & Jones, 1989). These possibilities are further explored in Discussion and conclusions Section 4.3.

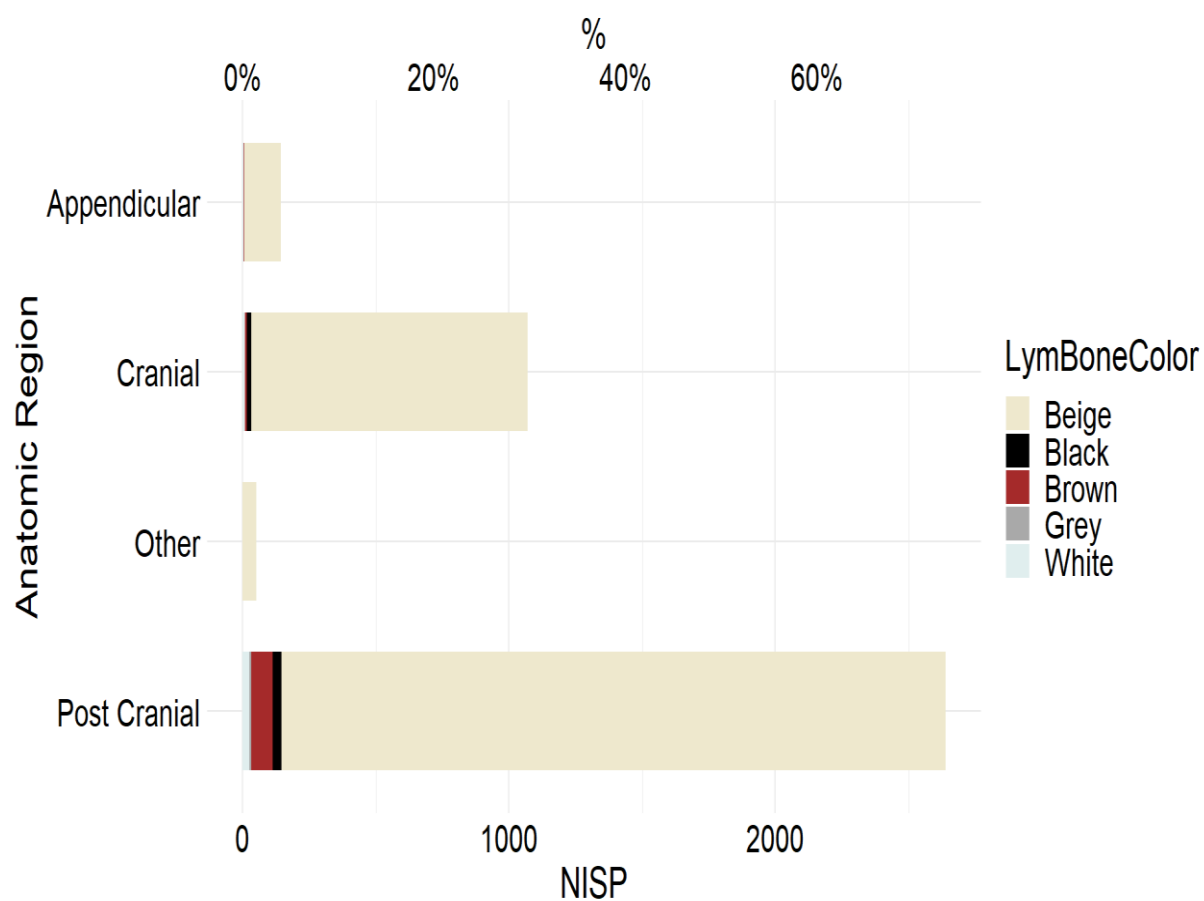
Table.3.8. NISPs and relative frequencies of burnt bones based on bone colour. Relative frequencies marked as % of total NISP (S.3.1).

Bone Colour	NISP	% of NISP from Total
Beige	4080	95
Black	61	1.42
Brown	102	2.37
Grey	7	0.16
White	45	1.05
Total	4295	100

A



C



D

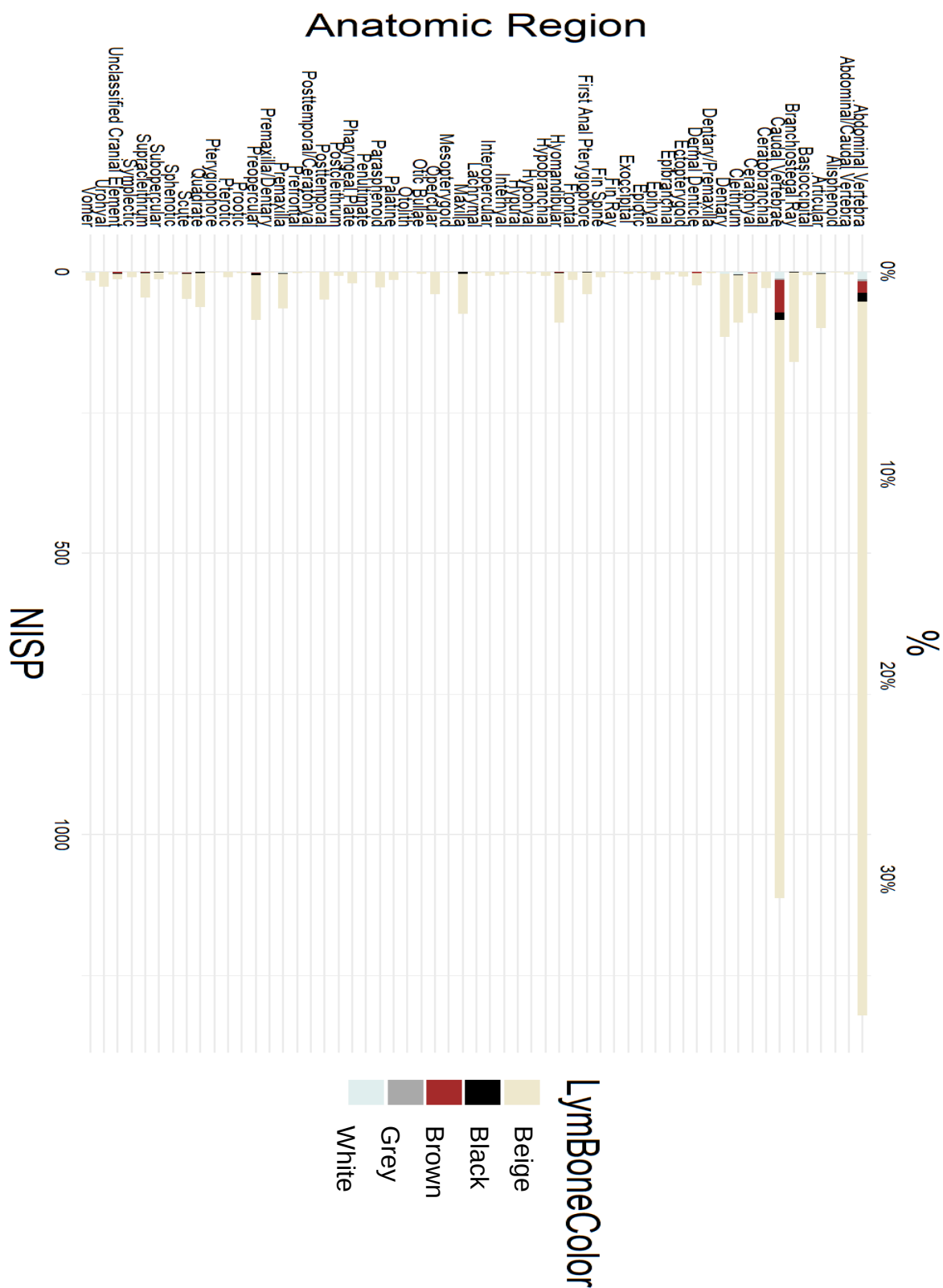


Figure.3.18. Bar charts of NISPs and relative frequencies of burnt fish bones from Lyminge by taxonomic levels: A. Family; B. Species; C. Anatomic region; D. Skeletal element. Plots coloured by bone colour. Relative frequencies marked as % of total NISP (S.3.1).

3.9.6. Size estimations of additional taxa

The measurements of skeletal elements from the identified species at Lyminge were incorporated into corresponding regression models from the existing literature to estimate their TLs (Methods and materials Section 2.6.6; S.2.8). The four species available for size estimations, based on existing regression models, were Atlantic herring (*Clupea harengus*), Atlantic cod (*Gadus morhua*), Whiting (*Merlangius merlangus*) and Atlantic mackerel (*Scomber scombrus*). Fish size was expressed as TL for all species except Atlantic mackerel (*Scomber scombrus*), where size was expressed as Fork Length (FL) based on conventions established by the existing literature (Methods and materials Section 2.6.6). The species and corresponding skeletal element measurements incorporated into pre-existing regression models to estimate fish sizes are displayed in Table.3.9, and visualised in Fig.3.19.A;B.

For all of the species selected, the Lyminge assemblage (with sample sizes between 21 and 140) displays higher frequencies of larger TLs compared to the modern datasets ($3,027 > n > 1,391$) (Fig.3.19.A,B, S.2.8). The mean increase in fish TL is between 11.6 % and 39.5 % over the modern datasets (Fig.3.19.A). These differences are significant based on Mann-Whitney-Wilcoxon tests ($p\text{-value} < 0.01$), and non-parametric effect sizes between 0.31 and 0.45 for all species (with the *Impact()* function and *ImpactEffectsize* package in R) (Lötsch & Ullsch, 2020). These results suggest that modern populations of marine fish have significantly declined in TL overall (Fig.3.19.A,B).

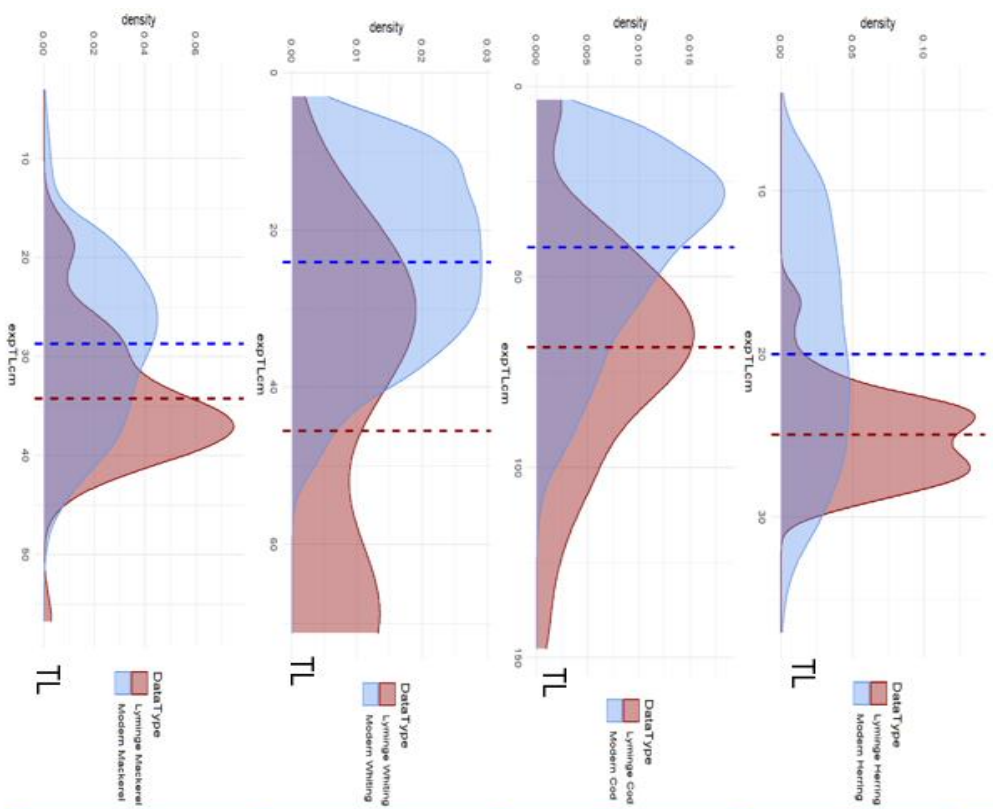
Although the TLs of the archaeological datasets were larger for all of the selected species, many sample sizes are small, especially for whiting and for Atlantic mackerel, $n = 25$ and $n = 22$ respectively (Fig.3.19.A). Another potential source of error relates to the archaeological TL estimations from the bone measurements of Atlantic herring (*Clupea harengus*). The first CV (CV1.1), is one of the rare skeletal elements that correlates to a published regression model for TL estimations of *Clupea harengus* (Watt et al., 1997). Remains of this species are abundant in the Lyminge assemblage, however, due to the difficulties in the morphological identification of CV1.1, this element cannot be confidently identified in the Lyminge assemblage. Subsequently, measurements of all CV elements that closely resembled CV1.1 are incorporated into the CV1.1 regression model (Fig.3.19.A,B). Atlantic herring possess approximately 30

CV elements (Archaeological Fish Resource, 2020), suggesting that some of these elements may be inaccurately incorporated into the CV1.1 regression model.

Table.3.9. Lyminge species chosen for size estimations from regression models in the published literature. R^2 values are specified for each measurement type. Number of modern specimens used to construct the regression models marked “n” (S.2.8).

Species	Common name	Element	Measurement Type	n	R^2	Reference
<i>Clupea harengus</i>	Atlantic herring	CV	CW, CH, LL	34	0.96, 0.92, 0.98	Watt et al., 1997
<i>Gadus morhua</i>	Atlantic cod	Dentary	M1	61	0.98	Jones, 1991
<i>Gadus morhua</i>	Atlantic cod	Premaxilla	M1, M2	51	0.98, 0.98	Jones, 1991
				34	0.99, 0.98	Watt et al., 1997
<i>Gadus morhua</i>	Atlantic cod	Cleithrum	M1	37	0.98	Jones, 1991
<i>Gadus morhua</i>	Atlantic cod	V1	CW	54	0.99	Enghoff, 1994
<i>Gadus morhua</i>	Atlantic cod	V2	CW	55	0.99	Enghoff, 1994
<i>Merlangius merlangus</i>	Whiting	Premaxilla	M1, M2	33	0.98, 0.97	Watt et al., 1997
<i>Merlangius merlangus</i>	Whiting	CV	CW, CH, LL	40	0.98, 0.98, 0.98	Watt et al., 1997
<i>Scomber scombrus</i>	Atlantic mackerel	Hyomandibular	M1, M2	41	0.93, 0.94	Klippel & Sichler, 2004
<i>Scomber scombrus</i>	Atlantic mackerel	V1	CW, CH	41	0.88, 0.91	Klippel & Sichler, 2004
<i>Scomber scombrus</i>	Atlantic mackerel	CV	CH	41	0.97	Klippel & Sichler, 2004

A



Species	8 th -9 th Cent. CE Lyminge	2018-2022 ICES
<i>Clupea harengus</i> (n=100), $\Delta=22.22\%$		
<i>Gadus morhua</i> (n=139), $\Delta=22.52\%$		
<i>Merlangius merlangus</i> (n=25), $\Delta=39.49\%$		
<i>Scomber scombrus</i> (n=22), $\Delta=11.62\%$		

André Brousse

B

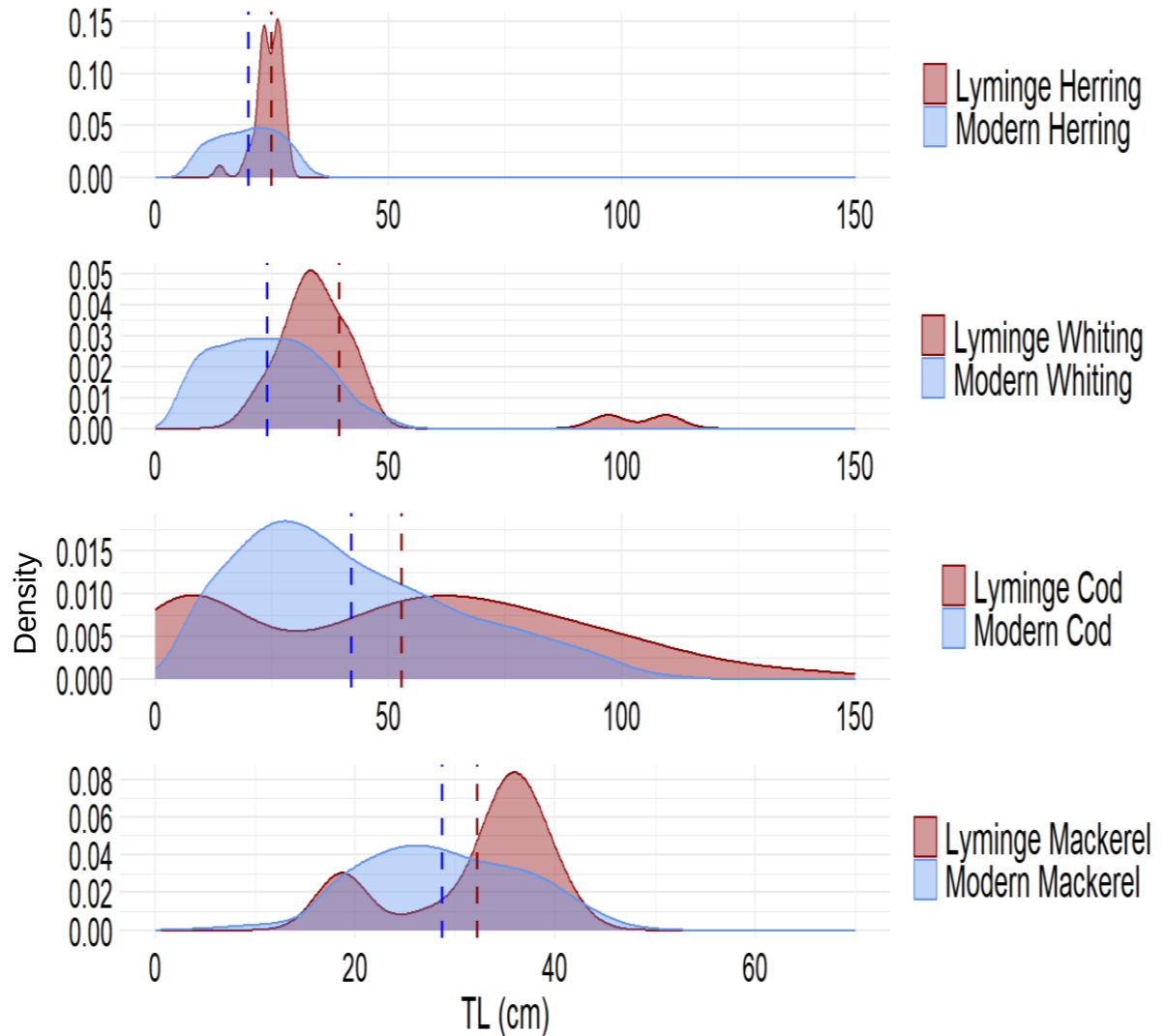


Figure.3.19. Comparisons of mean TLs for select species from 2008–2022 ICES data (DATRAS Specification Document) and from TL estimations for Lyminge skeletal elements: A. Visual representations, from top to bottom: Atlantic herring (*Clupea harengus*), Atlantic cod (*Gadus morhua*), Whiting (*Merlangius merlangus*), Atlantic mackerel (*Scomber scombrus*); B. Density plots, in the same order as visual representations. Modern samples marked in blue. Archaeological samples marked in red. n represents archaeological sample sizes. The Δ represents the percentage differences of the mean TL of the two datasets. Dotted lines represent mean TLs. Size estimations from Lyminge are based on new regression models from this study (Methods and materials Section 2.2; S.2.2; S.2.4; S.3.1) and on pre-existing regression models from the published literature (Table.3.9; S.2.8).

3.10. Scripts and datasets

Scripts

S.3.1. TaxaQauntificationHabitatsSkeletalElements.R

Datasets

D.3.1. aDNA_Samples_GarciaOsloUniversity.xlsx

D.3.2. LymSizeOtherSpecies1.xlsx

D.3.3. aDNA_Samples_AtmoreOsloUniversity.xlsx

4. Discussion and conclusions

This research presents ecological characteristics of 8th – 9th cent.CE cod populations, suggesting that healthier, larger-bodied, and more fecund populations flourished prior to anthropogenic influences such as commercialised fishing. The research also presents a statistical method for estimations of cod Total Length (TL) with a residual standard error $\leq 6\%$. The method utilises new regression equations fitted on vertebrae and cranial measurements of modern samples with known TL. The developed regression models enable more accessible and accurate assessments of archaeological cod sizes, by defining measurements of new skeletal elements from a uniquely large and diverse collated dataset of modern specimens. The research also reconstructs fishing and fish processing activities at the early medieval study site of Lyminge, including the capture and consumption of diverse marine taxa by the site's inhabitants, as well as the local production of cured fish products for consumption and for potential long distance trade.

Answers to the research questions outlined in the introduction Section 1.3 are detailed in this section, along with potential biases and future research directions.

4.1. Are the archaeological and modern cod TLs significantly different from each other, and do the former reflect baseline populations?

The current research revealed significantly larger and more diverse TL values in the distributions of archaeological cod from Lyminge and Coppergate than the modern distributions (Results Section 3.5), the former of which likely reflect natural baseline population fish sizes. The most likely factors influencing these distributions are detailed as follows.

Firstly, methodological factors such as sieving procedures at archaeological sites are known to affect the size distributions of recovered fish bones (Zohar & Belmaker, 2005). The main sieve size employed at Lyminge (5 mm) could have hindered the recovery of smaller skeletal elements. However, the 1 mm sieving test following the 5mm sieving (Methods and materials Section 2.1.1) recovered low frequencies of small cod bones (Fig.3.12). This shows that the archaeological TL distributions were minimally biased by the 5 mm sieving process, and that the complete TL range of cod

bones present at the site were recovered. Based on these sieving results from Lyminge, the 2 mm sieving employed at Coppergate (Methods and materials Section 2.1.1) further indicate unbiased retrievals of small cod bones from the site.

Secondly, the combination of the fishing gear used on the archaeological cod and the cultural preferences of the fishermen likely biased against the lower TLs at the archaeological sites (Introduction Section 1.5.3). The gear type utilised was likely hook and line (Introduction Section 1.5.3), which selects against cod with mouth sizes smaller than the utilised hook sizes (Ingólfsson et al., 2017; Myers & Hoenig, 1997). Cultural choices made by the fishermen may have also truncated the lower tails of the distributions, if the fishermen preferred to retain and/or transport larger fish yielding higher values, to sites such as Lyminge and Coppergate (Wouters et al., 2021).

In key comparisons of the archaeological and modern data, the biases at lower TL values, resulting from the aforementioned fishing gear utilised and from cultural preferences, were addressed by applying common cutoffs to the analysed distributions, at 50 cm for Lyminge and 60 cm for Coppergate, followed by analysis of the distributions above the cutoff. The cutoff values were derived from the calculated 95% highest-density region of the archaeological cod TL densities (Methods and materials Section 2.1.3), and enabled comparisons between the higher TL regions, while avoiding the potential biases in the lower TL regions of the distributions. (Results Section 3.7).

Lastly, it must be asked whether climatic influences could have affected the archaeological TL distributions (described in Introduction Section 1.5.2). The 8th – 9th cent.CE cod bones from Lyminge precede the Medieval Warm Period (MWP) (Rafferty, 2023), indicating that North Sea temperatures were likely lower and within a more optimal range for cod habitation (Barrett et al., 2004.b; Brander, 2000; O'Brien et al., 2000). In contrast, the 10th – 16th cent.CE cod remains from Coppergate mostly overlap with the MWP. As the Coppergate TLs may be expected to be smaller due to MWP influences, their larger values in this research (Fig.3.5; Table.3.2) show that climate is not responsible for the observed size distributions, and that other factors must be considered. Further evaluations of the impact of such climatic shifts on the status of cod populations would require additional estimations of cod TLs dated to intermediate

points between the 8th – 16th cent.CE and direct paleoenvironmental proxies regarding water temperature, which are beyond the scope of this thesis.

The described selectivity processes (i.e. gear selectivity; cultural preferences, and recovery bias) are candidates to affect the minimum TL of cod retained for consumption (Fig.3.5). However, as mentioned, these effects do not occur in the upper tails of these distributions, which were therefore compared separately by applying the highest-density region cutoffs (Methods and materials Section 2.1.3). Differences between the archaeological and modern TL distributions were observed and tested using Mann-Whitney-Wilcoxon tests (Results Section 3.5). The shifts in mean TL both with and without the cutoffs were shown in Tables 3.1 and 3.2. The tables show that the archaeological cod TL was 2.5 to 3 fold larger (+ 150 % to 200 %) in the raw data, and only 1.5 fold larger (+ 50 %) with the low TL cutoff for both Lyminge and Coppergate.

Anthropogenic influences such as commercial fishing commonly lead to reduced biodiversity (Narberhaus et al., 2012; Sobel, 1996). The TL distributions of the archaeological cod from Lyminge and Coppergate, which are significantly wider than the modern distributions (Fig.3.5; Table.3.2), can be inferred to be closer to natural ranges and baseline TLs, prior to centuries of subsequent commercial fishing.

Ultimately, modern trawl data was chosen as a comparison to the archaeological data, including fecundity and biomass comparisons in Section 4.2, due to the extensiveness of the databases; the uniform and well established sampling strategy; the addition of recent studies successfully utilizing similar datasets (Pedersen et al., 2022, Plank et al., 2018; West et al., 2022); and due to the focus of this research on comparing past TL distributions with natural populations. The wide scope of the associated biases are addressed in Introduction Section 3.6 – 3.7; Methods and materials Section 2.1.3 and in this section.

Potential Biases from the constructed regression models

As mentioned in the Results Section 3.5, candidate sources of error in the analysis include sample non-independence; prediction errors in the mathematical models; inter-study variation from separate researchers taking cranial and vertebrae measurements; and variation in the skeletal elements available for analysis (i.e. separate reference specimens with measured cranial and vertebrae elements).

Firstly, non-independence from the use of measurements from multiple correlated modern samples, as from multiple vertebrae of a single fish, was avoided for abdominal vertebrae by using the average measurements within vertebrae groups instead of individual vertebral measurements. The use of averaged measurements across vertebrae groups AV2 and AV3 ensure that each individual was associated with a single measurement for the regression analysis and model fitting (Methods and materials Section 2.2.1).

Secondly, for the case of the CV1 and CV2 vertebrae groups, simple measurements CH, CW, LL were found to depend on both TL and vertebra number, causing substantial inaccuracy in TL predictions if vertebra number was not taken into account. This was solved by including measurement ratios CW/LH and LL/LH, which were found to have reduced TL dependence. These ratios could be used to estimate vertebra number and to obtain more accurate TL estimations from the constructed models (Methods and materials Section 2.2.1). Including a CW/LH or LL/LH ratio was important in enabling cod size estimations from archaeological CV elements through the constructed models, at the statistical cost of non-independence when measurements of multiple bones from single reference specimens were included in regression analysis of the ratios on TL. This compromise does not invalidate resulting estimates of TL, but it does exaggerate summary statistics regarding the quality of the relevant models, such as R^2 .

The possibility of sample interdependence may further result from NISP counts of multiple skeletal elements originating from the same archaeological fish. This is mitigated by the fact that the bones were not from articulated skeletons, and were evenly distributed across both multiple pits ($n \sim 100$, Fig.2.1) and deposition layers (verified in several cases). The risk of multiple samples originating from the same individual is therefore unlikely to be significant.

Inter-study variation is another possible source of systematic error in the analysis. The modern TL data analysis was performed separately for the cranial and vertebrae elements by two separate researchers (Methods and materials Section 2.1.6), respectively (Results Section 3.2- 3.3), however, with some reference specimens in common ($n=17$). The use of the resulting regression models produced different TL distributions for the archaeological cranial elements and vertebrae from Lyminge

(Results Section 3.5; Fig.3.6. The resulting mean TL values were 87 cm and 93 cm, respectively. The difference could represent the upper limit of inter-study variation, however, the possible influence of stockfish production (leading to large decapitated fish being transported to Lyminge), discussed in section 4.3, is considered the main contributor to this variation.

To conclude, there are a few sources of error in the constructed regression models, with an additional residual standard error of $\leq 6\%$ from the regression models for TL calculations. Nevertheless, the decrease in mean TL in the modern cod distributions over the archaeological distributions was found to be 40 % or 30 % respectively for Lyminge ($n = 389$) and Coppergate ($n = 51$) (Table.3.2). These decreases are much larger than the error of the mean ($\sigma/\sqrt{n} = 20\%/\sqrt{400} = 1\%$, or, $17\%/\sqrt{35} = 3\%$, respectively for the two sites), and are therefore likely to be a reliable estimate of changes in cod populations.

Future work

Multilevel Bayesian models may improve the accuracy of the constructed regression models by incorporating prior information on the datasets used to construct the models (i.e. the training dataset). Examples of such priors include the range limits and variability of the training dataset. Furthermore, Bayesian models are often well suited to small sample sizes which are common in archaeological studies, and provide an ideal framework for accounting for the uncertainties associated with measurement and prediction errors when making comparisons between assemblages (McElreath, 2020).

GMM analysis could be used to solve potential errors related to inter-study variation from qualitative categorizations of cod vertebrae into their morphological groups, which lack definitive, quantitative markers. The use of GMM, which is often combined with statistical classification methods such as k-Nearest Neighbour or Principal Component Analysis, could result in quantitative categorizations of vertebrae based on customised landmarks, and reduce inter-study variation (Samper Carro et al., 2018; Guillaud et al., 2016). GMM has been used in past studies to classify fish vertebrae by species and by habitat, further suggesting the method's suitability in classifying vertebrae to individual numbers within the column.

In light of the previously discussed potential biases, and in order to further compare between archaeological and modern fish populations, studies of fish TLs from modern fish markets and comparisons with trawl survey data and archaeological fish TLs would be beneficial. Comparisons of modern market data with trawl survey data could enable quantifications of the intensity of human selectivity processes on TL distributions, and further enable assessments of these processes in the archaeological record. Such comparisons would help assess if temporal shifts in human selectivity processes for market economies can be detected.

4.2. How do the TLs from archaeological cod from Lyminge and Coppergate inform past ecologies and exploitation patterns?

Studies on modern cod have established that their fecundity is positively and curvilinearly related to their TL and weight (Carr & Kaufman, 2009; Froese, 2004; Marshall et al., 2003; May, 1967). These relationships have prompted fishery scientists to base recommendations for cod fishing practices on changes in TL frequencies (Froese, 2004). Furthermore, recent observations of cod spawning when they are shorter have been related to earlier mean ages of sexual maturity, which can reduce population sustainability due to reduced egg production at younger ages (Carr & Kaufman, 2009). Conversely, the disproportionately higher reproductive capacities observed in older, larger individuals support sustainability of cod populations and have significantly informed cod recruitment patterns (Ottersen et al., 2006). Importantly, larger females produce larger eggs in higher numbers (Froese, 2004; Marteinsdottir & Thorarinsson, 1998), leading to higher larvae survival rates (Froese, 2004; Ottersen et al., 2006).

Further studies on food-web interactions involving cod in both the west and east Atlantic have shown that at smaller sizes (< 50 cm length), cod mainly consume benthic invertebrates. Contrastingly, at larger sizes (> 50 cm length), cod prey on a variety of species (Link et al., 2009; Speirs et al., 2010). Such studies imply that shifts in cod lengths significantly influence the stability of additional species interacting in the same food web (EU, 2008).

Estimations of fecundity and biomass values, as well as food-web patterns, from TL distributions of cod remains from Lyminge (n = 118), highlight the health and

sustainability of these past populations (Results Section 3.8). Reconstructions of cod fecundity from Lyminge findings display a 1.4 fold increase compared to the modern ICES bottom trawl survey data (Fig.3.9). These results indicate higher fecundity values from past populations before the onset of commercialised fishing. Reconstructions of cod biomass from Lyminge data display a 27 fold increase compared to the modern ICES data (Fig.3.10). These increases remains significant when the size distributions are cut off at the minimum TL of cod retained for consumption ($n = 43$) to avoid known biases (as explained in the previous section), with a 1.4 fold and a 8 fold increase in fecundity and in biomass, respectively, between the archaeological and modern data (Appendix 3.2).

In conclusion, the larger estimated cod TLs from the archaeological study sites reflect higher biomass and higher reproductive capabilities, and point to a sharp decline in these measures in modern periods. Modern cod TLs reflect more vulnerable populations that are at higher risks of further declines in comparison to the archaeological samples. The results significantly contribute to the reconstruction of cod exploitation timelines prior to intensified fishing practices, and highlight the detrimental effects of modern fishing practices. As previously mentioned, these findings should inform future conservation efforts of both cod and other taxa within the same food webs.

Future work

While the present research has focused on the reconstruction and interpretation of cod TLs, future reconstructions of past cod fishing grounds should be expanded to rely on growth ring analysis of cod vertebrae centra and otoliths, which can reveal cod age. Juvenile cod under the age of 6 years inhabit coastal waters, while mature individuals often venture into deeper, colder waters (Frimodt, 1995; Rojo, 1988; Ólafsdóttir et al., 2017), enabling the use of cod age to inform whether cod were fished near or far from the coast. Such studies would further reveal past anthropogenic influences on cod ecosystems, as younger age distributions of captured cod likely reflect elevated fishing pressures on larger, more fecund individuals, while mature distributions reflect sustainable fishing of healthy populations (Ottersen et al., 2006).

4.3. Do the archaeological cod remains from Lyminge and Coppergate reflect stockfish?

Analysis of the cod remains in this research, combined with past studies, are congruent with the preparation of stockfish or a similar decapitated product at Lyminge and at Coppergate. The supporting arguments are presented below.

At Lyminge, some of the estimated cod TLs are over 80 cm (Fig.3.5), corresponding with known stockfish varieties (Harland et al., 2016; Perdikaris & McGovern, 2009). The significantly larger TL distributions from vertebrae in comparison to cranial elements (Fig.3.6) further suggest that large cod were decapitated for stockfish production. These larger distributions also re-emphasise the value of the present novel models, which enable the use of vertebrae for cod size estimates.

The estimated TLs from the vertebrae and cranial elements at Lyminge are further influenced by inter-analyst variation, i.e. the separate modern datasets of cranial and vertebrae measurements, which could have introduced error into the analysis (as detailed in Discussion and conclusions Section 4.1). However, the evidence presented above suggests that the difference in the estimated TLs from cranial and vertebrae elements from Lyminge may also relate to the production of stockfish.

The pattern of differing vertebrae versus cranial sizes has also been previously related to the production of decapitated dried stockfish. For example, at the 16th cent.CE town of Nya Lödöse, Sweden, cod of ~ 60 cm – 100 cm TL were represented by vertebrae, corresponding to decapitated stockfish, while cod of ~ 100 cm – 130 cm TL were represented by cranial elements, likely representing a traded product of dried fish heads (Maltin, E., 2020; Maltin & Jonsson., 2018).

Stockfish production at Lyminge is further evidenced by patterns of butchery marks on cod bones, following Barrett, 1997. Patterns indicative of stockfish preparation include decapitation and severing the vertebral column along the transverse plane (Fig.3.17; Appendix 3.7). Similar butchery patterns indicative of severing the vertebral column to remove anterior vertebrae were identified on cod from 7th – 9th cent.CE Flixborough, and have also been attributed to stockfish production (Dobney et al., 2007).

Furthermore, despite their relative fragility, cod cleithra are clearly present at Coppergate (n = 551) based on previous studies (Harland, 2016), and at Lyminge (n =

25) based on the present study (Appendix 3.6.A). Their presence, combined with both a relative abundance of vertebrae from the two sites (Fig.3.6; Harland, P.C), and the aforementioned variation in the size estimates from the cranial and vertebrae elements at Lyminge (Discussion and conclusions Section 4.1), suggests that some cod may have been transported to the sites for stockfish production. This suggestion is based on past studies which have concluded that both cleithra and vertebrae were sometimes left in the finished stockfish product (Barrett et al., 2016; Orton et al., 2017).

Lastly, the presence of stockfish at Coppergate is evidenced by past isotopic studies on 10th – 11th cent.CE cod bones (Barrett et al., 2011). The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of the sampled bones suggest Arctic Norway or northeastern North Atlantic origins. These non-local individuals would have been preserved for long-distance trade, presumably as stockfish.

In sum, the in-situ location of the Lyminge and Coppergate cod bones within the rubbish pits of the sites (Methods and materials Section 2.1.1) indicates that at least some stockfish were prepared and consumed locally as early as the 8th cent.CE. However, the additional possibility that some of these products were prepared to be traded elsewhere cannot be excluded.

Future work

Additional zooarchaeological analysis of contemporaneous English sites can further reveal the temporal and geographic range of the cod skeletal element patterns observed at Lyminge, i.e. the relative representation of large vertebrae and large cranial elements. In particular, potential representations of large vertebrae should be examined for the possibility of the decapitation of fish elsewhere, possibly near fishing sites, or, alternatively, for the marketing and trade of large cod heads as a separate product. Future isotopic research could further assess if cod bones from Lyminge and Coppergate originated from non-local fishing grounds, as demonstrated in past studies of Coppergate cod bones (Barrett et al., 2011).

4.4. How did the Lyminge inhabitants interact with the fish remains?

Identifications of marine and freshwater taxa in this research reflect 8th – 9th cent.CE fishing activities from diverse aquatic habitats surrounding the study site, either by the

site's inhabitants or by their close contacts (Results Section 3.9.4). The fish bone assemblage, which originated from the site's numerous rubbish pits (Methods and materials Section 2.2.1), was dominated by marine taxa, likely sourced from both littoral and deep-sea fishing activities in the North Sea, while the lower frequencies of freshwater taxa were likely sourced from local streams and rivers (Fig.3.15). These results were partially verified by the aDNA identifications of *Gadus morhua* (Atlantic cod) and *Clupea harengus* (Atlantic herring).

The representation of all anatomic regions from several of the identified Lyminge taxa, combined with the in-situ location of the assemblage within the rubbish pits of the site, suggests that mostly whole, fresh fish were consumed at Lyminge (Results Section 3.9.3), as seen at additional medieval English sites (Barrett et al., 2011; Hamilton-Dyer, 2000; Orton et al., 2014).

Burnt fish bones were also identified at Lyminge. It is unclear what process led to higher frequencies of burnt vertebrae in comparison to cranial elements (Fig.3.18.C), as studies on differential burning of these elements are rare (Wheeler & Jones, 1989; Zohar et al., 2016). The existing studies have noted that in cooked whole fish, posterior skeletal elements survive at higher temperatures compared to anterior elements (Zohar et al., 2016). A possible explanation for this pattern, and for the higher frequencies of burnt vertebrae at Lyminge, is that vertebrae are more robust compared to cranial elements due to their lower surface area to volume ratios. Vertebrae elements may therefore display higher degrees of preservation at elevated temperatures. Future research in experimental archaeology is needed to assess this theory, e.g. exposing different skeletal elements to elevated temperatures in a controlled environment.

Beyond the Lyminge cod TLs estimated through the regression models in this research, several additional identified species which dominated the fish bone assemblage were available for size estimations based on existing regression models. These taxa displayed significantly larger TL distributions in the archaeological data in comparison to modern distributions. These species, considered highly commercial in modern times (Froese & Pauly, 2023), included Atlantic herring (*Clupea harengus*), Whiting (*Merlangius merlangus*), and Atlantic mackerel (*Scomber scombrus*). The significantly larger archaeological TL distributions of the analysed species, combined

with their modern economic value, mirror the analysis of the past body sizes of Atlantic cod in Discussion and conclusions Section 4.1. These results show that various species besides Atlantic cod had significantly larger, healthier, and more sustainable populations in the past, which have been negatively impacted by the rise of commercial fisheries. Furthermore, the larger archaeological TL distributions of interacting species likely indicate different food web structures in medieval periods in comparison to the modern situations. This is demonstrated by the trophic cascade structures of Atlantic cod detailed in Introduction Section 1.4, where cod body size is shown to influence prey preferences.

The results in this section corroborate past research on contemporaneous fish bone assemblages from Lyminge (described in Introduction Section 1.5.2), which also reveal a dominance of marine taxa at the site (Reynolds, 2015). The displayed rise in marine fishing at Lyminge from this research can be linked to synchronous increases in meat from feasting layers, based on similar interpretations of faunal assemblages from other English sites (Knapp, 2019; 2017; Reynolds, 2015; Sykes, 2014; Thomas & Knox, 2017). Such increased feasting practices utilising more diverse foodstuffs such as marine resources and wild game has been attributed to the emergence of elite hierarchies and ultimately urbanisation, all within a new Christian landscape. These theories are further related to the phenomenon of the Fish Event Horizon (FEH) in the next section.

Potential biases in the zooarchaeological analysis

The interpretation of the zooarchaeological results from analysis of the Lyminge fish bone assemblage followed the four main processes affecting relative taxa abundances detailed in Methods and materials Section 2.5.5. These processes, which included sieve size; skeletal element preservation; skeletal element size and intricacy; and sample size and interdependence, were addressed through the methodological workflow chosen to record the fish bone assemblage (Methods and materials Section 2.5). The impact of these processes on interpretations of the zooarchaeological results in this section are discussed below.

1. *Sieve size* - the analysed fish bones mainly originated from the 5 mm sieved material (as mentioned in Discussion and conclusions Section 4.1), with only small frequencies originating from the further sieved 1 mm subsamples (Fig.3.12; Fig.3.13). This

indicates that small bones were not lost in the first 5mm sieving process, and that the identified taxa at Lyminge likely reflect the true nature of the fish bone assemblage. Nonetheless, future research should report the specific volumes of sediments associated with the different sieving strategies, to improve quantitative assessments of their influence on these results.

2. *Skeletal element preservation* - preservation levels demonstrated that most of the recorded fish bones were complete (preservation between 85 % - 100 %), with highly fragmented bones (preservation < 50 %) present only in low frequencies (Fig.3.16.A). These high preservation levels and low taphonomic modifications show that the present analyses of the Lyminge fish bones were minimally biased by taphonomic processes. Furthermore, most of the bones identified to species were complete (preservation > 75 %), supporting the reliability of the fish bone identifications to the highest taxonomic level (Fig.3.16.C).
3. *Skeletal element size and intricacy* - Interpretations of the relative frequencies of fish bones identified to taxa from Lyminge (Fig.3.16.C) are complicated by potential under-representations of taxa possessing relatively small (e.g. fragmented) skeletal elements with ambiguous morphological features, which hinder taxa identifications (Wheeler & Jones, 1989). In the future, this could be addressed by aDNA analysis of random samples from the fish bone assemblage. aDNA analysis can identify taxa from smaller bone fragments which are susceptible to exclusions from morphological identifications.
4. *Sample size and interdependence* - smaller sample sizes of fish bones may not represent true compositions of skeletal elements, species and TL distributions in fish bone assemblages (Methods and materials Section 2.5.5). Furthermore, as previously mentioned, multiple fish bones, i.e. the number of identified (skeletal) specimens (NISP) defined in Methods and materials Section 2.5.1, may originate from a single individual in any given assemblage. This multiplicity can lead to both interdependence in the form of false relative frequencies of the identified taxa, and to reduced estimates of variability (as discussed in Discussion and conclusions Section 4.1). The influence of this interdependence on interpretations of relative taxonomic frequencies at Lyminge (Results Section 3.9) is likely to be low, as, the mechanism producing the multiplicity likely impacts all taxa within the Lyminge assemblage equally, facilitating comparable

relative frequencies of the identified taxa (Methods and materials Section 2.5.1). Moreover, the bones originate from multiple rubbish pits and archaeological contexts, lowering the probability of the skeletal elements originating from the same individual (as discussed in Section 4.1). Comparisons of relative frequencies of NISP counts are further enabled by the similar number of individual bones within fish skeletons of multiple species (Cannon, 1987).

Future work

Similar to subsection 4.3 (regarding stockfish reconstructions), additional isotopic and zooarchaeological research could determine if the fish consumed at Lyminge were of local or non-local origin, drawing on past studies with similar objectives. For instance, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of identified cod vertebrae and cleithra elements have successfully indicated that imports of fresh, local cod to London increased in the 11th cent.CE, while imports of preserved cod (likely as stockfish) from distant, northern waters increased only in later centuries (Barrett et al., 2011).

Furthermore, as previously mentioned, aDNA analysis of random samples from the fish bone assemblage can identify taxa from smaller bone fragments which are susceptible to exclusions from morphological identifications.

Regarding the estimated TL distributions of additional identified species from Lyminge, future work can establish regression models for size estimations of these taxa based on measurements of skeletal elements still unutilized in current archaeological studies. Furthermore, expanding sample sizes of measurements of archaeological skeletal elements from the species analysed can improve the accuracy of their size estimations. This would especially benefit the size estimations for whiting and Atlantic Mackerel, both of which had relatively small sample sizes in this research (Fig.3.19.A). Lastly, expanding the number of species from various aquatic habitats (i.e. freshwater and estuarine) that have estimated archaeological body sizes can further contribute to reconstructions of past aquatic ecosystems.

4.5. How do the Lyminge analyses inform current FEH theories?

This research provides evidence of coastal and offshore marine fishing and stockfish preparations and consumption in the 8th – 9th cent.CE at the analysed site of Lyminge (Results Section 3.9). The present evidence is based on identifications of various marine taxa (Fig.3.15), and is further supported by findings from past studies in England (Hamilton-Dyer, 2001; Nicholson, 2015; Reynolds, 2015). Combined, these present an earlier placement for the appearance of marine fishing and for the start of the Fish Event Horizon (FEH) than the currently accepted 11th cent.CE date (detailed in Introduction Section 1.5.2).

Present estimations of large cod, Atlantic herring, Whiting, and Atlantic mackerel from Lyminge and Coppergate, using newly developed and preexisting regression models, demonstrate that significantly larger, healthier populations of cod and other marine species were obtained by middle Anglo-Saxon communities from as early as the 8th cent.CE, further supporting the earlier placement of the FEH. The estimated cod TLs further reflect their body sizes prior to intense exploitation in later periods (Barrett; 1997; Barrett et al., 2000; 2004.b; Orton et al., 2014; 2017), to the point of collapse in modern times (FAO, 2023; Sherwood, 2019).

Based on ecological studies that show adult cod over ~ 65.4 TL residing in depths over 30 m (Cohen et al., 1990), it is likely that the large cod from these early dates in the archaeological sites were captured during comparatively off-shore fishing activities (Fig.3.5). The identifications of Ling (*Molva molva*) and Blackspot seabream (*Pagellus bogaraveo*) from 8th – 9th cent.CE Lyminge in this research (Fig.3.11) also support off-shore fishing, as these pelagic species are normally found in depths of 100 m – 400 m (Muus & Nielsen, 1999). This interpretation assumes that these fish were not more common close to shore in the past (e.g. prior to centuries of commercial inshore fisheries).

The collation of the Lyminge analysis with data from other previously mentioned European sites displaying a similar dominance of marine taxa, and identifications of offshore taxa, including in France and Iberia (Hamilton-Dyer, 2001; Llorente-Rodríguez et al., 2022; Makowiecki et al., 2016; Nicholson, 2015; O’connor, 1991; Oueslati, 2019; Reynolds, 2015), further strengthens the theory of an earlier start date for marine fishing on a wider European scale prior to the turn of the first millennium and as early

as the 8th cent.CE. It follows that coastal communities from the study periods would have possessed considerable ecological and traditional knowledge of marine environments, and technological fishing and boating advancements, to successfully expand into offshore fishing grounds.

These results encourage reassessment of the *pull* and *push* theories behind the rise in the exploitation of northwest Atlantic waters for European markets from the 15th cent.CE. The *pull* theory argues that European markets shifted due to the attraction of the particularly bioproductive waters of the West Atlantic. The *push* theory argues instead that depleted local resources led Europeans to seek marine fish from greater distances (Holm et al., 2022.b,c).

The comparison of the estimated cod length from Lyminge (Fig.3.5), mean-TL = 93.2 ± 0.9 cm (error is sem, standard error of the mean), to that of 16th – 17th cent.CE. Newfoundland, taken from published FL data, mean-TL = 77.5 ± 1.4 cm (Betts et al., 2014; see Glossary entry FL) shows a significant difference in the means: $\Delta = 93.2 - 77.5 \text{ cm} = 15.7 \text{ cm} = 10 \times (\text{combined sem})$. This difference may support the *push* theory, suggesting that the shift to Newfoundland cod fishing was not necessarily in pursuit of more bioproductive waters (which would likely contain larger-sized cod), but rather due to depleted local resources (Carr & Kaufman, 2009; Froese, 2004; Holm et al., 2022.a; Marshall et al., 2003; May, 1967). However, although the two datasets display different mean TLs, they possess broadly similar ranges of fish sizes, i.e. 40 cm to 150 cm TL for Lyminge and 45 cm to 175 cm TL for Newfoundland. These similar ranges are also compatible with the *push* theory, as they suggest similar levels of bioproductivity in both English and Newfoundland waters. Additional studies on depleted local waters and political events in periods following the 8th – 9th cent.CE at Lyminge are required to provide more thorough reassessments of these theories.

The *push* theory may be further supported by the present Lyminge research through the paucity of identified freshwater taxa and the dominance of marine taxa (Fig.3.15). A similar trend is present at contemporaneous coastal sites such as Bishopstone, Canterbury, Sandtun, and Sedgeford, where marine fish were noted to dominate 8th – 9th cent.CE assemblages (Hamilton-Dyer, 2001; Nicholson, 2015; Reynolds, 2015; 2016). The collation of this trend with later textual sources, such as the 13th cent.CE

legislative manuscript instructing weirs to remain near the sea coast and be removed from freshwater sources, seemingly reflects the increased focus on marine fishing by parliament at the time (Bond, 2016; Hoffmann, 1996). Additional textual evidence for the pollution of freshwater sources at Coppergate (Hall & Hunter-Mann, 2002) may also suggest that depletions of freshwater fish encouraged markets to turn to marine resources.

The marine fishing practices reconstructed at Lyminge could have been influenced by two additional factors thought to have shaped the FEH (Introduction Section 1.5.2; Barrett et al., 2004.a; Hoffman 2001; 2005; Star et al., 2017). Firstly, religious developments such as the rise of Christianity in medieval England could have led to dietary changes. It is generally accepted that absence of meat and a presence of fish at medieval sites is in keeping with Christian dietary rules documented in medieval texts (Dobney, 2007; Ervynck, 2004). Despite the challenges in relating archaeological fish remains to Christian practices and values (discussed in Introduction Section 1.5.2), the presence of both meat and fish at Lyminge (Results Section 3.9; Thomas & Knox, 2017) could indicate a loosened adherence to Christian rules by the site's inhabitants, as seen already at the rural, elite site of 7th – 10th cent.CE Flixborough. Alternatively, groups of different status may have had different diets, i.e. ecclesiastical groups may have consumed more fish, while secular groups may have consumed more meat.

At Lyminge, the latter explanation seems more likely. St. Benedict's Rule, a seminal book, was already written in the 6th cent.CE, and describes the role of fish in Christian fasting practices in several chapters (Dembinska, 1986). The extensive dietary guidelines outlined in St. Benedict's Rule would likely have been familiar to a Christian society present at monastic Lyminge by the 8th cent.CE. The coastal location of the site, and the accessibility of the community to marine fish, would have facilitated and promoted the following of these rules.

Furthermore, this explanation likely applies to the contemporaneous coastal sites of Bishopstone, Canterbury, and Sedgeford, which were converted to Christianity around the 8th cent.CE (Baker, 1990; Hamilton-Dyer, 2001; Nicholson, 2015; Reynolds, 2015; Schoss, 2007; Smith, 1978).

Secondly, climatic influences such as the MWP (discussed in Discussion and conclusions Section 4.1) and other climatic shifts might have influenced the availability

of some freshwater and marine fish, in turn leading to changes in fishing practices. Although the Lyminge fish bone assemblage was likely unaffected by the MWP (thought to have occurred in later periods), earlier climatic shifts cannot be excluded, and may have influenced fish populations (Sigl et al., 2015, Smerdon & Pollack, 2016).

Thesis contributions- addressing FEH research limitations

The present findings reduce knowledge gaps within the FEH theory, as described in Introduction Section 1.5.2, as follows:

The early dates of the analysed Lyminge assemblages broaden the temporal scope of the FEH phenomenon by presenting significant levels of marine fishing from the 8th cent.CE, 300 years prior to the previously assumed onset of the FEH.

The analysed fish remains from 8th – 9th cent.CE Lyminge further add to a limited number of published fish bone assemblages reporting sieving strategies and comprehensive zooarchaeological analysis from middle Anglo-Saxon sites (Gardiner et al., 2001; Barrett, 1997; 2004.a; Dobney et al., 2007; Hamilton-Dyer 2001; Reynolds, 2015; Nicholson, 2015; Orton et al., 2014). The application of the sieving strategy at Lyminge, including the biases associated with the interpretation of the zooarchaeological results (see Research results Section 3.6; 3.9.2), has enabled more comprehensive and accurate interpretations of the temporal and spatial chronology of the FEH phenomenon. In particular, the Lyminge analysis provides evidence of both marine fishing in offshore waters, and of stockfish consumption at English sites several centuries prior to the previously established onset of the FEH.

The zooarchaeological results from Lyminge also strengthen past theories of regional variability in the timing and location of the shift to marine fishing (Reynolds, 2015, Barrett, 2019, Holm et al., 2022.a). Contrasting fishing practices in northwest Europe in the 8th – 9th cent.CE include selections of mainly marine fish at coastal sites, as seen in the recent Lyminge analysis, while inland sites still focused on freshwater and estuarine fish.

The variations in onset dates for marine fishing are clearly associated with geographic and cultural-religious factors. The analysis from the coastal site of Lyminge establishes the central role of the geographic factor, joining data from previously studied coastal sites with similar early evidence of marine exploitation, while sites with later evidence (10th – 11th cent.CE) are mostly located inland (Barrett, 1997; Dierickx et al., 2022; Dobney et al., 2007; Hamilton-Dyer, 2001; Harland et al., 2016; Nicholson, 2015; O'connor, 1991; Orton et al., 2014; Reynolds, 2015).

Additionally, in line with past studies and as noted earlier in this discussion (Barret et al., 2004.a; Harland et al., 2016; Knapp, 2019), the rise of Christianity in early medieval England likely influenced the earlier shift to marine exploitation observed at both Lyminge and the previously studied coastal sites, most of which had converted to Christianity by the 8th cent.CE and were ecclesiastical in nature. These sites would have been familiar with the listing of fish as appropriate fasting food in Christian texts, which likely contributed to the presence of significant amounts of locally sourced marine fish from domestic contexts at the sites.

Future work

The present findings pertaining to the FEH phenomenon, and those research limitations described in Introduction Section 1.5.2 that have remained unresolved, both demonstrate that future work should broaden the geographic and temporal scope of zooarchaeological and isotopic analysis of medieval fish bone assemblages. Such work would significantly improve assessments of regional variability within the FEH. In particular, comparisons of additional sites from a wider geographic range within western Europe- inland and coastal, elite and rural, would yield more nuanced evidence on the nature of the shift to marine fishing by past communities. Systematic sieving of new assemblages would be beneficial in further strengthening the conclusions regarding the earlier onset of the FEH, as excavated sites from the study period still lack reports on utilized sieving strategies (Cowie & Blackmore, 2008; Reynolds, 2015).

Additionally, the role of Christianity in facilitating the FEH phenomenon can be further assessed through stable isotope analysis. Isotopic nitrogen research has been used to evaluate the intake levels of aquatic resources by past communities (Lambert & Leggett, 2022; Leggett & Lambert 2022), including at early medieval Bishopstone (Thomas, 2010). These values can therefore serve as a proxy for adherence to Christian fasting practices, which are thought to include diets with mainly aquatic components. In particular, isotopic nitrogen values of bones of human residents from Lyminge and from additional medieval sites can assist in evaluating Christian influences on the FEH.

4.6. Conclusions

Studies on past fish populations provide unique and important information for archaeological, historical and ecological research questions. This research has utilised newly defined measurements of archaeological and modern cod bones and additional zooarchaeological analysis to reveal novel ecological and historical information on baseline cod populations from as early as the 8th – 9th cent.CE, well before the onset of commercialised fishing in the North Sea. The evidence presented, combined with past studies from northwest Europe, has pushed back the assumed rise in marine fishing (i.e. the FEH) from the 11th cent.CE to the 8th cent.CE. The evidence has also revealed offshore fishing by middle Anglo-Saxon communities of larger and healthier marine taxa, compared to modern populations, including cod, as well as processing of cod catches as stockfish for local consumption and potential trade. Novel regression models of previously unutilized vertebrae and cranial measurement enabled the estimations of archaeological cod TLs, and are useful for future archaeological studies of cod assemblages.

The estimated cod TL distributions from the study sites of Lyminge and Coppergate were found to be significantly larger and wider in comparison to modern distributions. These results suggest more reproductive and sustainable populations in early medieval periods. Additionally, in line with studies showing that anthropogenic influences commonly lead to reduced biodiversity (Narberhaus et al., 2012; Sobel, 1996), the archaeological distributions appear closer to natural, baseline ranges. These results highlight the damaging effects of intensified fishing in later periods, including modern collapses and still-vulnerable populations (FAO, 2023; Sobel, 1996; Tveteraas, 2004). The larger archaeological cod sizes further indicate shifts in both food web interactions and the stability of prey species, as types of cod prey are known to shift according to cod size (EU, 2008; Link et al., 2009; Speirs et al., 2010). The TL distributions of several additional species identified from Lyminge, including Atlantic herring, whiting, and Atlantic mackerel, were also found to be larger in comparison to modern populations, suggesting them to be healthier and part of different food web structures in periods predating intensified fishing practices. These findings demonstrate that middle Anglo-Saxon communities had access to larger and healthier populations of various fish species compared to the present. From a conservation perspective, the combined results suggesting larger sizes and healthier past populations of multiple species should inform future conservation efforts.

This research has further demonstrated the reliability, robustness and convenience of previously unutilized vertebrae measurement variables in estimating cod TLs. The high R^2 values (> 0.97) and small residual standard error ranges ($< 6\%$) of the newly constructed vertebrae regression models support the use of the morphological vertebrae groups defined in this research. To date, methods for estimation of cod TL utilised only select cranial elements and vertebrae (Enghoff, 1994; Jones, 1991; Rojo, 1988; Watt et al., 1997), while TL estimation methods from numerous additional skeletal elements often found in archaeological excavations had not been established (Harland et al., 2016; Orton et al., 2017). The chosen morphological vertebrae groups in this study and their corresponding regression models have enabled both the utilisation of additional, “less unique” vertebrae elements in the column (Gabriel et al., 2012; Harris et al., 2017), and of previously unutilized cranial elements, including the quadrate and supracleithrum. The developed vertebrae and cranial models, constructed from uniquely large and diverse datasets of modern specimens, enable more accessible and accurate assessments of cod sizes from archaeological sites. Studies of medieval “consumer sites” with stockfish remains would particularly benefit from the new models, as they are often rich in vertebrae that until now could not be used in size estimations.

In light of these results, the methods developed for fish body size estimations in this research should be considered in future archaeological and environmental research, particularly regarding conservation efforts of intensely exploited fauna.

This present evidence adds to a limited number of studies comparing fish size data from modern trawl surveys and archaeological assemblages (Pedersen et al., 2022, Plank et al., 2018; West et al., 2022). These comparisons are beneficial in assessing temporal shifts in body size and related measures of health, and in the present study have demonstrated significant temporal differences at the study sites of Lyminge and Coppergate. However, the selectivity processes unique to archaeological fish bone assemblages present new challenges in such comparisons. In this study, in the case of Lyminge, fishing gear has been suggested as a key selectivity process influencing the archaeological cod size distributions. Gear type, cultural preferences, and additional selectivity processes were addressed by the application of cutoffs to areas of the modern trawl data and archaeological size distributions most likely affected. Future research focusing on additional types of reference modern data that contain

similar selectivity processes to the archaeological data have been suggested. Notably, fish market data could estimate the influence of both economic and cultural preferences on cod size distributions.

This research has also presented comprehensive zooarchaeological evidence for early marine fishing and fish processing activities at the study site of Lyminge, 300 years before the currently defined start of the Fish Event Horizon in the 11th cent.CE. Based on the 34 species identified morphologically, and on aDNA based verifications, it has been shown that Lyminge residents in the 8th – 9th cent.CE consumed whole, fresh fish, captured from a diverse range of aquatic environments, including freshwater, coastal, and offshore marine habitats. The preparation of stockfish for local consumption and for potential trade at Lyminge and Coppergate was demonstrated, both from reconstructed size estimations from the newly developed regression models, and from the zooarchaeological analysis of cod remains. The established presence of stockfish at the study sites, particularly at Lyminge, marks an especially early production date in England of a commodity that flourished in the following centuries (Barrett; 1997; Barrett et al., 2000; 2004.b; Orton et al., 2014; 2017).

The findings reduce additional knowledge gaps in current FEH theories through the contribution of a comprehensive, zooarchaeological analysis of a well sieved fish bone assemblage from 8th – 9th cent.CE Lyminge, joining a limited number of similarly analysed assemblages from contemporary sites (Hamilton-Dyer, 2001; Nicholson, 2015; Reynolds, 2015; 2016).

The present analysis, particularly the large cod size estimations (Fig.3.5) and identifications of offshore taxa has been collated with data from additional European sites displaying a dominance of marine taxa in their assemblages, including offshore taxa (Hamilton-Dyer, 2001; Llorente-Rodríguez et al., 2022; Makowiecki et al., 2016; Nicholson, 2015; O'connor, 1991; Oueslati, 2019; Reynolds, 2015), to further extend the new 8th cent.CE date for the start of marine fishing from England to the rest of northwestern Europe.

These findings further suggest that coastal communities in 8th cent.CE northwest Europe possessed the required technological capabilities and familiarity with marine environments to expand their fishing grounds beyond the coast. These findings point

to significant levels of marine fishing, and related technological advances, well before intensified fishing practices in later medieval periods.

The collation of the thesis findings with additional archaeological studies reveal distinct regional variability in the geographic and temporal scope of the FEH phenomenon (Reynolds, 2015, Barrett, 2019, Holm et al., 2022.a). This includes contrasting fishing practices in northwest Europe in the 8th – 9th cent.CE, where selections of mainly marine fish were evidenced at coastal sites (Lyminge, Bishopstone, Canterbury, and Sedgeford), while inland sites (Coppergate, Fishergate, Flixborough, and London) still focused on freshwater and estuarine fish (Fig.1.3). The observed variability in fishing practices between the two site types is attributed not only to the direct access of coastal sites to marine taxa, but also to the rise of Christianity and monastic sites in these periods. In line with Knapp, 2019, local marine fishing practices were likely encouraged by the elite, monastic community at Lyminge, due to their adherence to fish related guidelines outlined in St. Benedict's Rule. Similar processes were likely present at other coastal sites, i.e. Bishopstone, Canterbury, and Sedgeford, as they had converted to Christianity around the 8th cent.CE as well (Baker, 1990; Hamilton-Dyer, 2001; Nicholson, 2015; Reynolds, 2015; Schoss, 2007; Smith, 1978).

The results of this thesis further support the *push* theory, suggesting that European markets expanded into northwest Atlantic waters following local depletions of freshwater resources, rather than that the northwest expansion was due to particularly bioproductive waters that attracted European fisheries (the pull theory, Holm et al., 2022.b,c). The supporting results include the estimated cod TLs from 8th – 9th cent.CE Lyminge, which are significantly larger on average compared to 16th – 17th cent.CE Newfoundland (Betts et al., 2014). This, combined with similar TL ranges observed from both datasets, suggest that the shift to Newfoundland cod fishing was unlikely to have been in pursuit of larger-sized cod and more bioproductive waters. Additional supporting results include the dominance of marine taxa identified in the Lyminge assemblage, a pattern observed at additional contemporary sites (Hamilton-Dyer, 2001; Nicholson, 2015; Reynolds, 2015; 2016). Later evidence from the 13th cent.CE corroborates this pattern, in the form of a legislative manuscript instructing weirs to remain solely near the sea coast and to be removed from freshwater locations (Bond, 2016; Hoffmann, 1996).

Overall, the findings in this thesis highlight the intensity and wide range of anthropogenic influences on marine ecosystems, beginning as early as 1,300 years ago and extensively shaping early, baseline populations of cod and other taxa. The importance of consolidating archaeological, statistical and ecological analyses to reconstruct past ecologies of marine fauna is similarly highlighted. The combined findings from Lyminge and Coppergate with past studies from northwest Europe illustrate the advanced knowledge of marine environments and fishing technologies and strategies obtained by coastal communities in the 8th – 9th cent.CE. The research clearly indicates that this early marine fishing was motivated by the coastal location of the sites, as well as the rise of new ecclesiastical, elite hierarchies in the wider area of northwest Europe.

Finally, in light of the size reduction of marine taxa such as cod due to human exploitation in modern periods, further studies that would reveal a detailed chronology of this decline are needed. Archaeological and biological research can assist in informing and refining the emerging timeline of this chain of events. This research, has provided methods for cod size estimations and presented exploitation efforts of larger-bodied, healthier, and more reproductive populations from the 8th – 9th cent.CE. It has therefore demonstrated the importance of revealing baseline populations and corresponding archaeological fishing and fish processing activities prior to large-scale commercial fishing practices.

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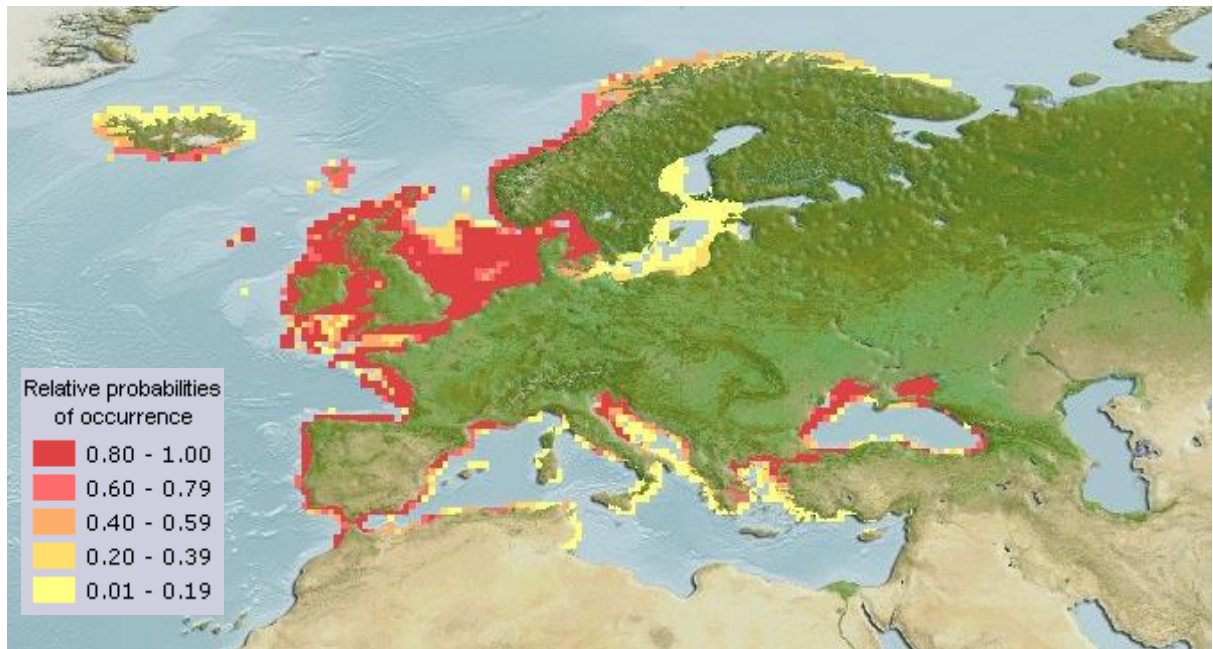
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Appendices

Appendix.1. Distribution maps of the native ranges of species involved in this study, listed alphabetically

Maps taken from Kaschner et al., 2019, Introduction Section. Updated versions are scheduled for release in 2024.

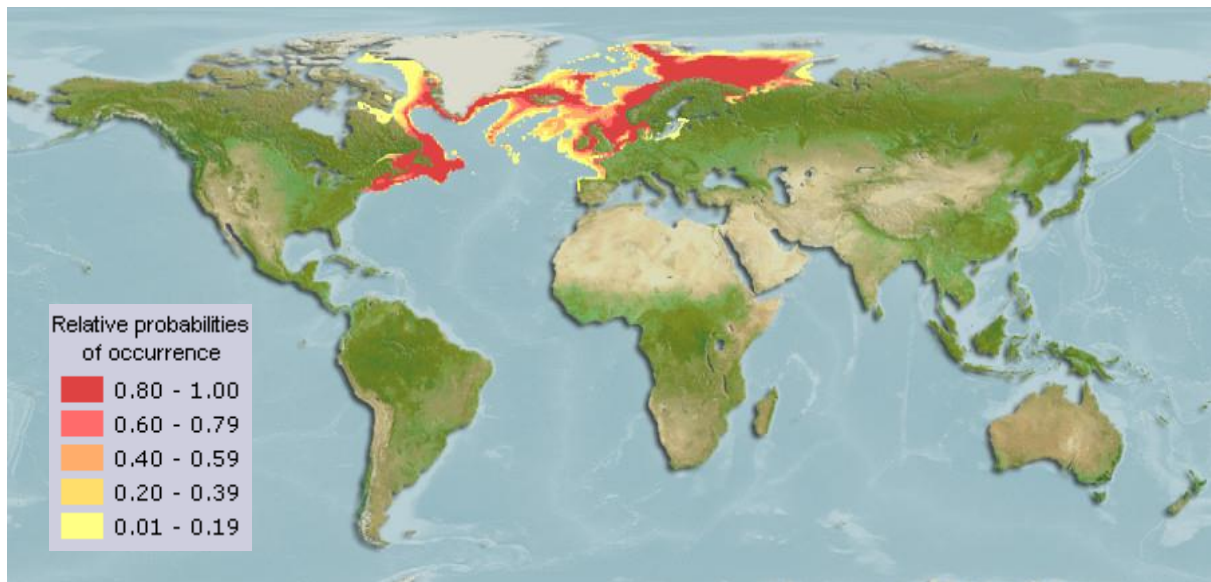
***Acipenser sturio* (European sea sturgeon)**



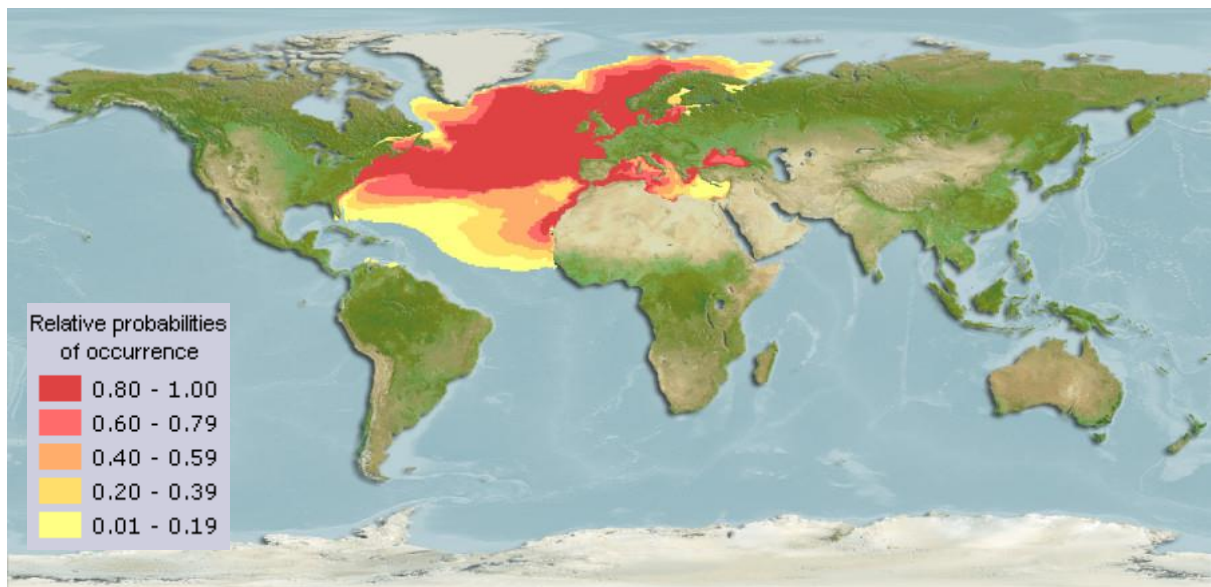
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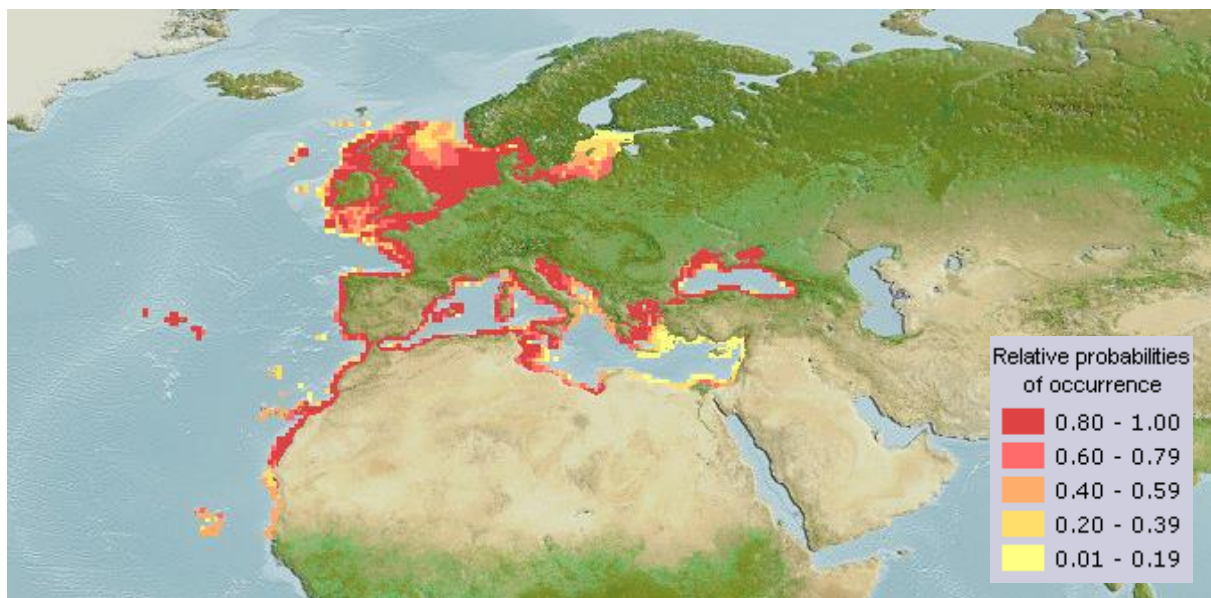
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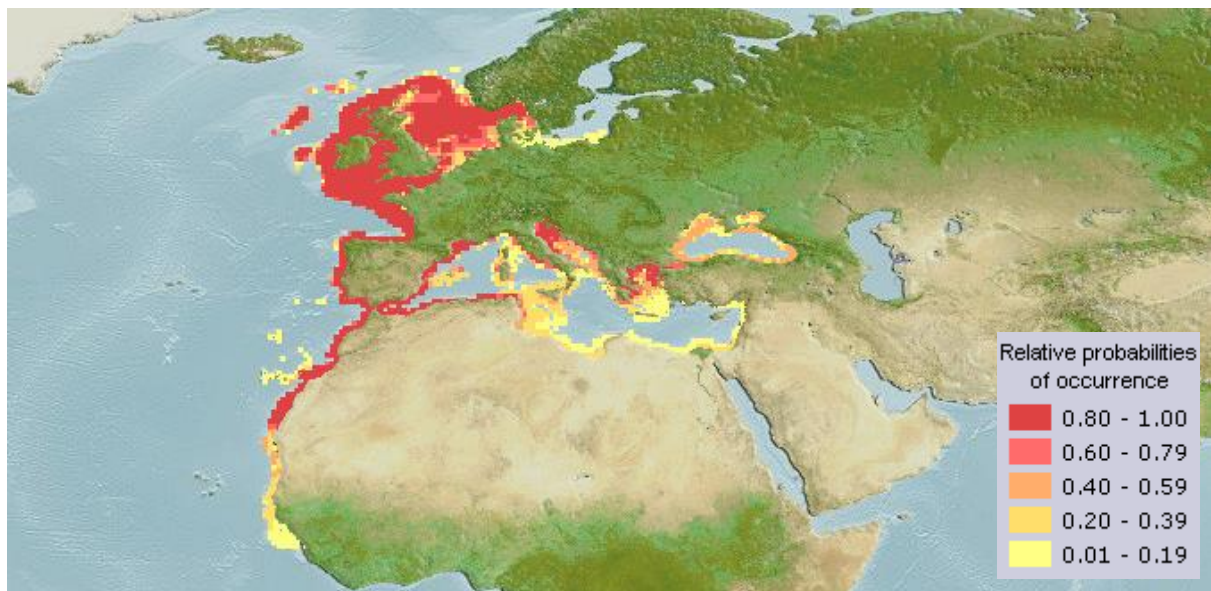
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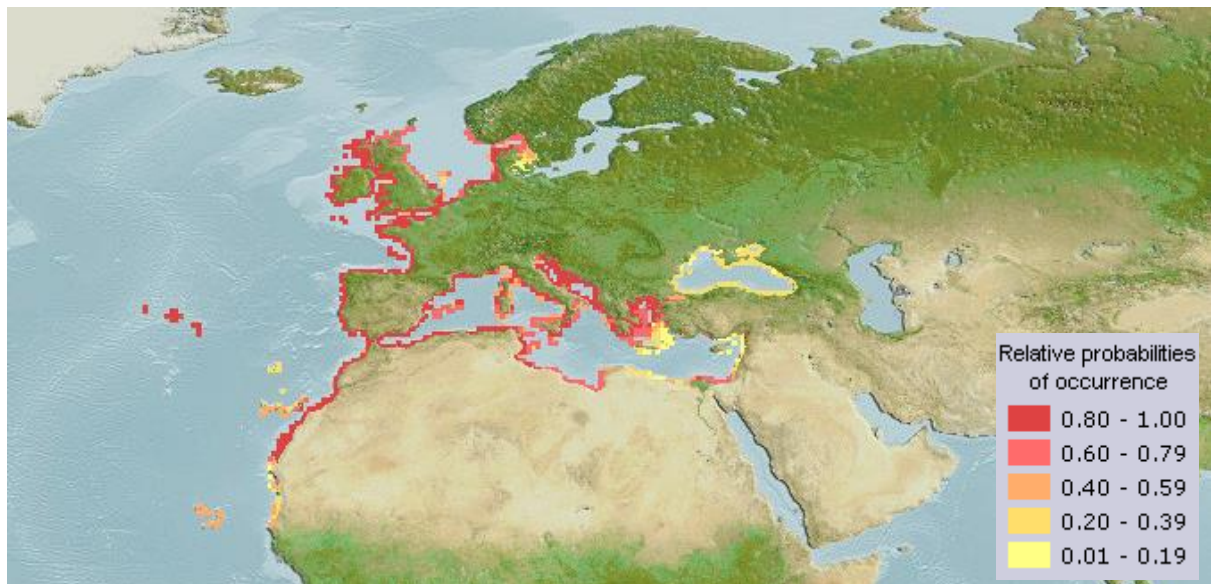
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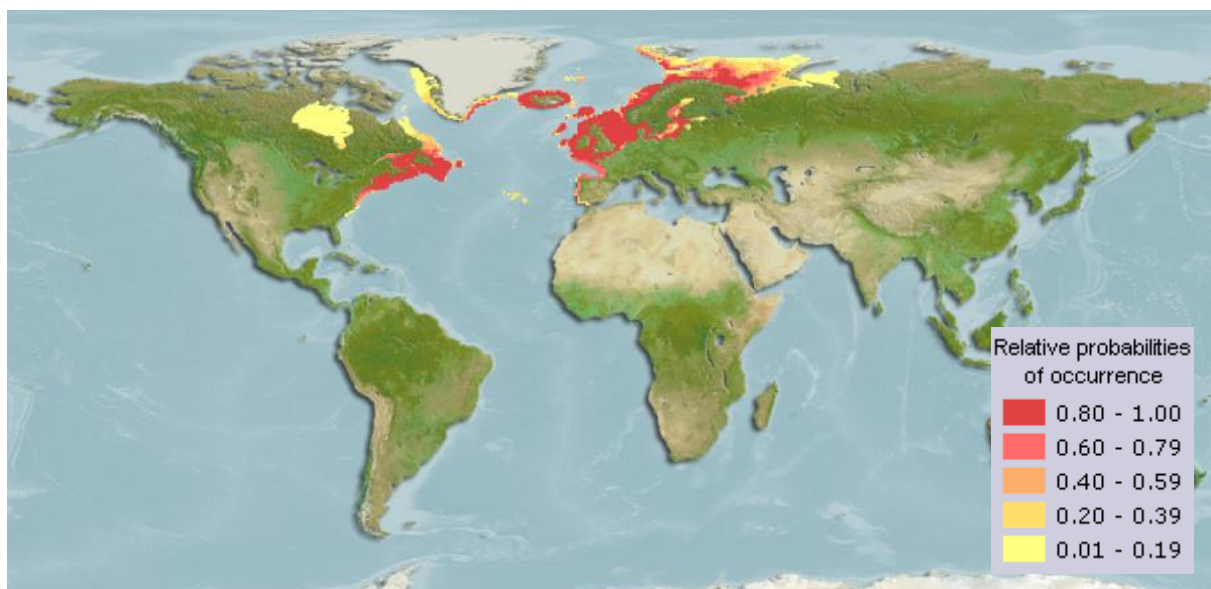
***Chelidonichthys lucerna* (Tub gurnard)**



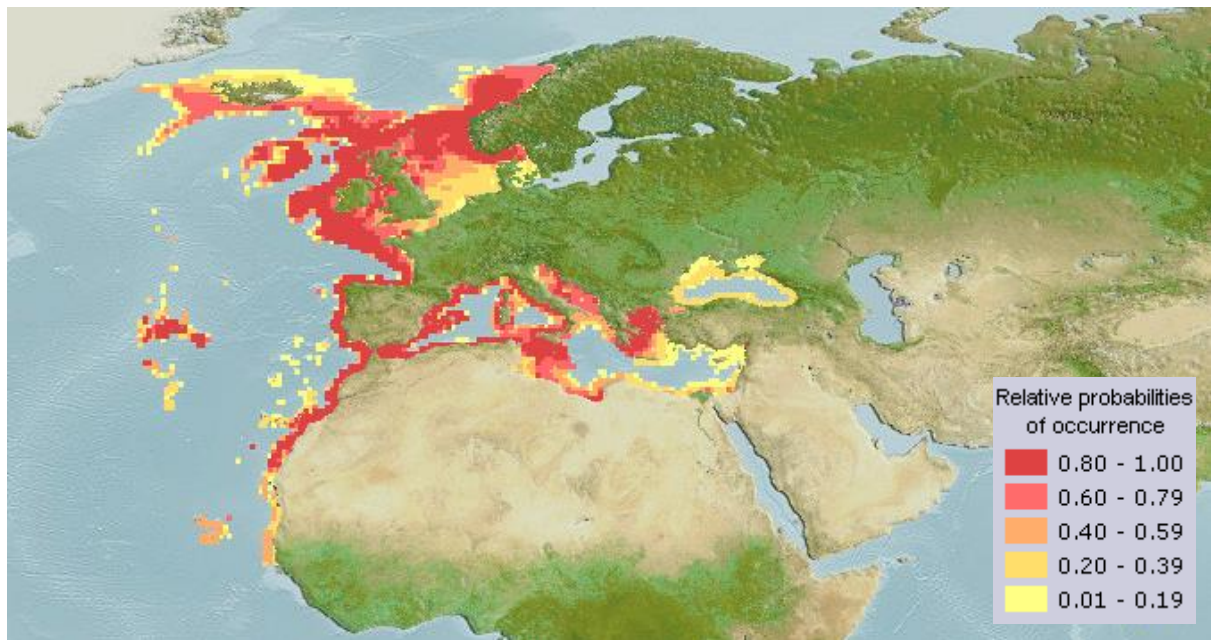
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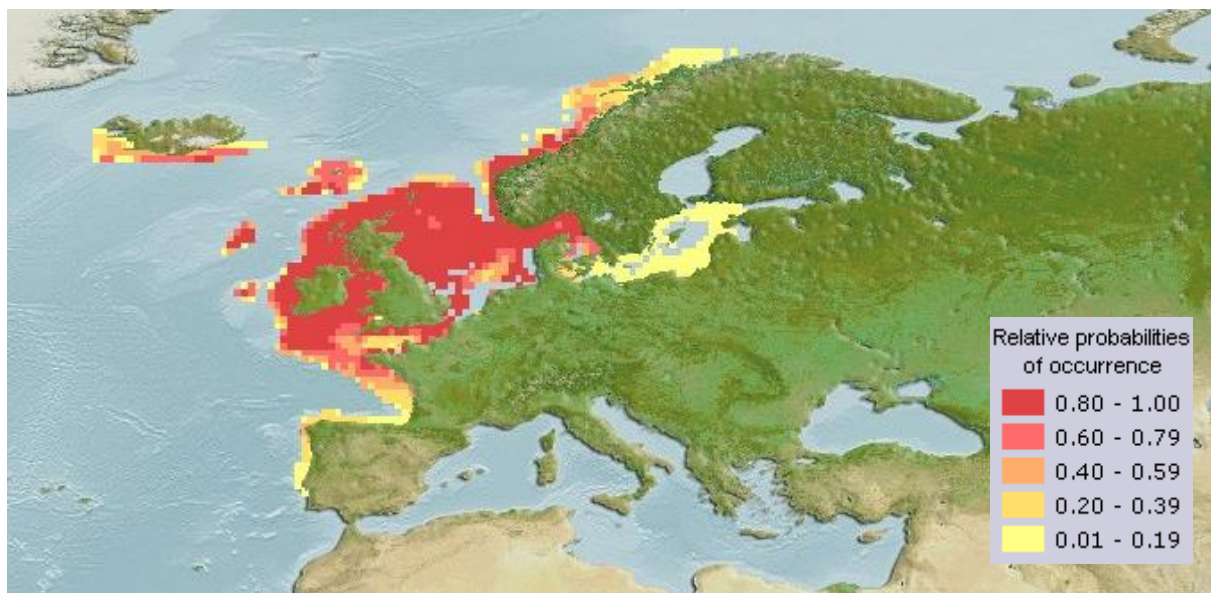
***Clupea harengus* (Atlantic herring)**



***Conger conger* (conger eel)**



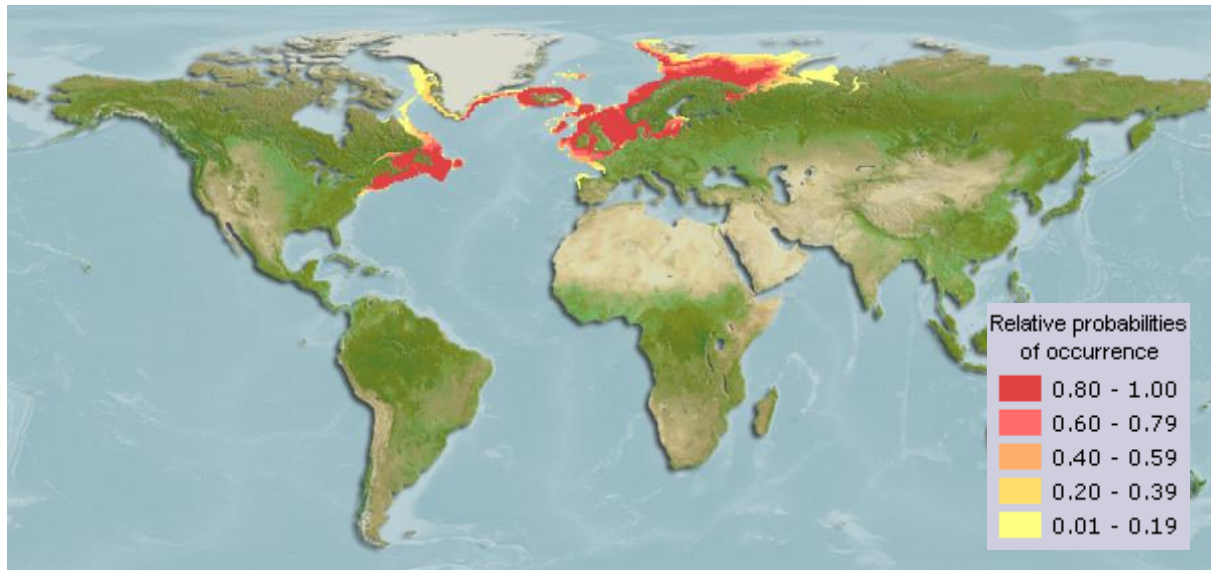
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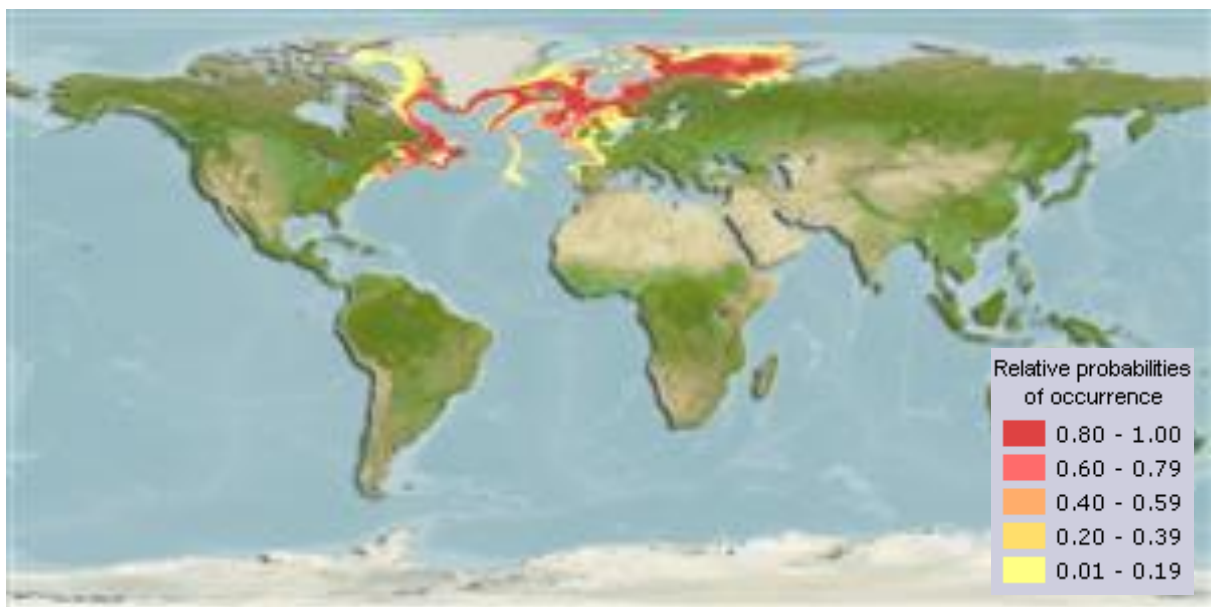
***Esox lucius* (Pike)**

Published distribution data not mapped for this species

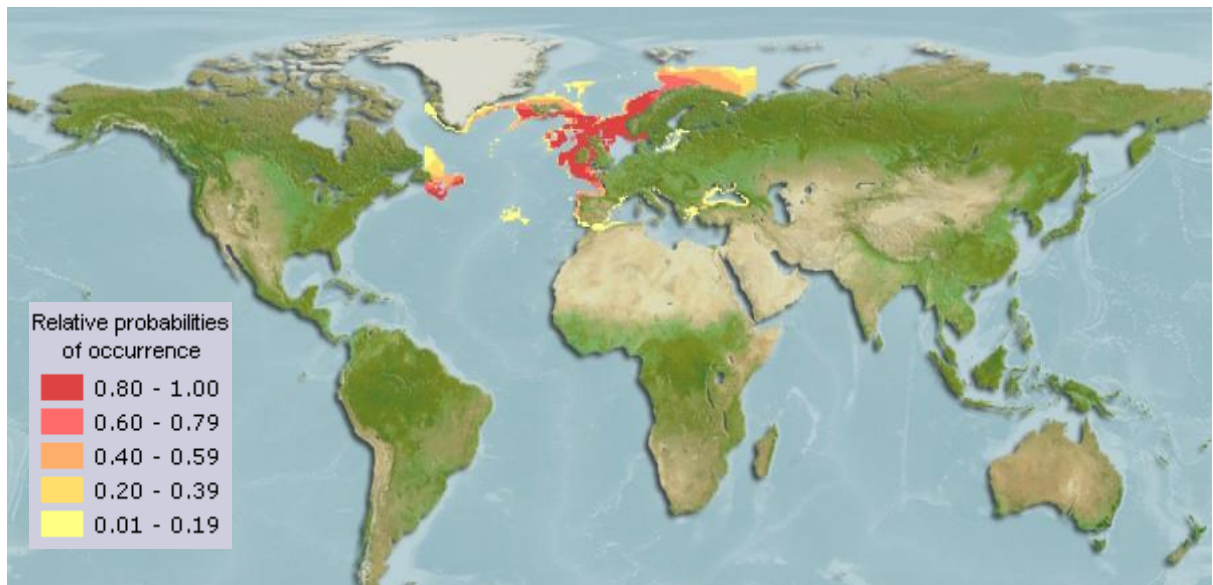
***Gadus morhua* (Atlantic cod)**



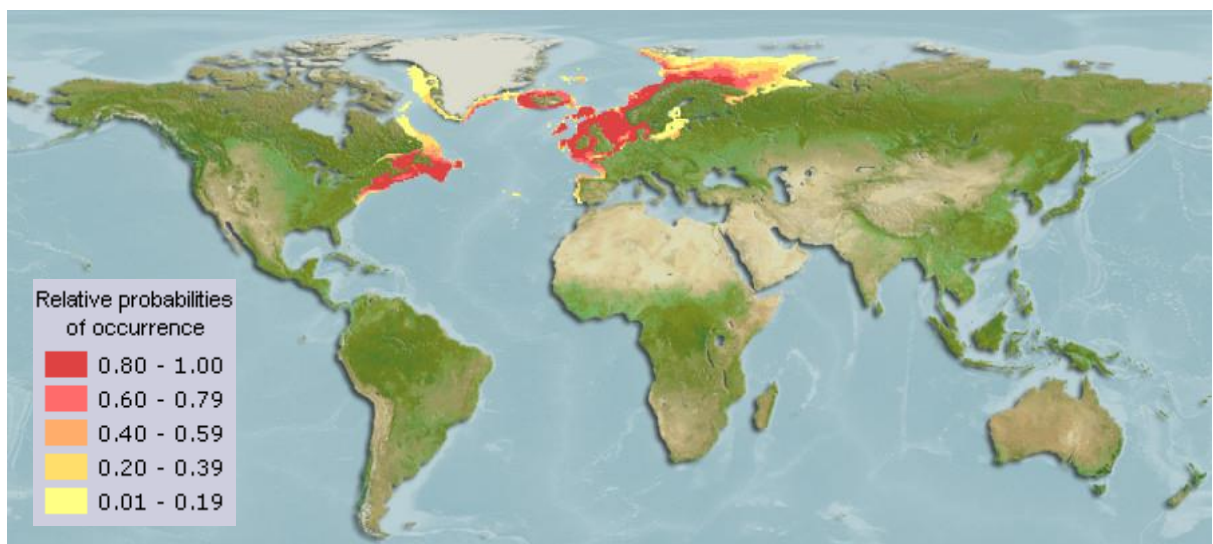
***Hippoglossus hippoglossus* (Atlantic halibut)**



***Leucoraja naevus* (Cuckoo ray)**



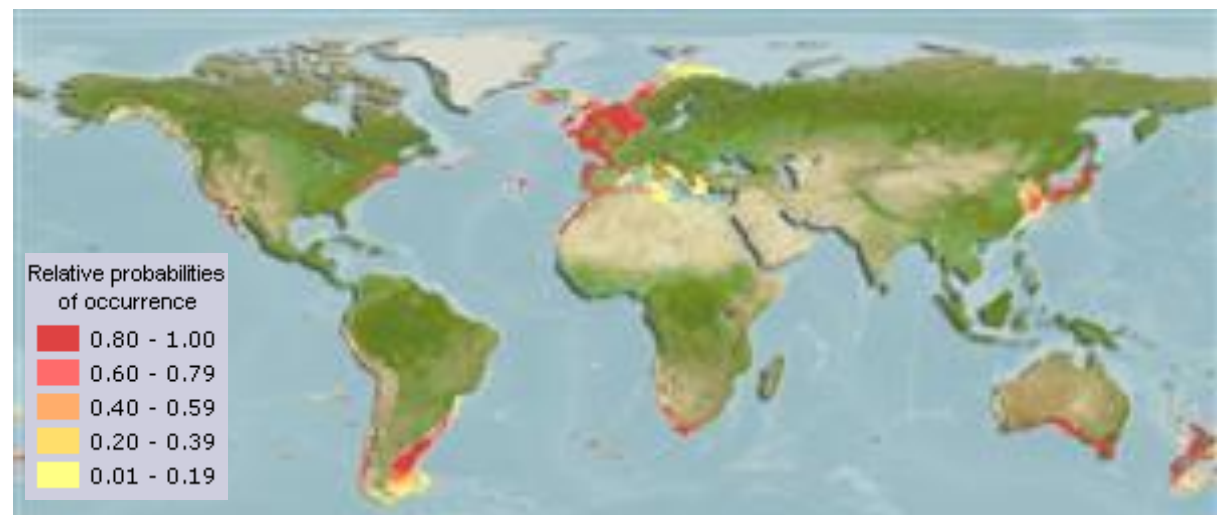
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***Merlangius merlangus* (Whiting)**



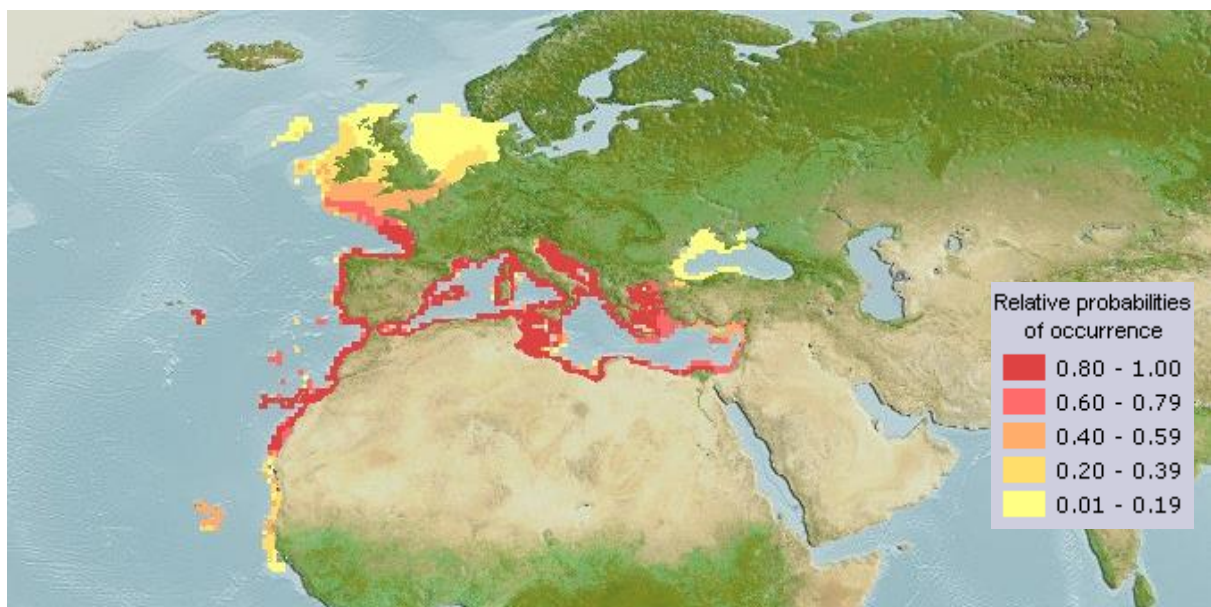
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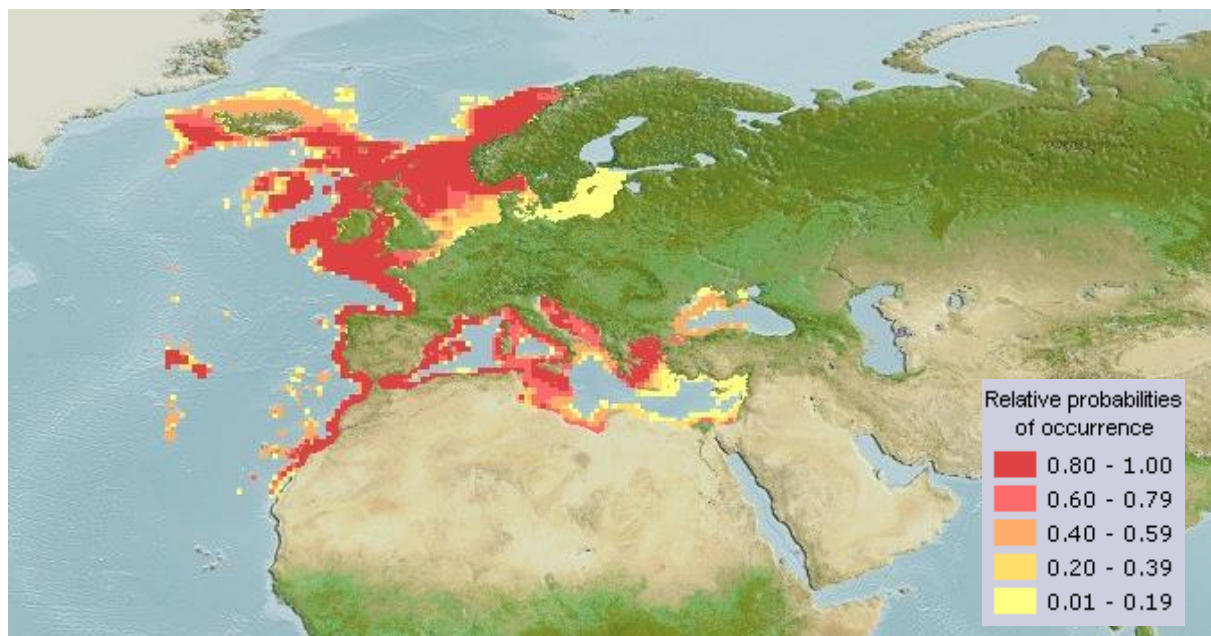
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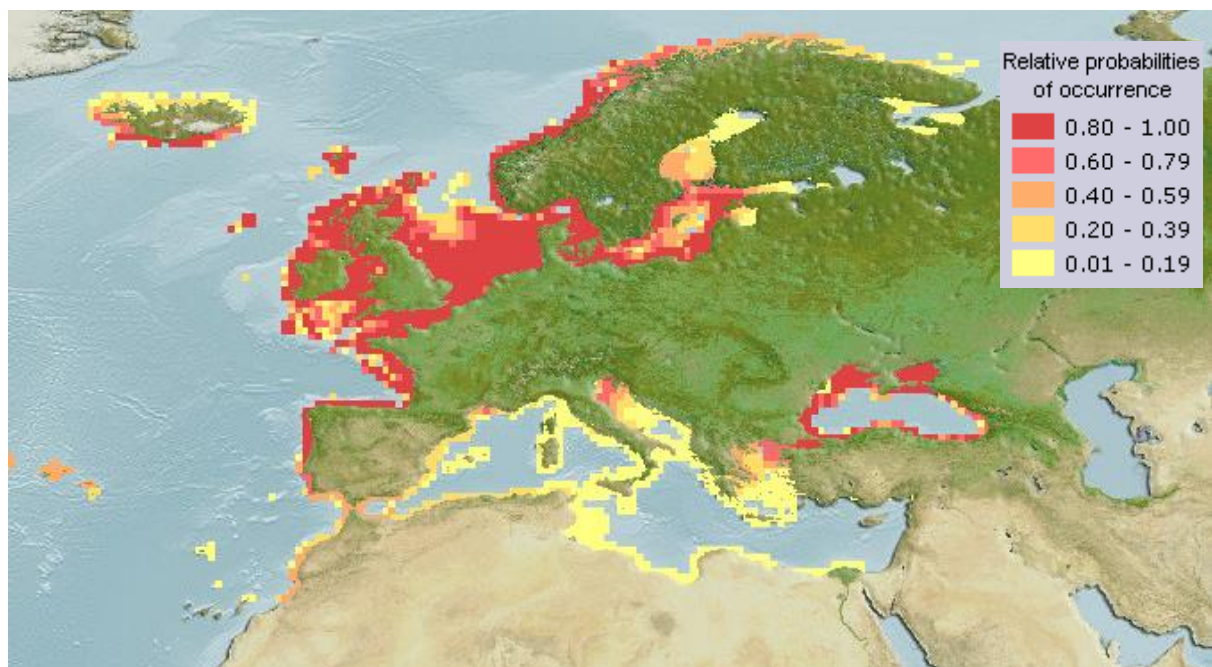
***Pegallus erythrinus* (Common pandora)**



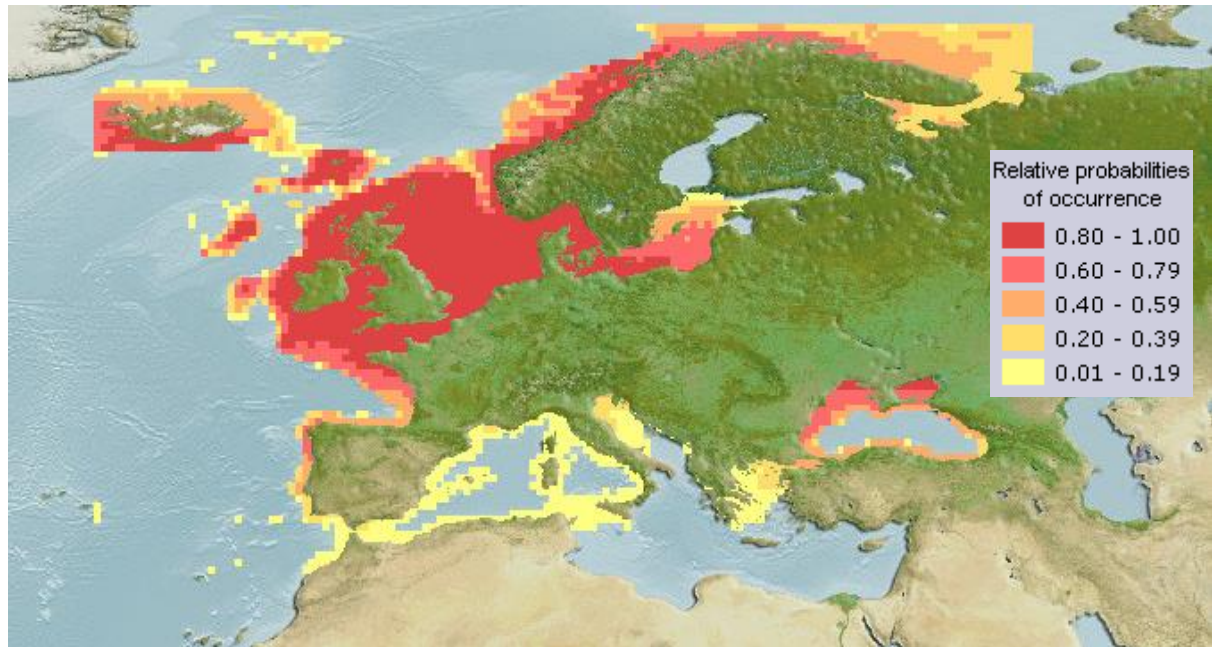
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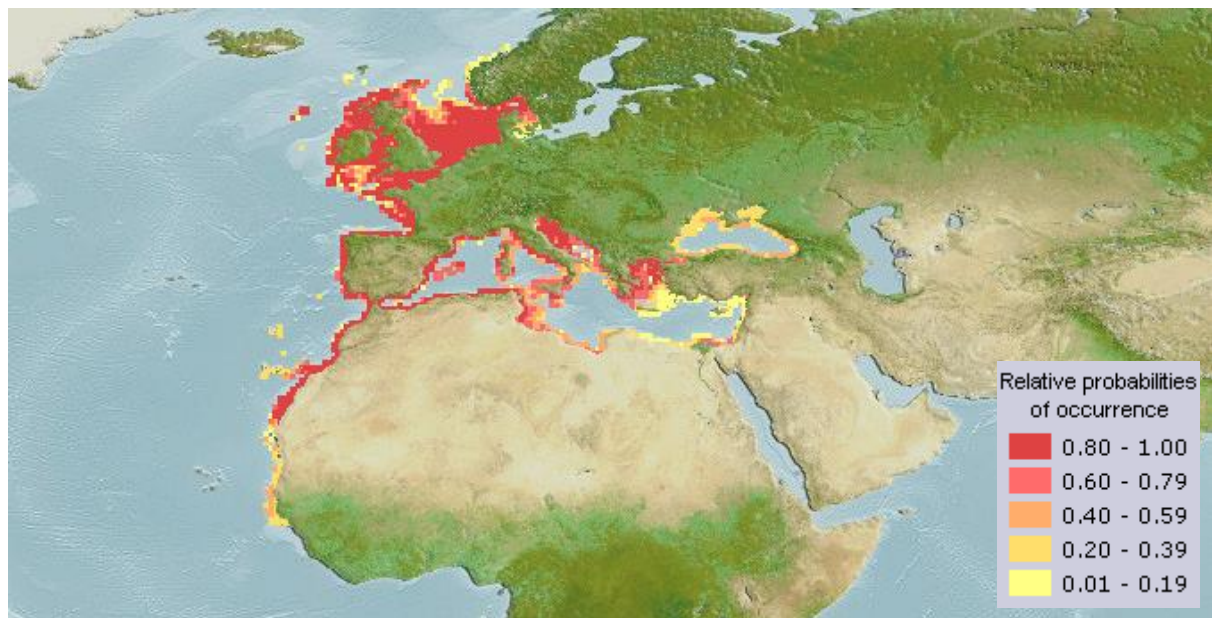
***Platichthys flesus* (European flounder)**



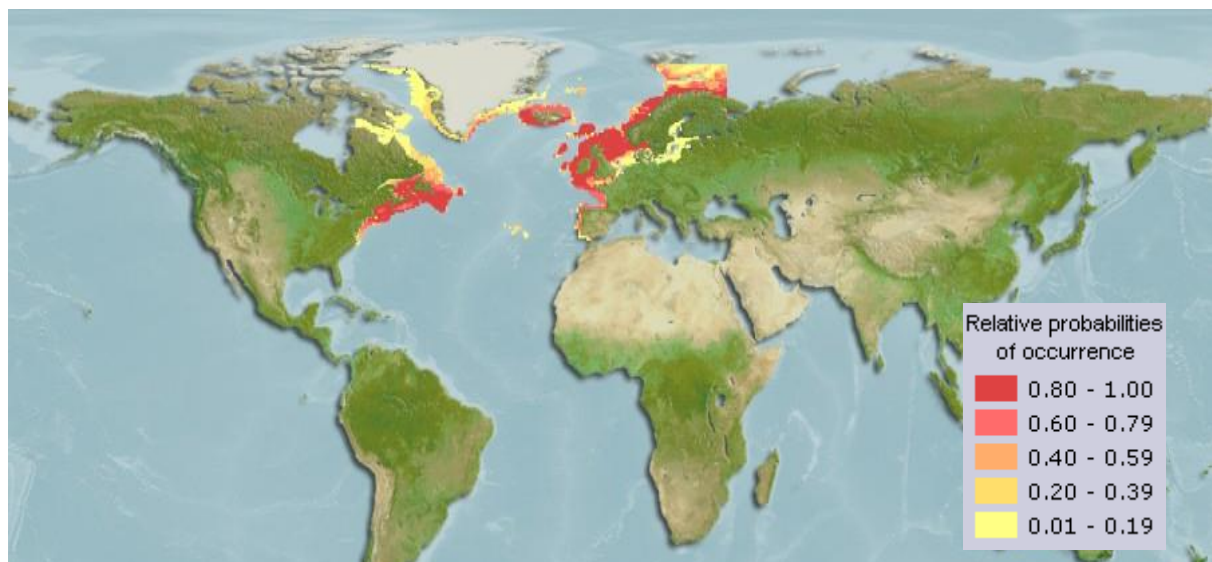
***Pleuronectes platessa* (European plaice)**



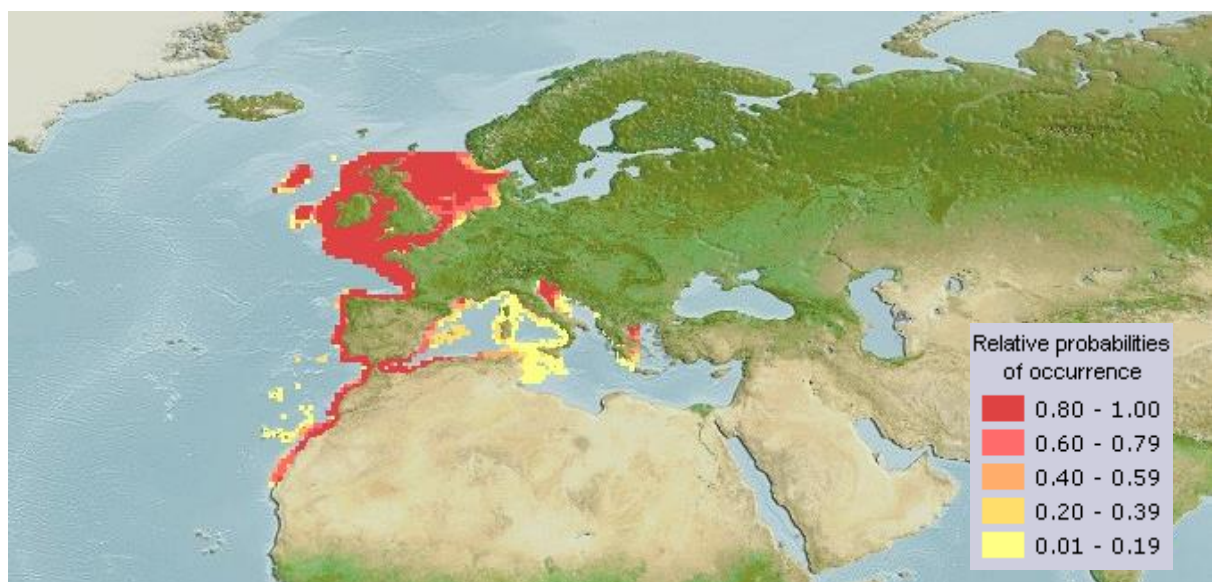
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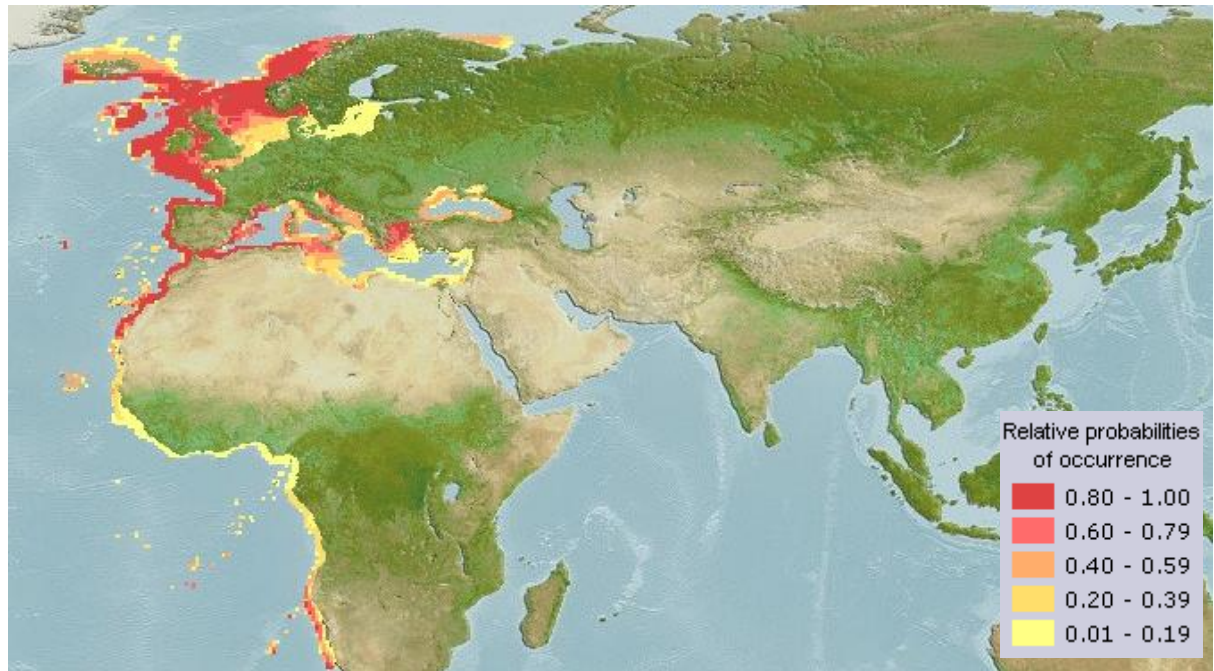
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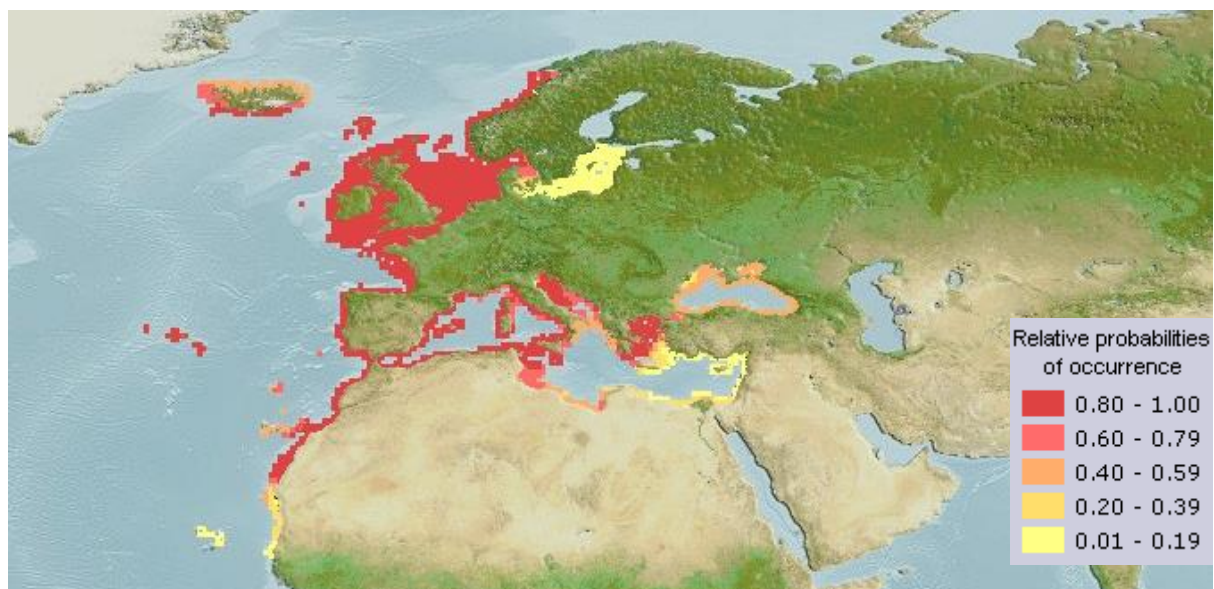
***Raja brachyura* (Blonde ray)**



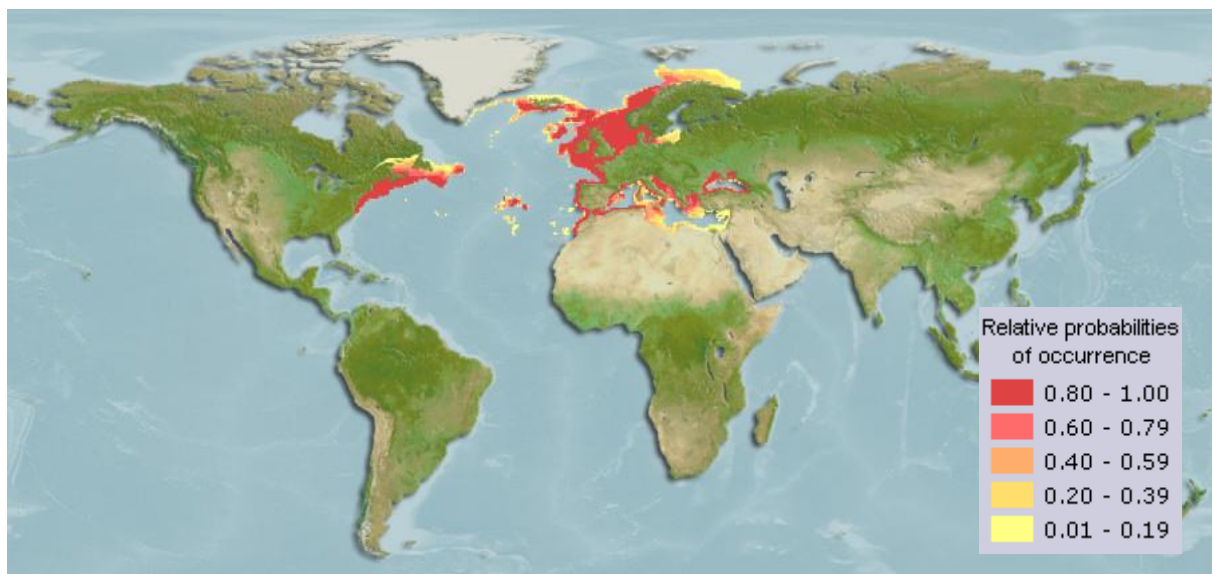
***Raja clavata* (Thornback ray)**



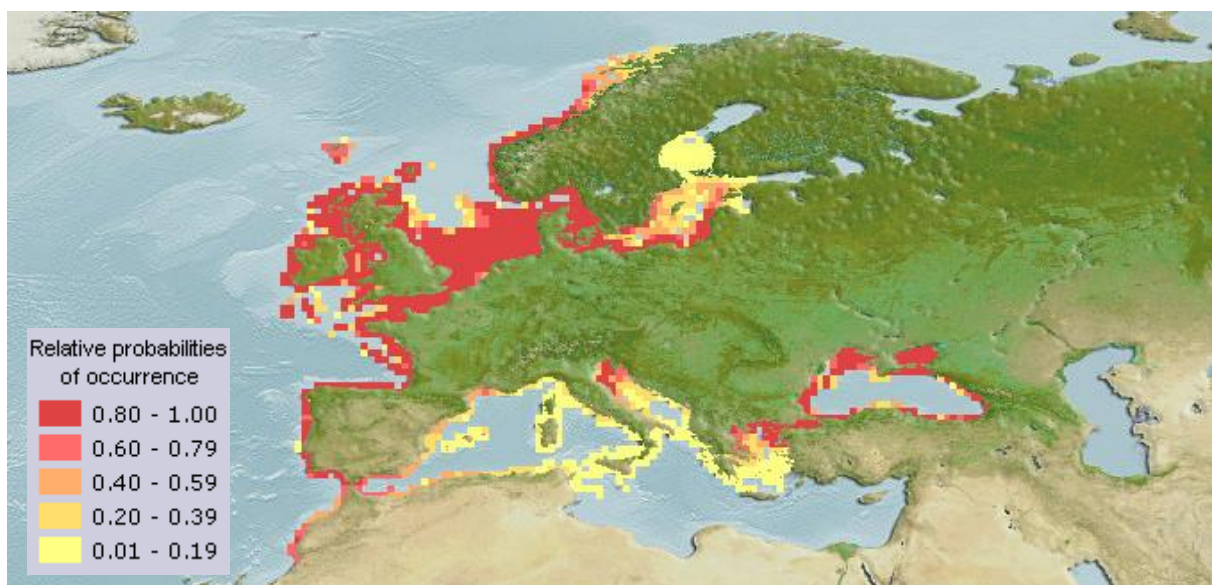
***Sardina pilchardus* (European pilchard)**



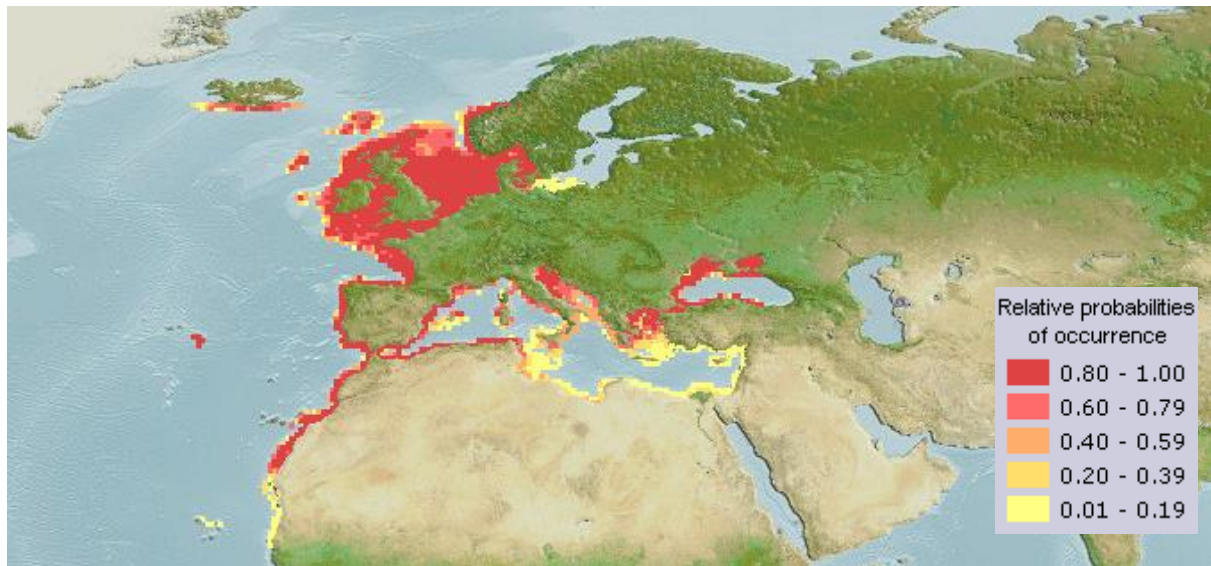
***Scomber scombrus*, (Atlantic mackerel)**



***Scophthalmus maximus* (Turbot)**



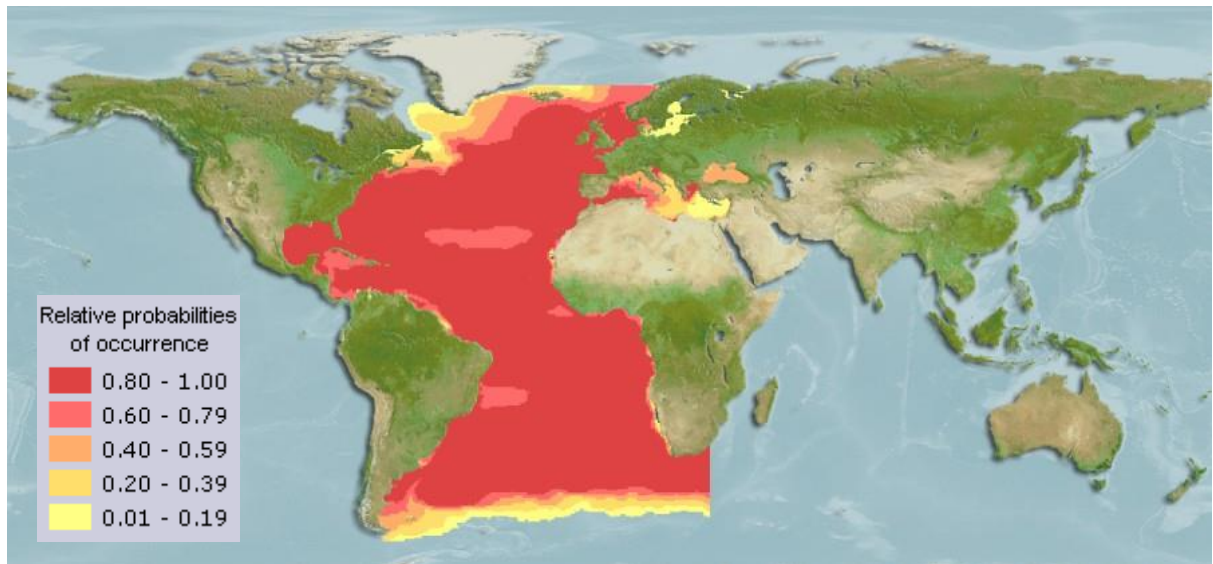
***Solea solea* (common sole)**



***Spondyliosoma cantharus* (Black Seabream)**



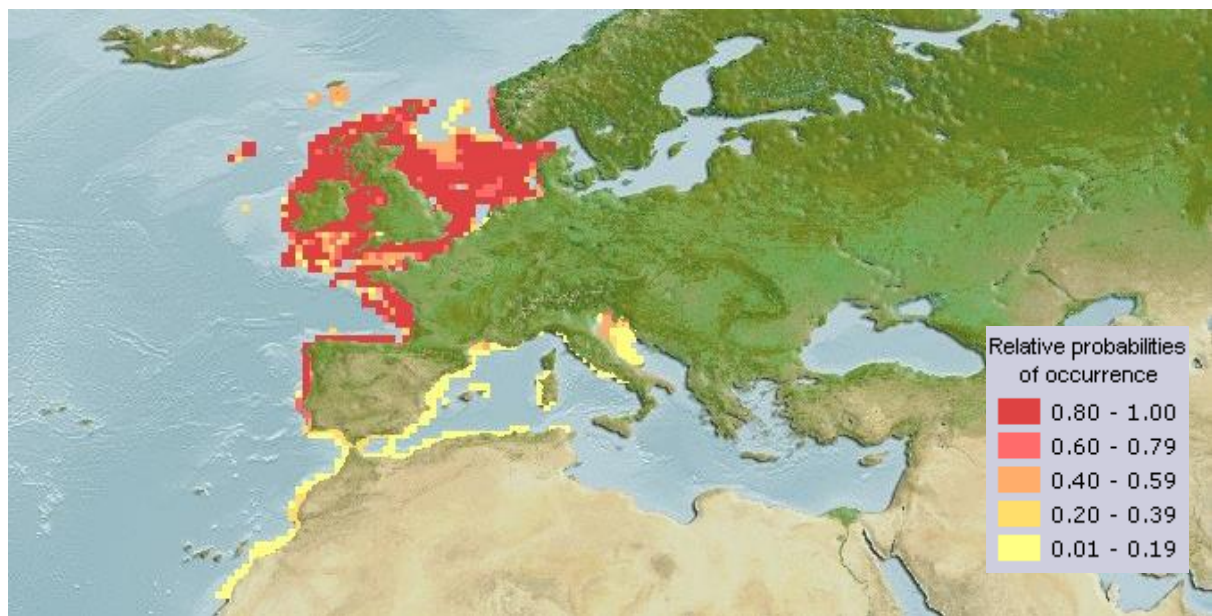
***Thunnus thynnus* (Atlantic bluefin tuna)**



***Trachurus trachurus* (Atlantic horse mackerel)**



***Trisopterus luscus* (Pouting)**



Appendix.2.1. Table of Atlantic cod (*Gadus morhua*) reference specimens used to construct the vertebrae regression models in this research, sorted from smallest to largest Total Length (TL)

ID	TL (cm)	Collection
JHB210	15.50	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB209	20.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB201	30.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
YZL1449	40.30	University of York
YZL1627	45.00	University of York
RB4	47.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
RB3	47.10	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
RB1	50.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
RB2	50.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB501	51.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB11	56.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB104	60.50	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB112	62.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB119	62.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB707	62.50	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge

ID	TL (cm)	Collection
JHB117	65.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB111	65.50	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB114	66.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB709	67.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB116	69.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
JHB115	70.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
YZL1943	82.00	University of York
JHB719	86.50	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
YZL1272	89.00	University of York
JHB720	95.00	The Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge
YZL1271	97.00	University of York
1054SOU	100.00	University of Southampton
YZL1267	102.00	University of York
457SOU	103.00	University of Southampton
YZL1268	106.00	University of York
YZL1269	107.00	University of York
YZL1274	109.00	University of York
579SOU	116.90	University of Southampton
O943Bergen	118.00	University of Bergen

ID	TL (cm)	Collection
O386Bergen	141.00	University of Bergen
YZL1610	150.00	University of York

Appendix.2.2. Morphological characteristics of the Atlantic cod (*Gadus morhua*) vertebrae groups used in this research

The vertebral column of Atlantic cod (*Gadus morhua*) was divided into three morphologically distinct abdominal groups (Table.A.2.2, Fig.A.2.2). The first five abdominal vertebrae (AV1 - 5) were later placed into individual sub-groups due to their distinct morphology and to the increased accuracy of using individual vertebrae numbers in the regression models. The caudal vertebrae were classified into two groups, CV1 and CV2, while the most posterior vertebrae, CV3, (V.46 - V.53, including penultimate and ultimate vertebrae), were omitted from this research due to their relatively small size (<0.85 cm) and to their rare occurrence in the archaeological record. The determination of the morphological groups was based on the original groups defined in Barrett, 1997 (p.621). The names and definitions of vertebrae anatomy followed Wheeler & Jones, 1989, and Watt et al., 1997.

Table.A.2.2. Vertebrae group division based on morphological characteristics.

Vertebrae Group	Vertebrae numbers	Morphological Characteristics	Regression Model Provision
First vertebrae (FV)	1	Robust neural parapophysis, two anterior proximal processes connecting to the basioccipital.	Provided for individual vertebrae number.
Abdominal group 1 (AV1)	2-5	Each vertebra has a unique morphology, including the side grooves and parapophysis.	Provided for individual vertebrae numbers.
Abdominal group 2 (AV2)	6-10	Sharp, shallow asymmetrical grooves on the ventral side; parapophysis at sharp angles to the centrum body; ridges on the dorsal side.	Provided for vertebrae group.

Vertebrae Group	Vertebrae numbers	Morphological Characteristics	Regression Model Provision
Abdominal group 3 (AV3)	11-20	Deep grooves on the ventral side; parapophysis at a decreasing angle to the centrum body.	Provided for vertebrae group.
Caudal group 1 (CV1)	21-37	Square shape of the lateral sides and neural spines at a relatively large angle to the centrum body.	Provided for vertebrae group.
Caudal group 2 (CV2)	38-45	Waisted/hourglass shape of the lateral side; neural spines at decreased angles to the centrum body; ventral ridges that decrease and disappear with vertebrae number.	Provided for vertebrae group.
Caudal group 3* (CV3) *Includes penultimate + ultimate vertebrae	46-53	Features are relatively ambiguous due to the small size; decreased waisted/hourglass shape of the lateral side; neural spines lie nearly flat against the dorsal and ventral sides of the centrum body.	Not provided.

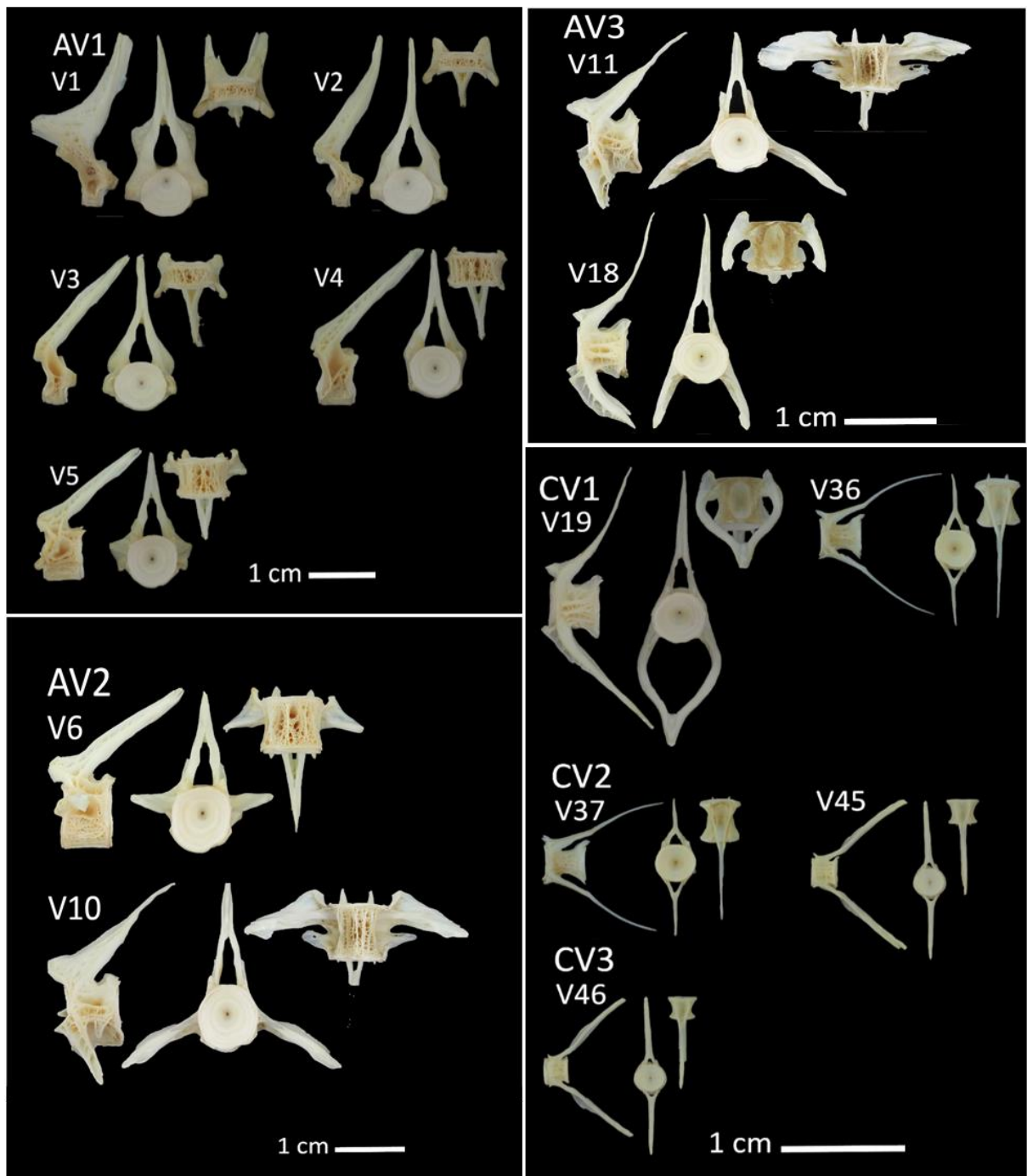
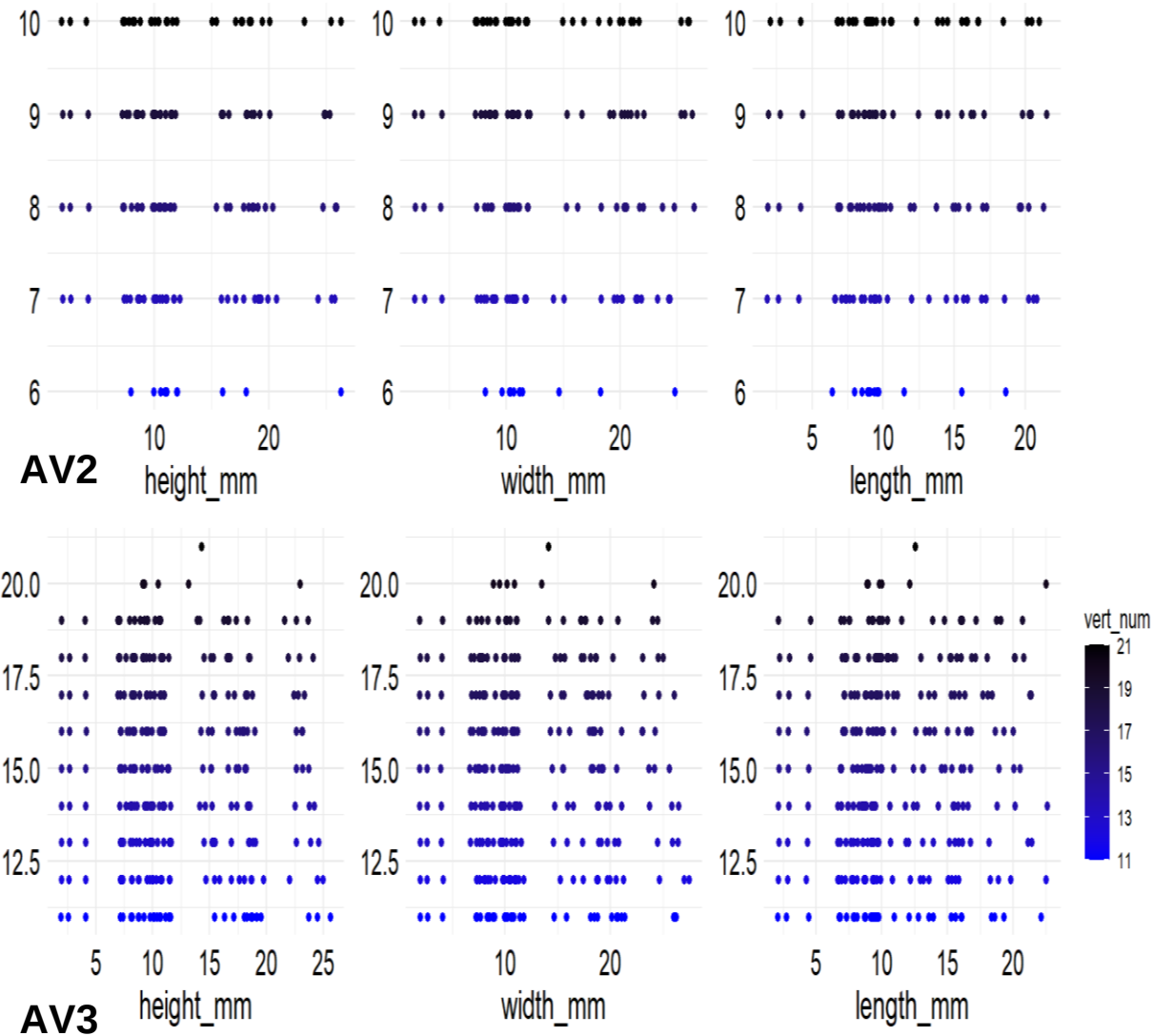
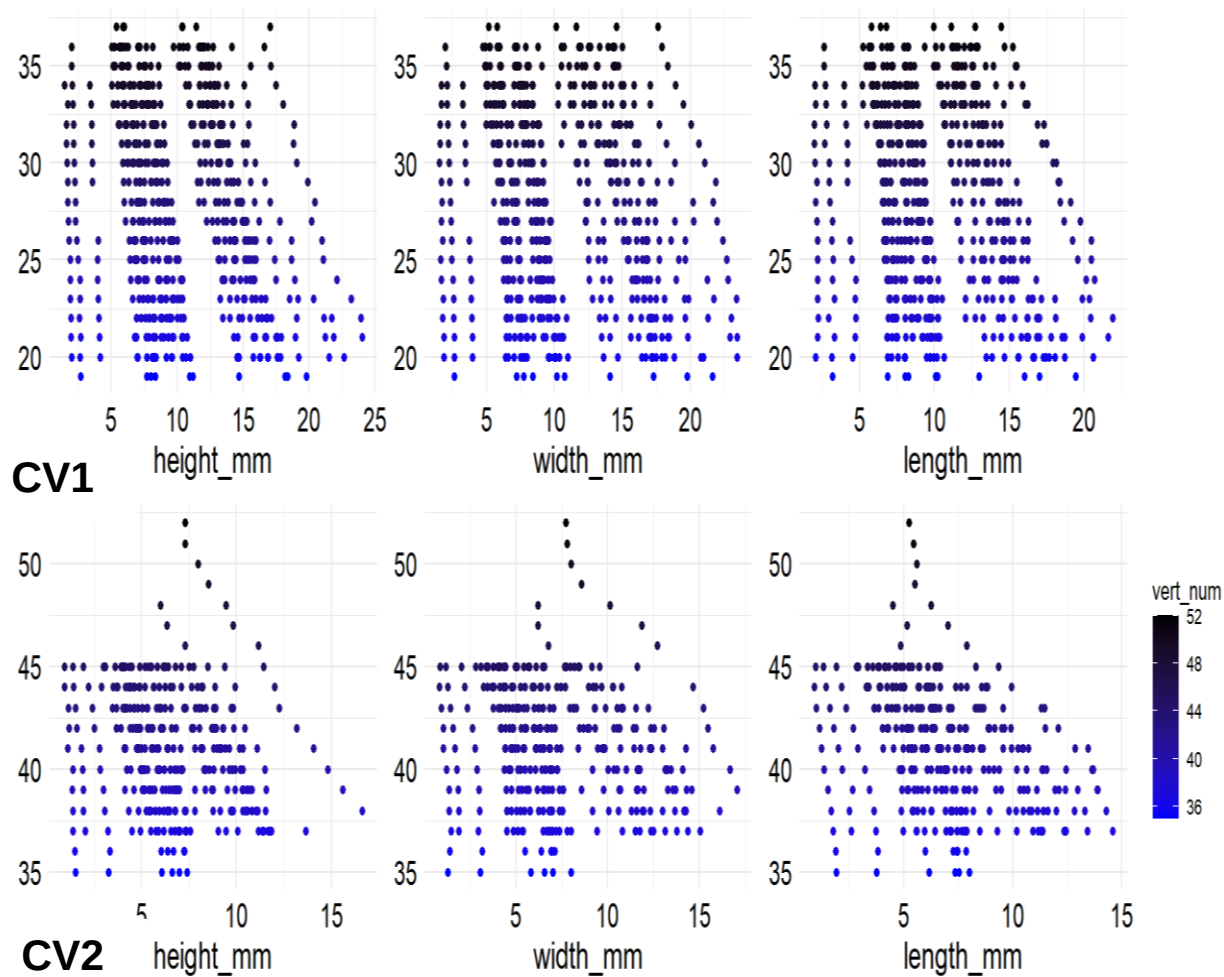


Figure.A.2.2. Classifications of vertebrae into five morphological groups: V1; V2; V3; V4; V5; AV2; AV3; CV1; CV2. The first and last vertebrae of each morphological group, including the omitted CV3 group, is displayed.

Appendix.2.3. Dot plots of Atlantic cod (*Gadus morhua*) vertebra number vs. measurement parameters CH, CW, and LL, by morphological vertebrae group

Dot plots are displayed for the following morphological vertebrae groups, from top to bottom, by row: AV2, AV3, CV1, CV2. For each group, measurement parameters are displayed from left to right: posterior Centrum Height (CH), Centrum Width (CH), Lateral Length (LL), in mm.





Appendix.2.4. AICc (Akaike Information Criterion) selections for Atlantic cod (*Gadus morhua*) vertebrae and cranial regression models.

Vertebrae groups are shown in Table.A.2.4.a and Table.A.2.4.b Cranial elements are shown in Table.A.2.4.c and Table.A.2.4.d.

Table.A.2.4.a AICc rankings of vertebrae groups. AV2 and AV3 groups averaged by individual vertebrae. DF = Degrees of Freedom; Int = intercept ;LogLik = Log Likelihood; AICc = AIC value for small samples; Delta = difference between the best and current model; Weight = proportion of the total predictive power in the model (S.2.1).

Vertebrae group	Model	DF	Int	LogLik	AICc	Delta	Weight
V1	V1_LogTL_h_l	4	2.03	69.56	-129.70	0	0.72
V1	V1_LogTL_h_l_i	5	2.02	69.63	-127.10	2.62	0.19
V1	V1_LogTL_height	3	1.95	65.70	-124.60	5.14	0.06
V1	V1_LogTL_w_h	4	1.96	65.82	-122.30	7.48	0.02
V1	V1_LogTL_length	3	2.14	63.57	-120.30	9.40	0.01
V1	V1_LogTL_w_l	4	2.08	64.78	-120.20	9.55	0.01
V1	V1_LogTL_w_h_i	5	1.92	66.00	-119.90	9.87	0.01
V1	V1_LogTL_w_l_i	5	2.05	64.93	-117.70	12.01	0
V1	V1_LogTL_width	3	1.93	58.71	-110.60	19.12	0
V2	AV1_LogTL_height2	3	1.94	67.33	-127.80	0	0.48
V2	AV1_LogTL_h_l2	4	2.00	67.99	-126.60	1.28	0.26
V2	AV1_LogTL_w_h2	4	1.94	67.35	-125.30	2.57	0.13
V2	AV1_LogTL_h_l_i2	5	2.02	68.16	-124.10	3.73	0.08
V2	AV1_LogTL_w_h_i2	5	1.97	67.47	-122.70	5.12	0.04
V2	AV1_LogTL_w_l2	4	2.08	64.77	-120.10	7.72	0.01
V2	AV1_LogTL_w_l_i2	5	2.07	64.79	-117.40	10.48	0
V2	AV1_LogTL_length2	3	2.22	62.09	-117.30	10.49	0
V2	AV1_LogTL_width2	3	1.91	60.21	-113.60	14.24	0
V3	AV1_LogTL_h_l3	4	1.99	70.37	-131.30	0	0.38
V3	AV1_LogTL_height3	3	1.95	68.99	-131.10	0.17	0.35
V3	AV1_LogTL_h_l_i3	5	2.02	70.72	-129.20	2.10	0.13
V3	AV1_LogTL_w_h3	4	1.95	69.15	-128.90	2.44	0.11
V3	AV1_LogTL_w_h_i3	5	1.98	69.38	-126.50	4.78	0.03
V3	AV1_LogTL_w_l3	4	2.03	64.71	-120.00	11.33	0
V3	AV1_LogTL_length3	3	2.14	62.15	-117.50	13.84	0
V3	AV1_LogTL_w_l_i3	5	2.05	64.77	-117.30	14.00	0
V3	AV1_LogTL_width3	3	1.92	61.46	-116.10	15.22	0
V4	AV1_LogTL_height4	3	1.93	75.05	-143.30	0	0.33
V4	AV1_LogTL_w_h4	4	1.93	76.16	-142.90	0.35	0.28
V4	AV1_LogTL_w_h_i4	5	1.99	77.16	-142.20	1.13	0.19
V4	AV1_LogTL_h_l4	4	1.91	75.55	-141.70	1.58	0.15

Vertebrae group	Model	DF	Int	LogLik	AICc	Delta	Weight
V4	AV1_LogTL_h_l_i4	5	1.94	76.04	-139.90	3.36	0.06
V4	AV1_LogTL_width4	3	1.92	62.90	-119.00	24.30	0
V4	AV1_LogTL_w_l4	4	1.95	64.12	-118.90	24.43	0
V4	AV1_LogTL_w_l_i4	5	1.95	64.12	-116.10	27.19	0
V4	AV1_LogTL_length4	3	2.05	57.48	-108.20	35.13	0
V5	AV1_LogTL_height5	3	1.92	75.69	-144.60	0	0.45
V5	AV1_LogTL_h_l5	3	1.94	76.45	-143.50	1.06	0.27
V5	AV1_LogTL_w_h5	4	1.92	75.72	-142.10	2.52	0.13
V5	AV1_LogTL_h_l_i5	5	1.97	76.85	-141.60	3.01	0.10
V5	AV1_LogTL_w_h_i5	5	1.96	76.18	-140.20	4.36	0.05
V5	AV1_LogTL_w_l5	4	1.96	71.69	-134.00	10.57	0
V5	AV1_LogTL_width5	3	1.94	69.80	-132.80	11.78	0
V5	AV1_LogTL_w_l_i5	5	1.96	71.69	-131.20	13.33	0
V5	AV1_LogTL_length5	3	2.00	66.29	-125.80	18.80	0
AV2	AV2_LogTL_height	3	1.94	74.24	-141.70	0	0.56
AV2	AV2 AV2_LogTL_w_h	4	1.94	74.34	-139.20	2.41	0.17
AV2	AV2_LogTL_h_l	4	1.94	74.24	-139.10	2.60	0.15
AV2	AV2_LogTL_w_h_i	5	1.97	74.59	-137.00	4.69	0.15
AV2	AV2_LogTL_h_l_i	5	1.97	74.53	-136.80	4.82	0.05
AV2	AV2_LogTL_width	5	1.96	69.60	-132.40	9.29	0.01
AV2	AV2_LogTL_w_l	4	1.94	70.13	-130.80	10.82	0
AV2	AV2_LogTL_w_l_i	5	1.94	70.14	-128.00	13.61	0
AV2	AV2_LogTL_length	3	1.92	67.18	-127.50	14.13	0
AV3	AV3_LogTL_width	3	1.97	75.59	-144.40	0	0.53
AV3	AV3_LogTL_w_l	4	1.95	75.90	-142.40	1.98	0.20
AV3	AV3_LogTL_w_h	4	1.97	75.65	-141.90	2.48	0.15
AV3	AV3_LogTL_w_l_i	5	1.94	75.92	-139.60	4.73	0.15
AV3	AV3_LogTL_w_h_i	5	1.96	75.69	-139.20	5.19	0.04
AV3	AV3_LogTL_height	3	1.93	71.47	-136.10	8.25	0.01
AV3	AV3_LogTL_h_l	4	1.90	72.75	-136.10	8.27	0.01
AV3	AV3_LogTL_length	3	1.86	70.71	-134.60	9.75	0
AV3	AV3_LogTL_h_l_i	5	1.92	72.88	-133.50	10.82	0
CV1	LogTL_height_length_i_w thp	9	1.88	1096.66	-2175.00	0	0.99
CV1	LogTL_length_width_i_w thp	9	2.13	1091.65	-2165.00	10.01	0.01
CV1	LogTL_height_width_i_w thp	9	1.98	1086.25	-2154.20	20.83	0
CV1	LogTL_height_length_m_ wthp	5	1.70	1082.05	-2154.00	21.02	0
CV1	LogTL_length_width_m_w thp	5	1.76	1082.01	-2153.90	21.08	0
CV1	LogTL_height_width_m_w thp	5	1.79	1079.12	-2148.10	26.86	0
CV1	LogTL_height_i_wthp	5	1.94	1067.49	-2124.90	50.13	0

Vertebrae group	Model	DF	Int	LogLik	AICc	Delta	Weight
CV1	LogTL_width_m_wthp	4	1.84	1061.81	-2115.60	59.45	0
CV1	LogTL_width_i_wthp	5	1.84	1061.81	-2113.50	61.48	0
CV1	LogTL_length_i_wthp	5	1.95	1061.77	-2113.40	61.57	0
CV1	LogTL_height_m_wthp	4	1.73	1057.36	-2106.70	68.35	0
CV1	LogTL_length_m_wthp	4	1.66	1047.59	-2087.10	87.89	0
CV1	LogTL_width	3	2.02	963.87	-1921.70	253.31	0
CV1	LogTL_length	3	1.86	930.71	-1855.40	319.63	0
CV1	LogTL_height	3	1.98	891.05	-1776.00	398.95	0
CV2	LogTL_height_length_i_lp	9	2.48	577.89	-1137.2	0	1
CV2	LogTL_length_width_i_lp	9	2.52	565.02	-1111.5	25.74	0
CV2	LogTL_height_width_i_lp	9	2.26	541.63	-1064.7	72.52	0
CV2	LogTL_height_width_m_lp	5	2.34	532.48	-1054.8	82.44	0
CV2	LogTL_height_m_lp	4	2.33	524.72	-1041.3	95.90	0
CV2	LogTL_height_i_lp	5	2.29	525.12	-1040.0	97.18	0
CV2	LogTL_height_length_m_lp	5	2.32	524.96	-1039.7	97.47	0
CV2	LogTL_width_m_lp	4	2.356	514.62	-1021.1	116.09	0
CV2	LogTL_length_width_m_lp	5	2.34	515.39	-1020.6	116.62	0
CV2	LogTL_width_i_lp	5	2.34	514.77	-1019.4	117.85	0
CV2	LogTL_length_m_lp	4	2.47	464.13	-920.1	217.07	0
CV2	LogTL_length_i_lp	5	2.52	464.69	-919.2	218.01	0
CV2	LogTL_width	3	2.15	398.57	-791.1	346.13	0
CV2	LogTL_height	3	2.10	387.13	-768.2	369.02	0
CV2	LogTL_length	3	2.14	252.09	-498.1	639.09	0

Table.A.2.4.b. Regression models of vertebrae groups ranked highest by the AICc selections. Groups AV2 and AV3 are averaged by individual vertebrae, marked MEAN. R^2 values are adjusted. Measurement variables are in mm, resulting TLs and errors are in cm (S.2.1).

Vertebrae Group/Number of Measurements	Regression Equation	Residual Standard Error	R^2	n
Pooled Vertebrae	$10^{(2.32+1.93*\text{Log}_{10}(\text{CW})-1.22*\text{log}_{10}(\text{LL})-0.13*\text{Log}_{10}(\text{CW})*\text{Log}_{10}(\text{LL}))/10}$	0.09	0.81	34
V1 (2 measurements)	$10^{(2.03+0.38*\text{Log}_{10}(\text{LL})+0.48*\text{Log}_{10}(\text{CH}))/10}$	0.03	0.98	34
V2 (1 measurement)	$10^{(1.94+\text{Log}_{10}(\text{CH})*0.86)/10}$	0.03	0.98	33
V3 (2 measurements)	$10^{(1.99+0.62*\text{Log}_{10}(\text{CH})+0.24*\text{Log}_{10}(\text{LL}))/10}$	0.03	0.98	33
V4 (1 measurement)	$10^{(1.93+\text{Log}_{10}(\text{CH})*0.85)/10}$	0.03	0.99	34
V5 (1 measurement)	$10^{(1.92+\text{Log}_{10}(\text{CH})*0.84)/10}$	0.03	0.99	34
AV2 MEAN	$10^{(1.94+0.84*\text{Log}_{10}(\text{CH}))/10}$	0.03	0.99	33
AV3 MEAN	$10^{(1.97+\text{Log}_{10}(\text{CW})*0.82)/10}$	0.03	0.99	33
CV1	$10^{(1.87+\text{Log}_{10}(\text{CH})*0.21+\text{Log}_{10}(\text{LL})*0.60+(\text{CW}/\text{LH})*0.04-\text{Log}_{10}(\text{CH})*\text{Log}_{10}(\text{LL})*0.08+\text{Log}_{10}(\text{CH})*(\text{CW}/\text{LH})*0.18-\text{Log}_{10}(\text{LL})*(\text{CW}/\text{LH})*0.10+\text{Log}_{10}(\text{CH})*\text{Log}_{10}(\text{LL})*(\text{CW}/\text{LH})*0.07)/10}$	0.04	0.97	572
CV2	$10^{(2.48+\text{Log}_{10}(\text{CH})*2.47-\text{Log}_{10}(\text{LL})*1.65-(\text{LL}/\text{LH})*0.31-\text{Log}_{10}(\text{CH})*\text{Log}_{10}(\text{LL})*0.012-\text{Log}_{10}(\text{CH})*(\text{LL}/\text{LH})*1.39+\text{Log}_{10}(\text{LL})*(\text{LL}/\text{LH})*1.50+\text{Log}_{10}(\text{CH})*(\text{LL}/\text{LH})*\text{Log}_{10}(\text{LL})*0.005)/10}$	0.03	0.98	324

Table.A.2.4.c. AICc rankings of cranial elements. Cranial elements are averaged by side. DF = Degrees of Freedom; Int =intercept ;LogLik = Log Likelihood; AICc = AIC value for small samples; Delta = difference between the best and current model; Weight = proportion of the total predictive power in the model (S.2.3).

Cranial Skeletal Element	Model	DF	Int	LogLik	AICc	Delta	Weight
Dentary	DentPowerModel10	3	2.10	127.84	-249.40	0.00	1.00
Dentary	DentPowerModel	3	4.84	51.94	-97.60	151.79	0
Dentary	DentLinearModel	3	73.76	-513.33	1032.90	1282.34	0
Supracleithrum	SupracIPowerModel10	3	2.11	114.80	-223.30	0.00	1
Supracleithrum	SupracIPowerModel	3	4.87	45.58	-84.80	138.45	0
Supracleithrum	SupracILinearModel	3	4.87	45.58	-84.80	138.45	0
Quadrate	QuadPowerModel10	3	1.91	134.20	-262.10	0.00	1.00
Quadrate	QuadPowerModel	3	4.40	60.81	-115.30	146.79	0
Quadrate	QuadLinearModel	3	62.80	-482.57	971.40	1233.54	0
Premaxilla	PremaxPowerModel10	3	1.88	116.88	-227.50	0.00	1.00
Premaxilla	PremaxPowerModel	3	4.34	46.82	-87.30	140.12	0
Premaxilla	PremaxLinearModel	3	40.84	-469.97	946.20	1173.69	0

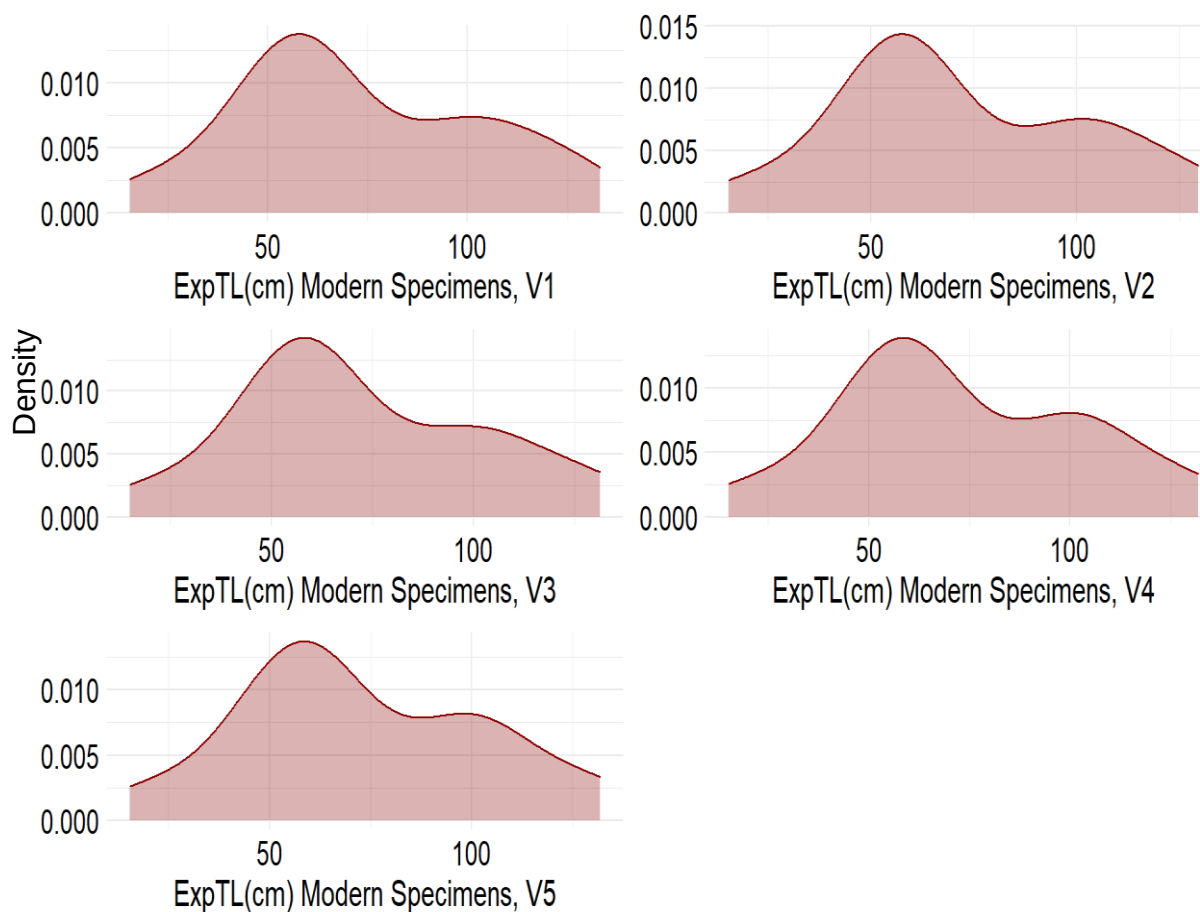
Table.A.2.4.d. Regression models of cranial elements ranked highest by the AICc selections. Cranial elements are averaged by side. R^2 values are adjusted. Measurement variables are in mm, resulting TLs and errors are in cm (S.2.3).

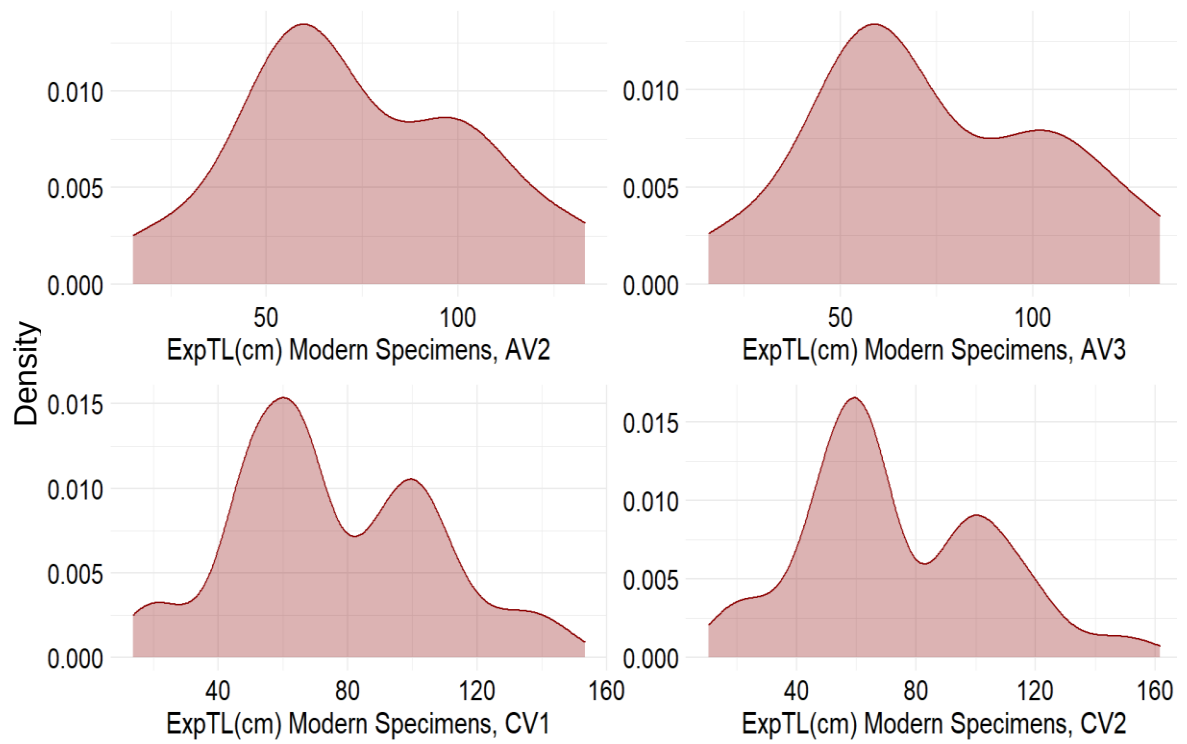
Cranial Skeletal Element	Regression Equation	Residual Standard Error	R^2	n
Dentary	$10^{(2.10+0.92*\log_{10}(M1))/10}$	0.06	0.88	91
Premaxilla	$10^{(1.89+0.96*\log_{10}(M1))/10}$	0.06	0.88	84
Quadrate	$10^{(1.91+0.94*\log_{10}(M1))/10}$	0.05	0.91	88
Supracleithrum	$10^{(2.11+0.88*\log_{10}(M1))/10}$	0.06	0.86	83

Appendix.2.5. Density plots of predicted TLs of modern Atlantic cod (*Gadus morhua*) reference specimens from the constructed regression models

Density plots displayed for: A. Predicted TLs from vertebrae measurements of modern reference specimens by morphological vertebrae groups, top to bottom, left to right: V1, V2, V3, V4, V5, AV2, A3, CV1, CV2 (S.2.1); B. Predicted TLs from cranial measurements of modern reference specimens by individual elements, from top left corner, clockwise: dentary, premaxilla, quadrate, supracleithrum (S.2.3).

A





B



Appendix.2.6. Unique morphological traits of first caudal vertebrae in cod and in close species, summarized from Watt et al., 1997

Variation in the morphological traits of the first caudal vertebrae in cod and other species is described, following Watt et al., 1997 (A-E). Terminology used to describe the vertebrae anatomical regions is further described (F).

A. Cod (*Gadus morhua*)

Contains fewer oblique septa on the lateral sides compared to pollack, giving a less compacted appearance. Horizontal ossifications on the lateral sides often form clear ridges. Contains septa between horizontal ossifications, with shorter prezygapophyses compared to pouting. The sides of the cavity on the ventral side of anterior caudals are convex in cod, while in pollack they are straight. The centra are relatively shorter in cod, compared to saith and whiting, with broader dorsal prezygapophyses compared to saith.

B. Pouting (*Trisopterus luscus*)

Contains fewer oblique septa between ribs and over surface of centra on the lateral sides compared to cod.

C. Pollack (*Pollachius pollachius*)

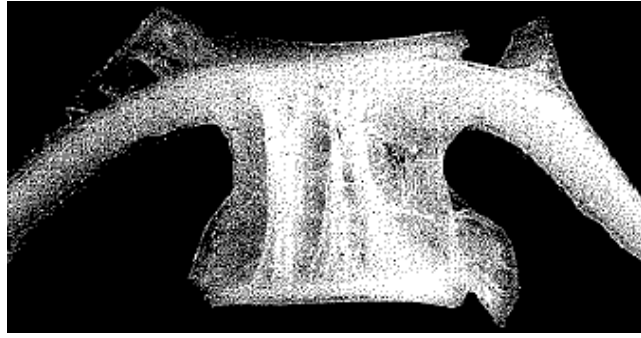
Possesses a greater density of septa between horizontal ossifications on the lateral sides, giving the centrum a more compacted appearance compared to cod. Horizontal ossifications do not form clear ridges as they often do in cod. The sides of the cavity on the ventral side of anterior caudals are straight in pollack, while in cod they are convex.

D. Saithe (*Pollachius virens*)

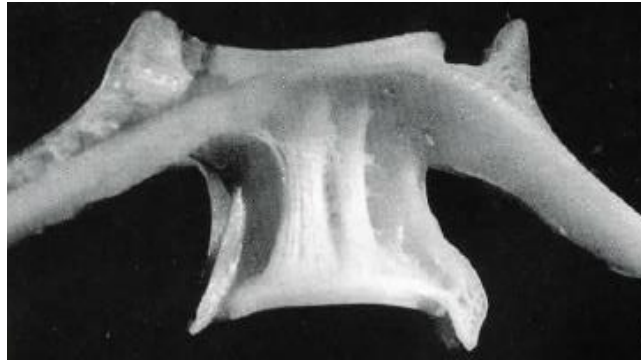
Centra are relatively longer with narrower prezygapophyses compared to cod. The sides of the cavity on the ventral side of anterior caudals are relatively straight in saithe, while in cod they are convex.

E. Whiting (*Merlangius merlangus*)

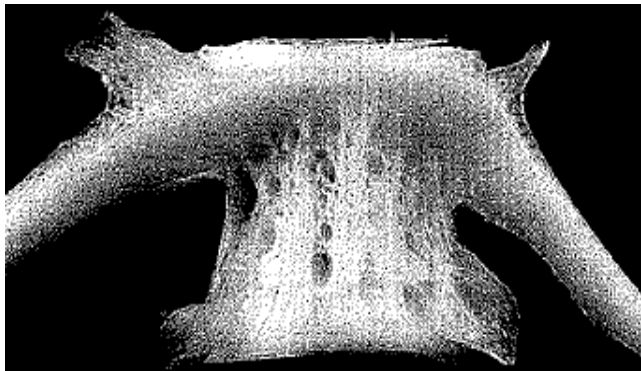
Vertebrae are relatively longer, with thinner horizontal ossifications compared to cod.



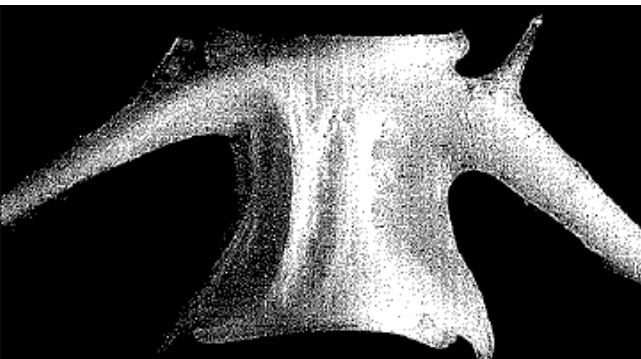
A



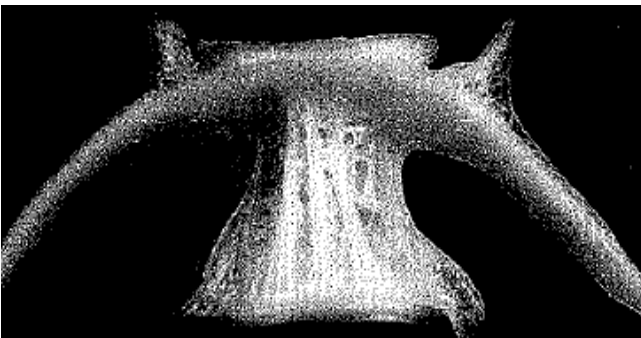
B



C



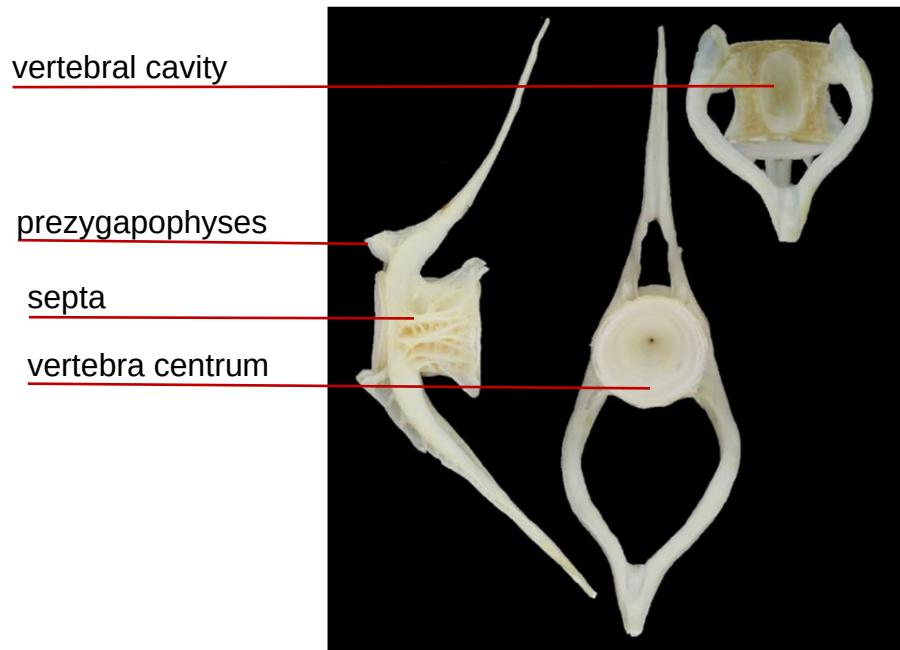
D



E

F

From left to right: Lateral view, posterior view, and ventral view of anterior caudal vertebra

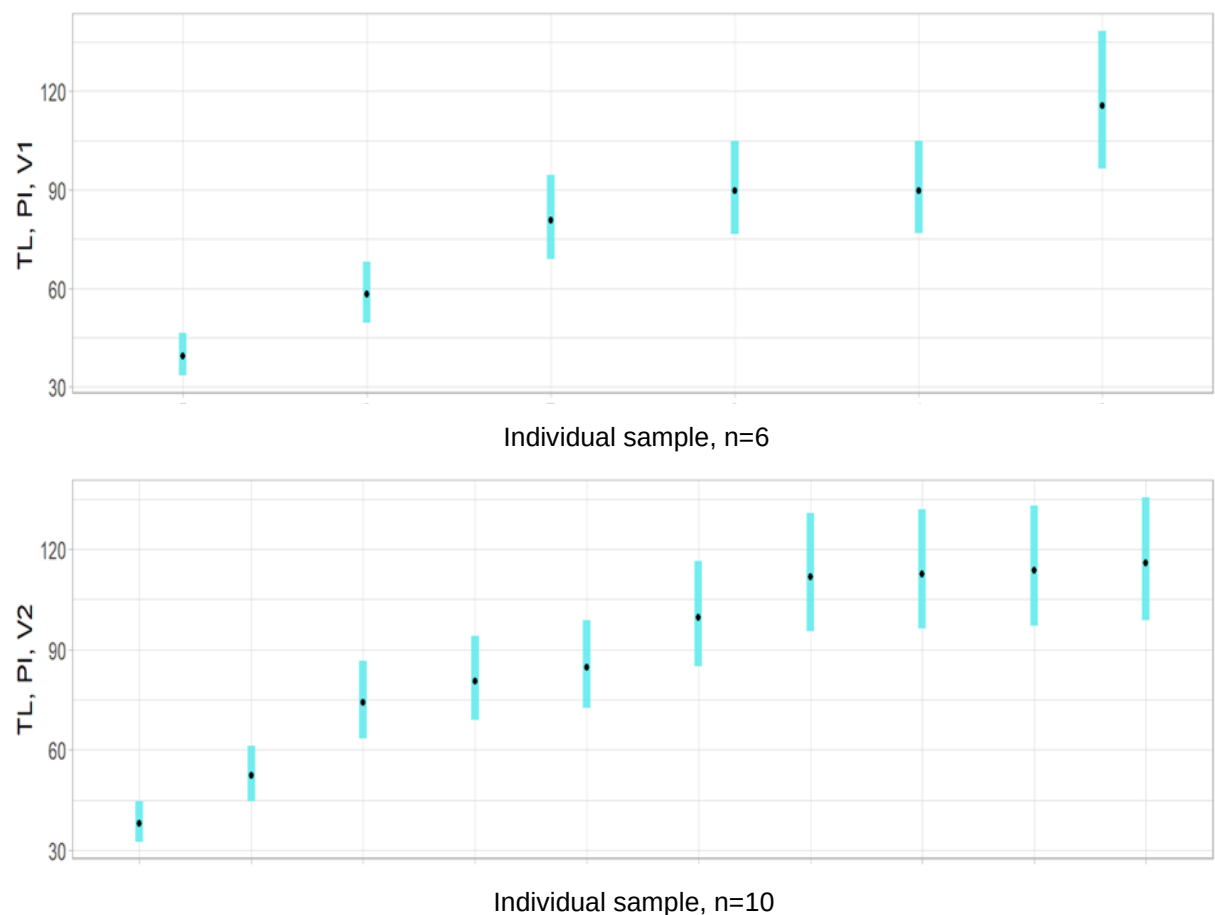


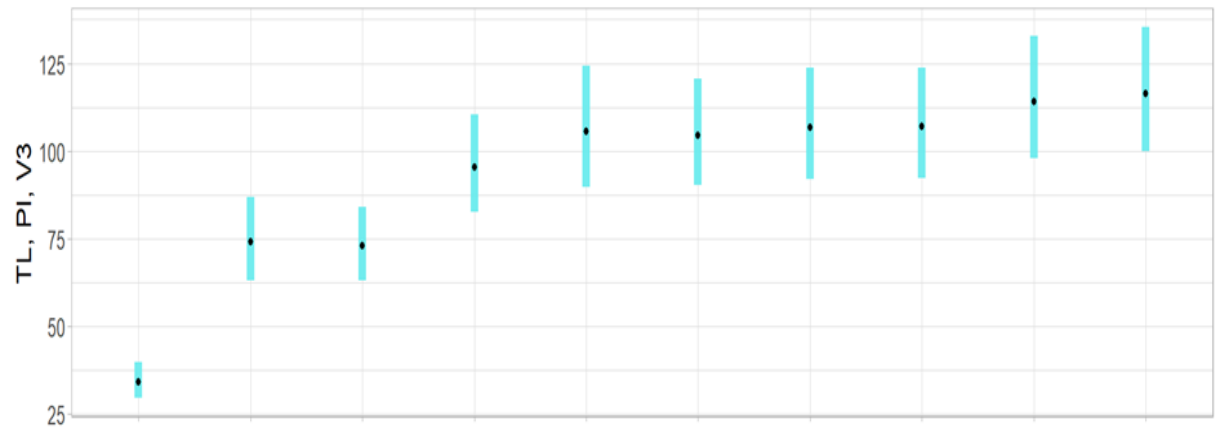
Appendix.3.1. Scatter plots of estimated TLs and corresponding Prediction Intervals (PI) from incorporating skeletal element measurements of Atlantic cod (*Gadus morhua*) from Lyminge and Coppergate into the regression models

Lyminge estimated TLs (black dots) and PIs (blue lines) displayed for vertebrae and for cranial elements, from top to bottom: A. V1 - V5; B. AV2, AV3, CV1, CV2; C. quadrate, supracleithrum; dentary, premaxilla (S.2.2; S.2.4).

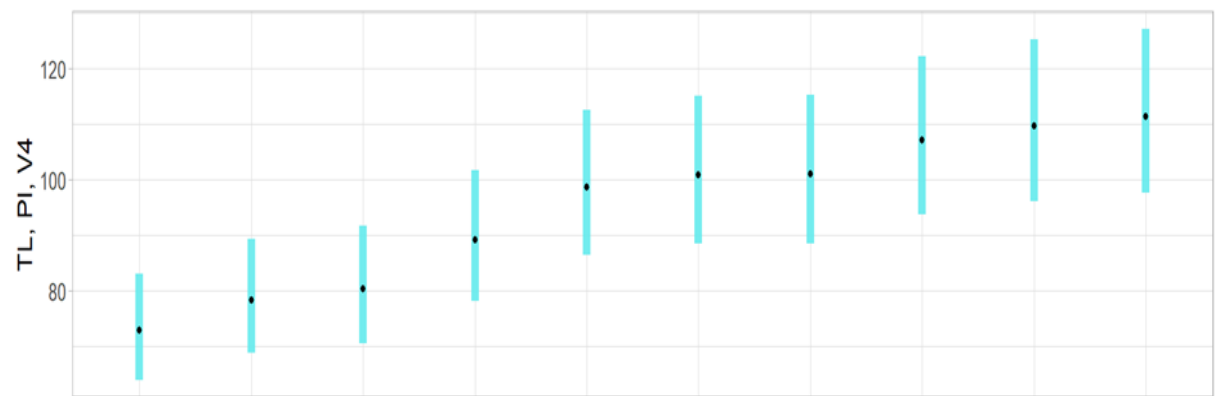
Coppergate estimated TLs and PIs displayed for cranial elements, from top to bottom: D. quadrate; dentary, premaxilla (S.2.5).

A

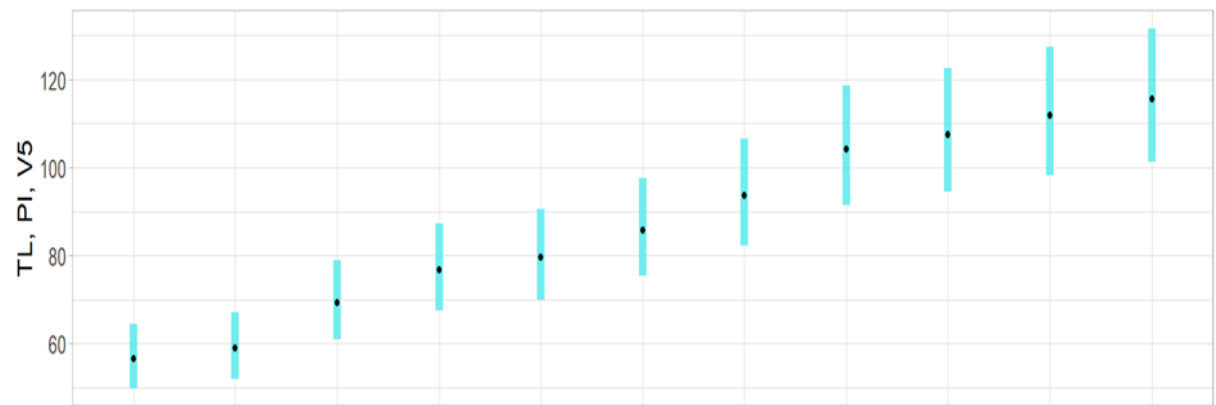




Individual sample, n=10

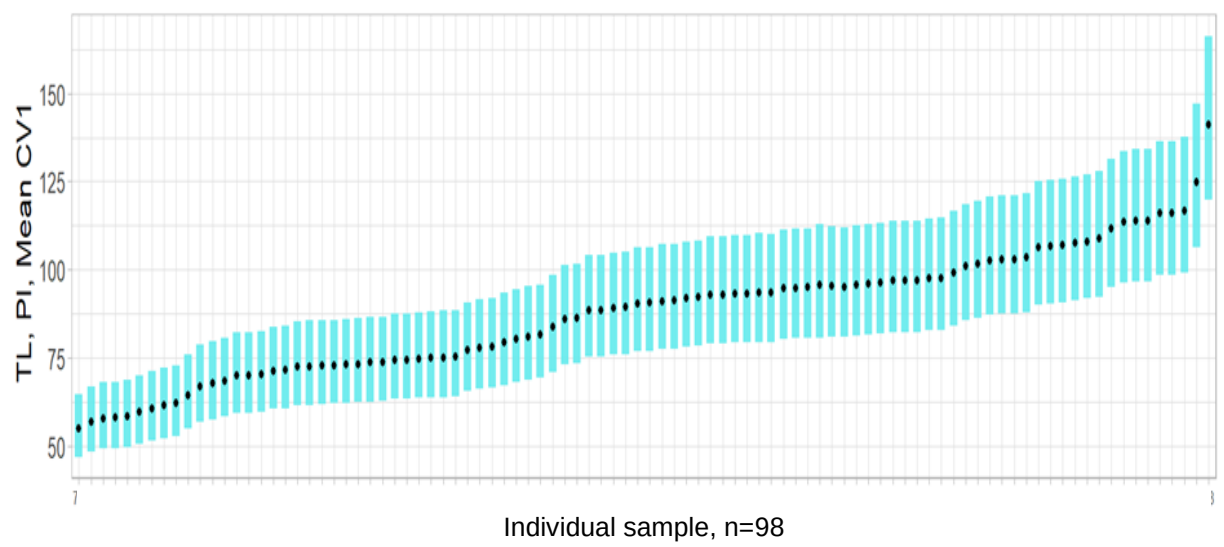
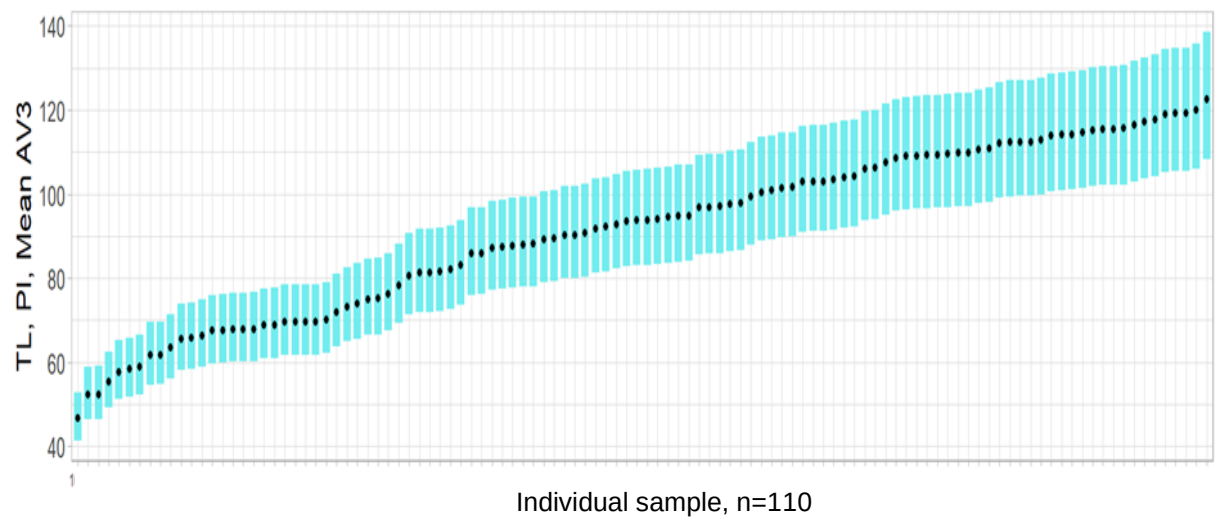
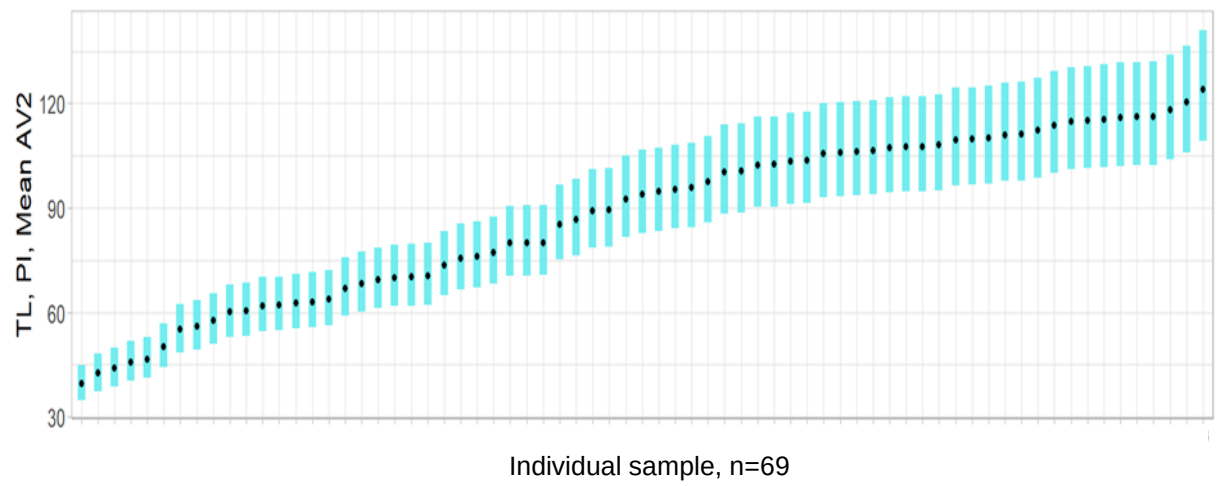


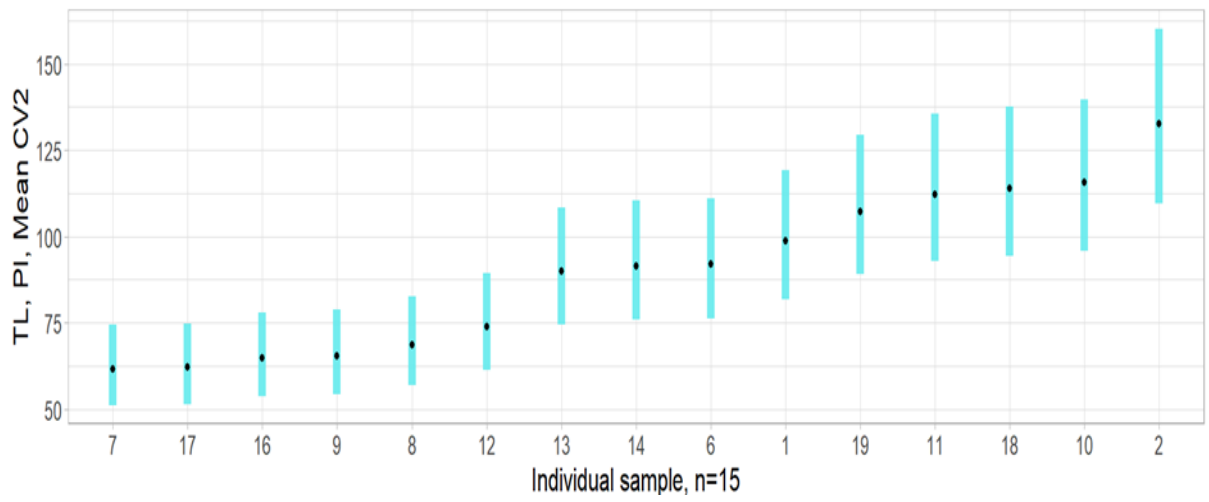
Individual sample, n=10



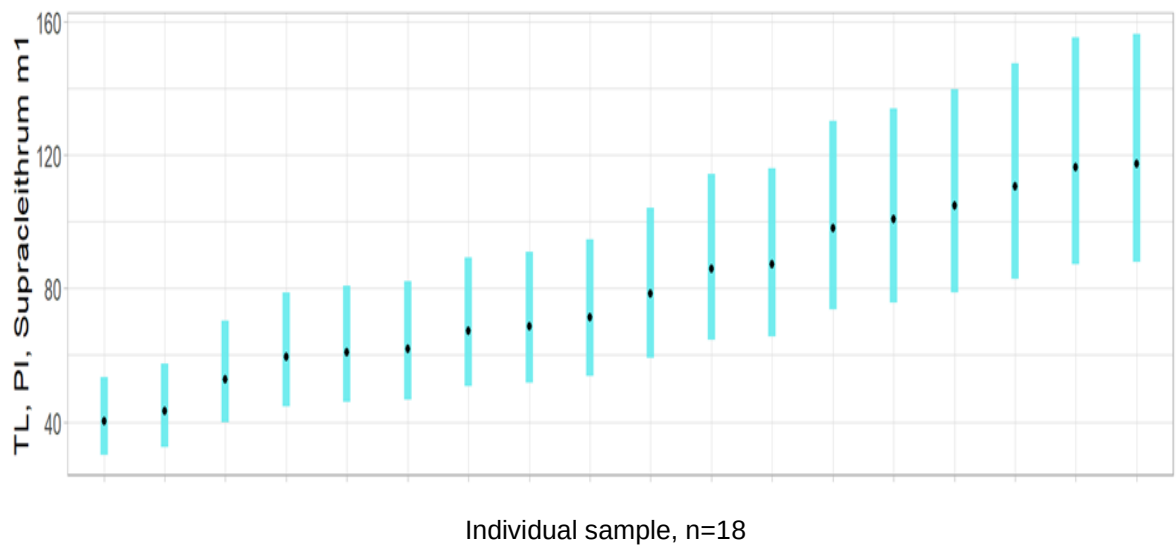
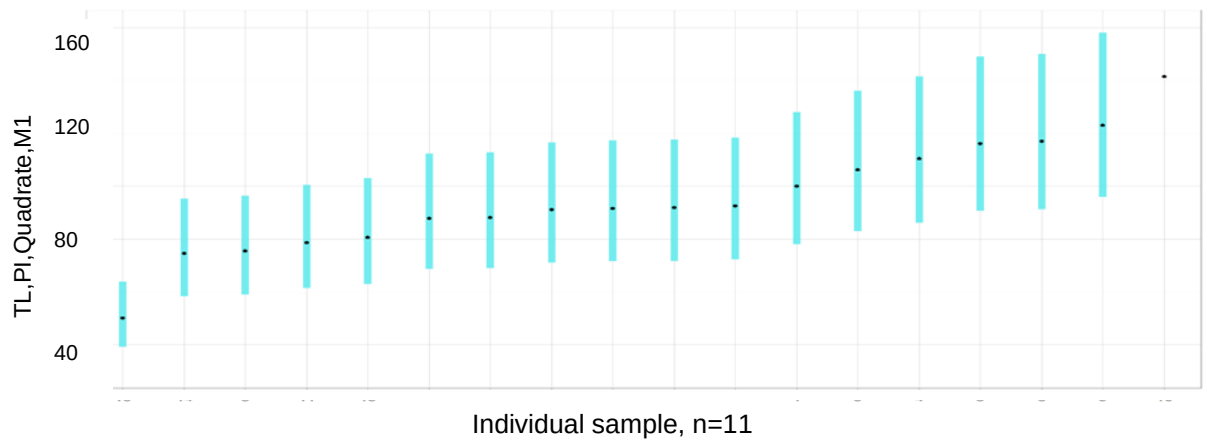
Individual sample, n=11

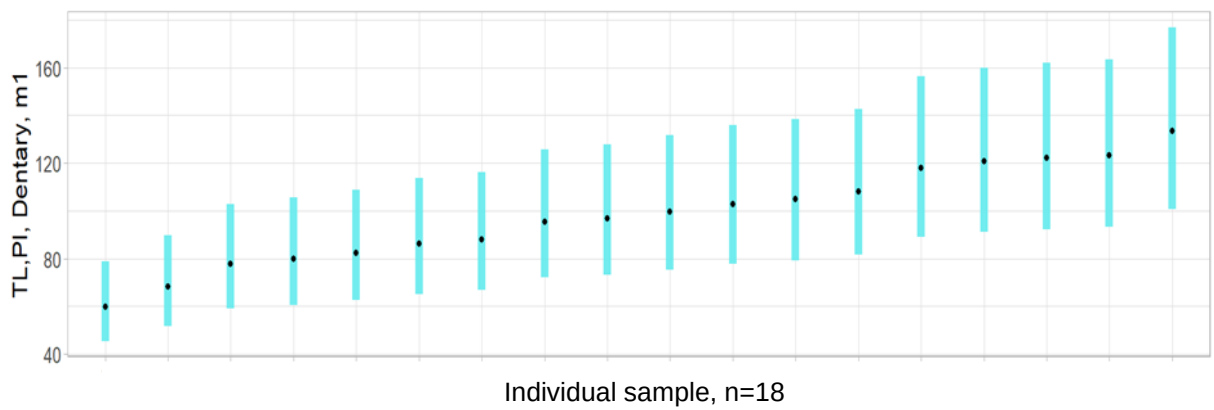
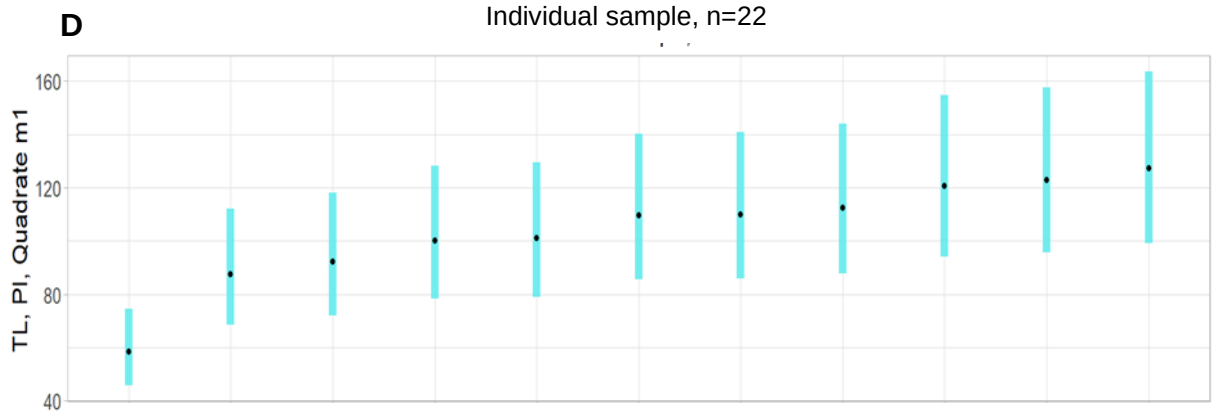
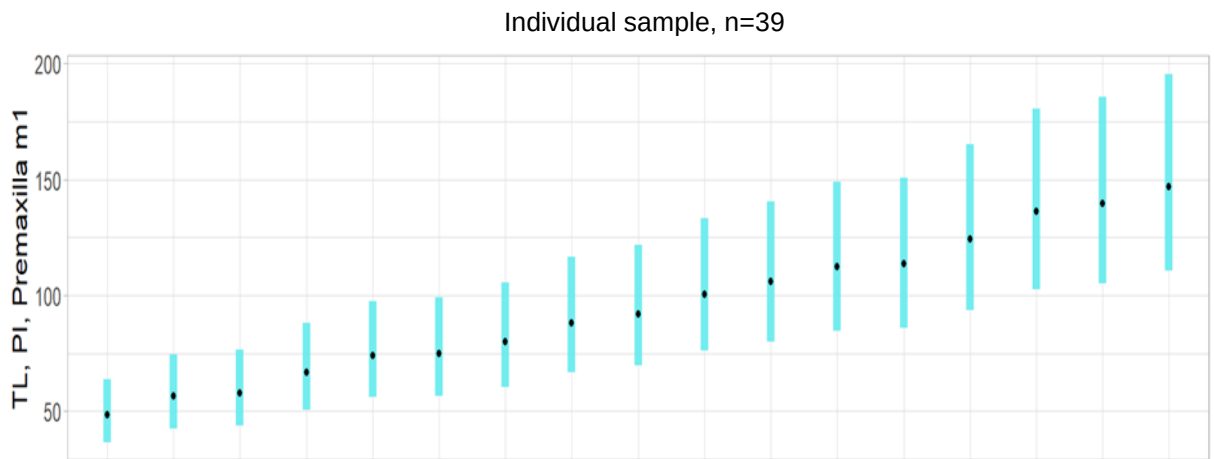
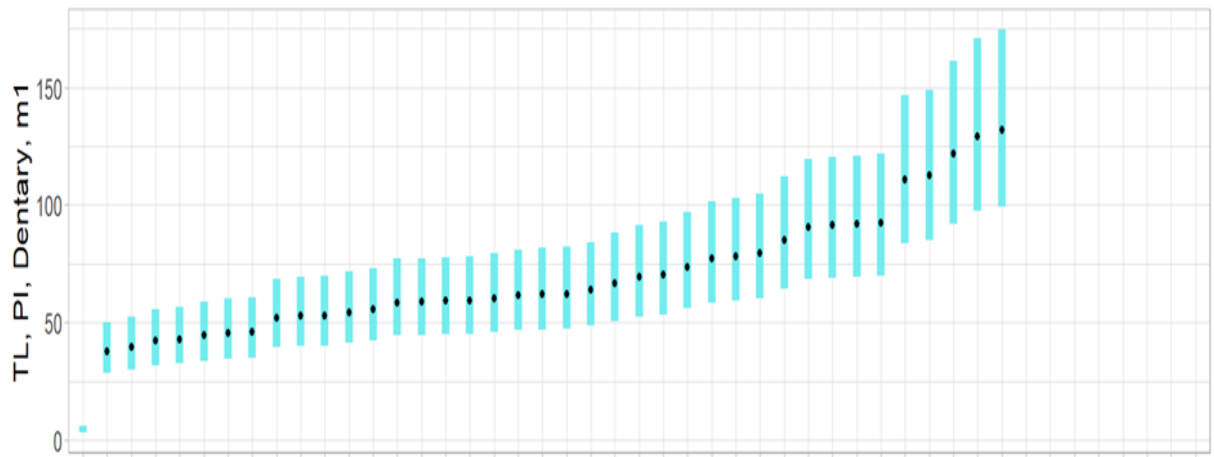
B

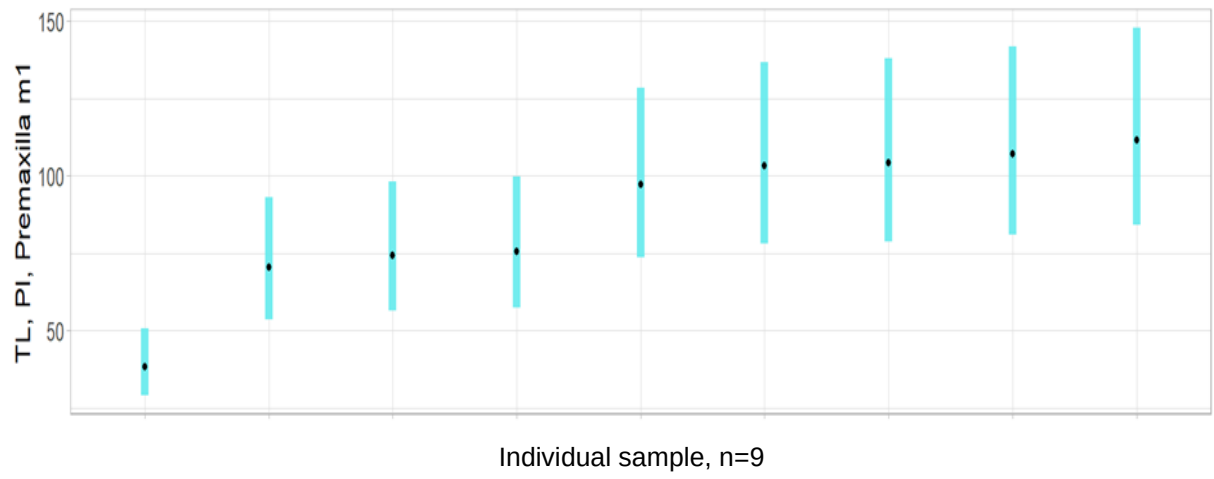




C

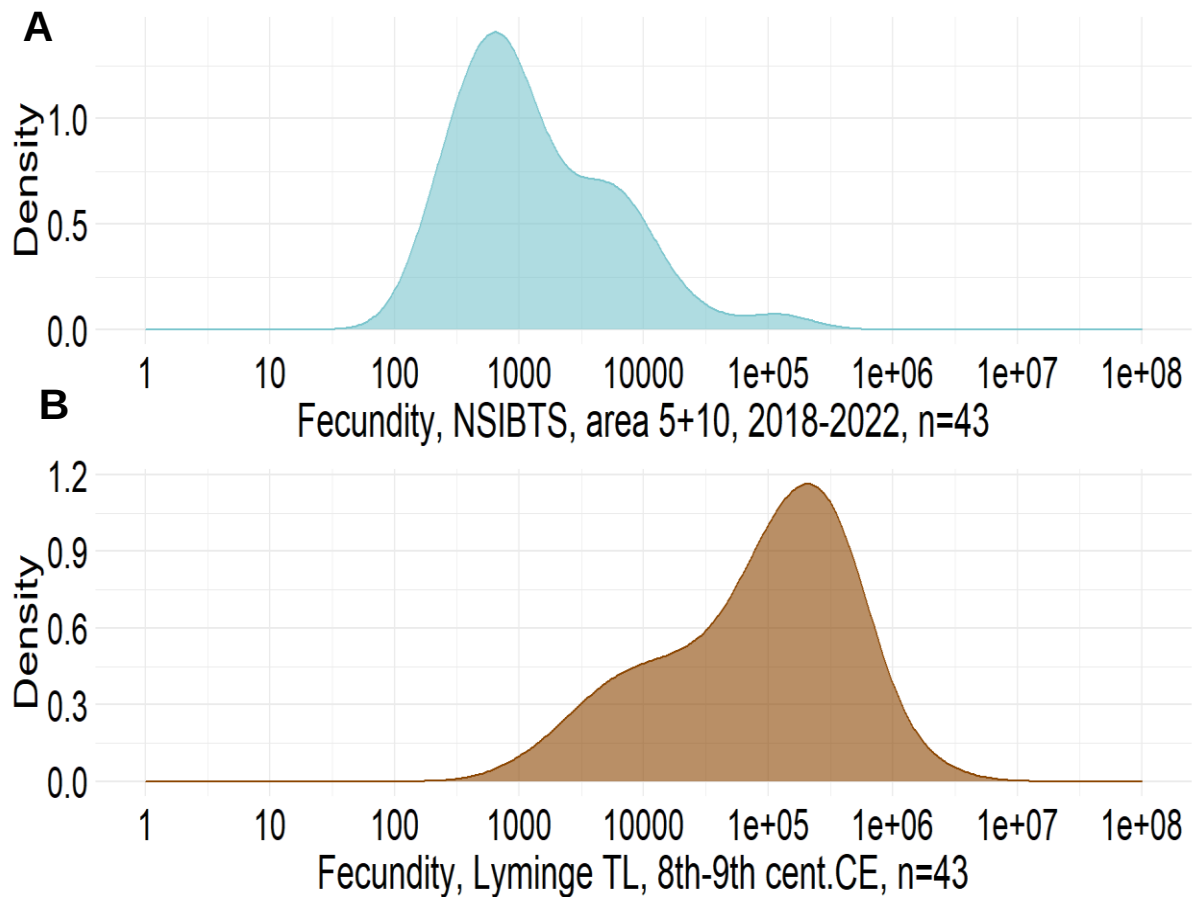


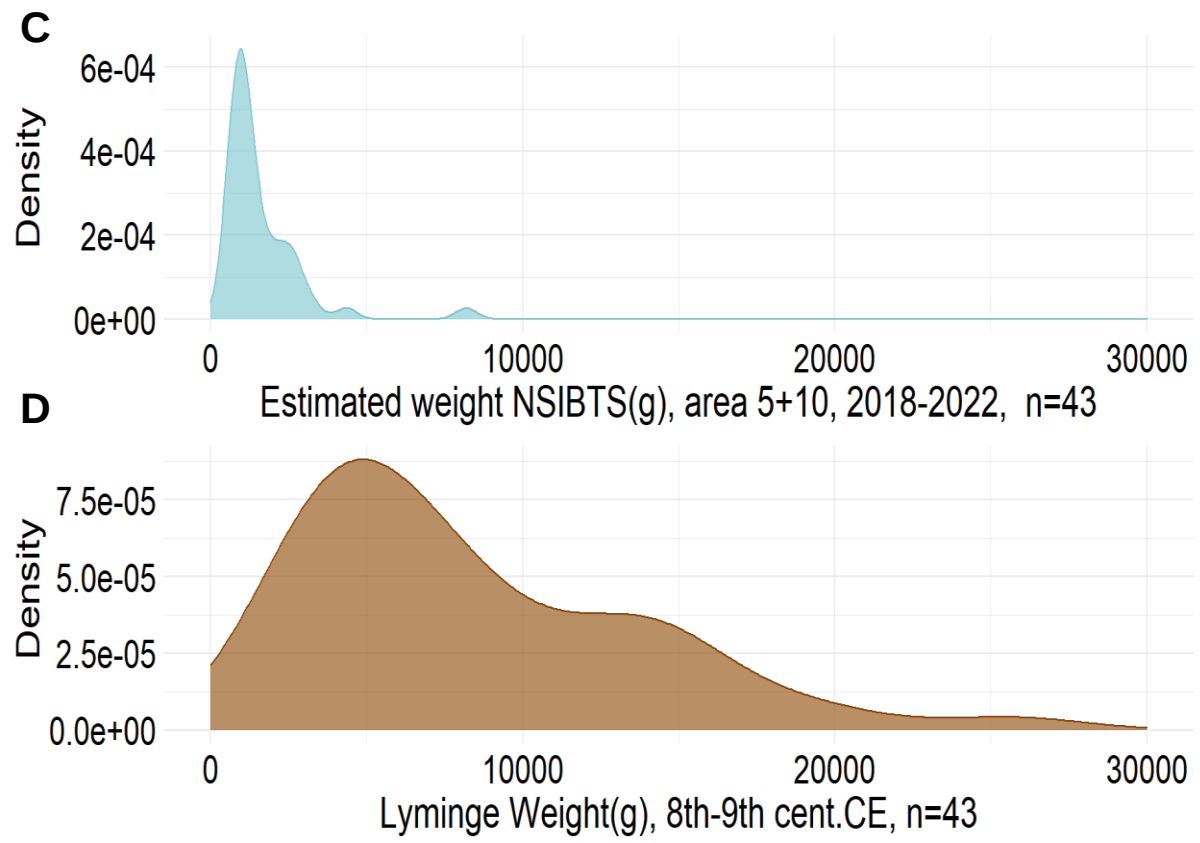




Appendix.3.2. Density plots of potential Atlantic cod (*Gadus morhua*) fecundity and biomass estimates, based on TL estimates from Lyminge

Potential fecundity and biomass estimates displayed after applying minimum fish-size thresholds (at 50 cm TL for Lyminge and at 60 cm TL for Coppergate, see Results Section 3.8): A. fecundity estimates of Modern ICES bottom trawl survey data (NS-IBTS); B. fecundity estimates of archaeological Lyminge data; C. biomass estimates of Modern NS-IBTS data; D. biomass estimates of archaeological Lyminge data (S.2.7).

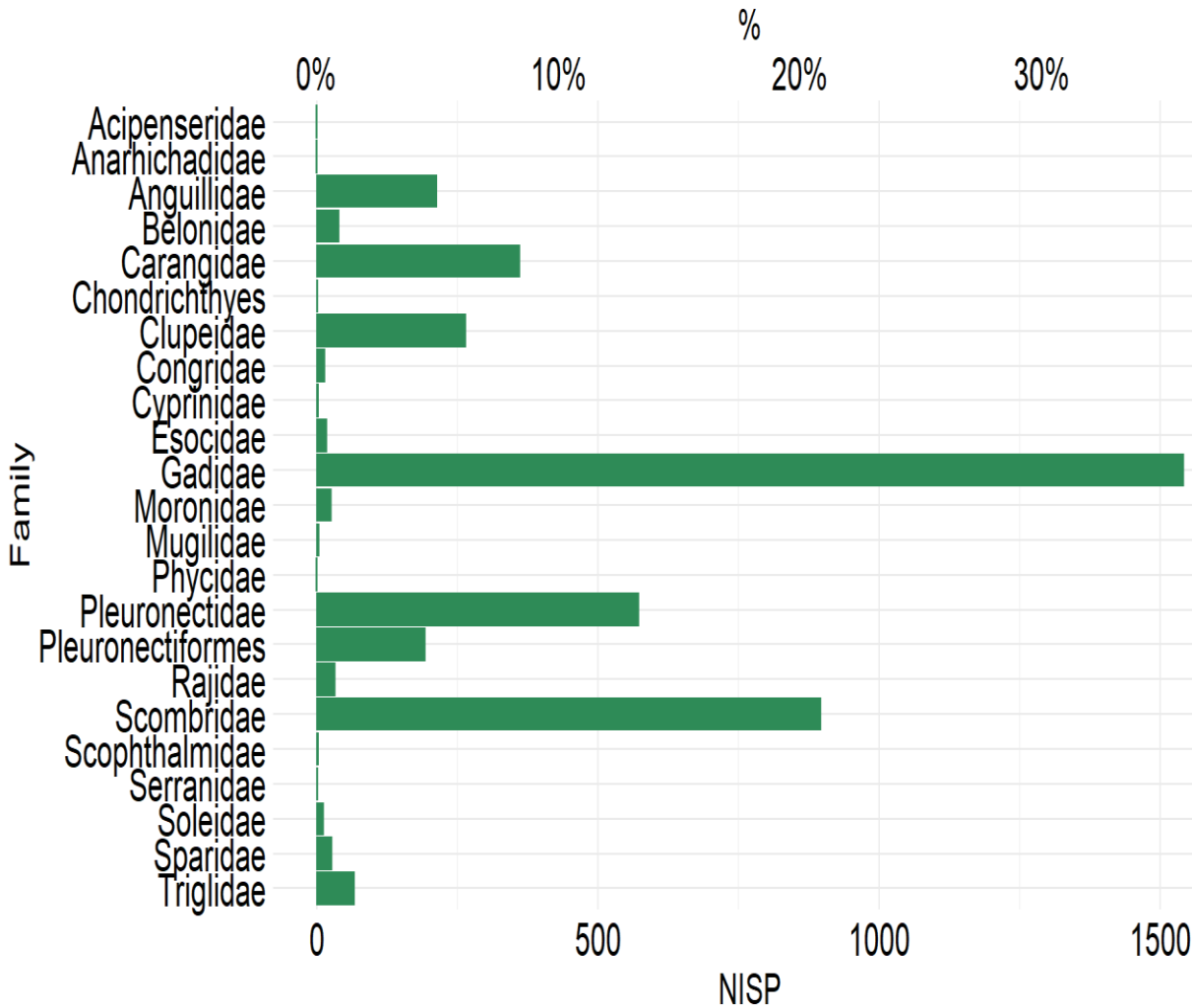


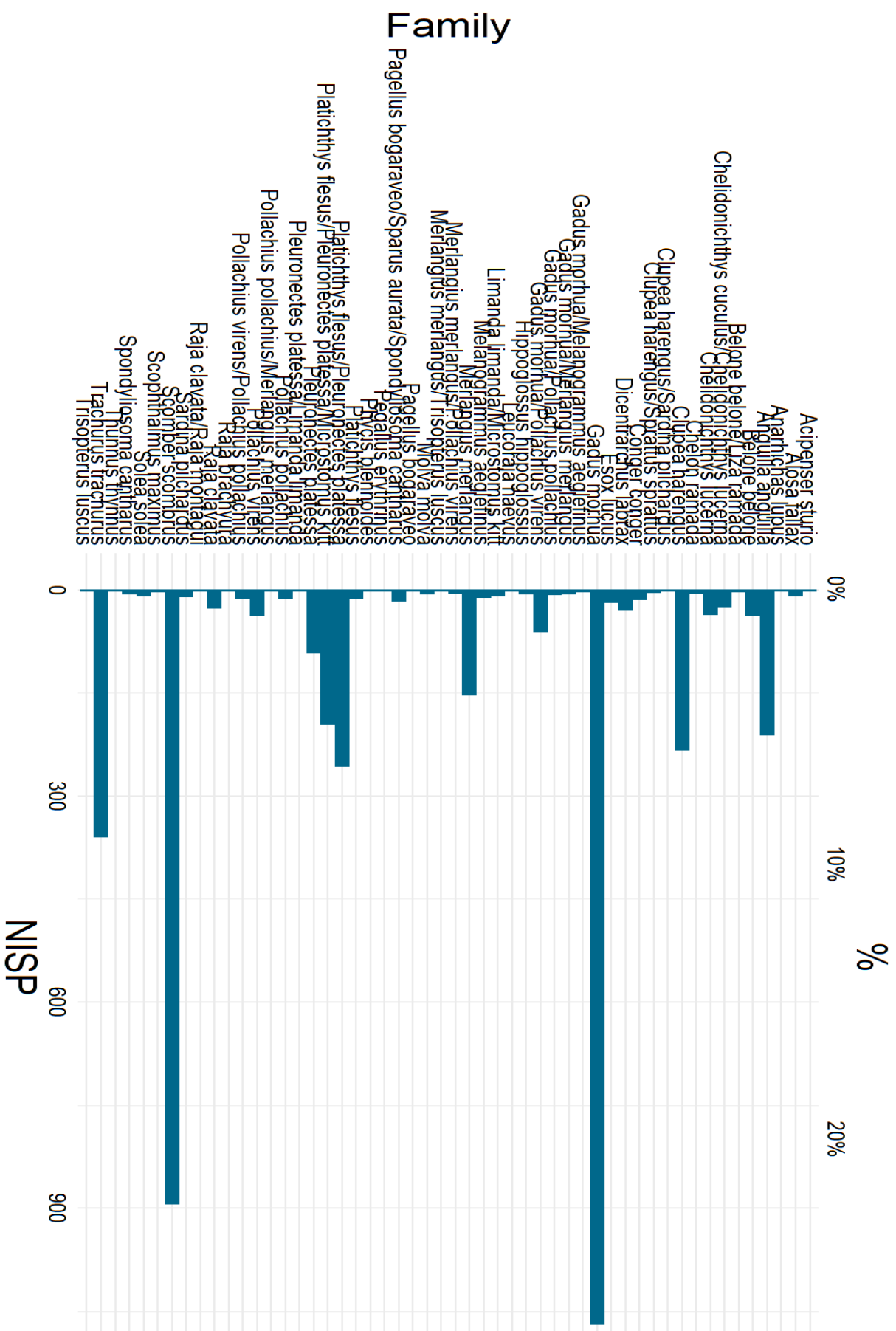


Appendix.3.3. Bar charts of NISPs and relative frequencies of fish bones identified to taxonomic levels from Lyminge, listed alphabetically

The identified taxa from Lyminge are listed by: A. Family, B. Species. Relative frequencies marked as % of total NISP (S.3.1).

A





B

Appendix.3.4. NISP and relative frequency values of fish identified to taxonomic levels at Lyminge, listed by the two utilised sieving procedures

Lyminge fish identified to taxonomic levels from 5 mm sieved material and from 1 mm wet sieving and flotation of soil subsamples are listed in Table.A.3.4.a and Table.A.3.4.b, respectively (S.3.1). Relative frequency marked as % of total NISP. For families that include more than one species, the total NISP value is marked in the “NISP Family” column, and the NISP value for each species is marked in the “NISP Species” column.

Table.A.3.4.a. NISP and relative frequencies of families and species identified at Lyminge from 5 mm sieved material.

Family	NISP Family	% Family	Species	NISP Species	% Species
Anarhichadidae	1	0.04	<i>Anarhichas lupus</i>	1	0.04
Anguillidae	3	0.11	<i>Anguilla anguilla</i>	2	0.07
Anguillidae			Unidentified	1	0.04
Belonidae	32	1.14	<i>Belone belone</i>	32	1.14
Carangidae	297	10.54	<i>Trachurus trachurus</i>	295	10.47
Carangidae			Unidentified	2	0.07
Chondrichthyes	1	0.04	Unidentified	1	0.04
Clupeidae	44	1.56	<i>Alosa fallax</i>	6	0.21
Clupeidae			<i>Clupea harengus</i>	32	1.14
Clupeidae			<i>Clupea harengus/Sprattus sprattus</i>	1	0.04
Clupeidae			<i>Sardina pilchardus</i>	3	0.11
Clupeidae			Unidentified	2	0.07
Congridae	14	0.50	<i>Conger conger</i>	14	0.50
Esocidae	9	0.32	<i>Esox lucius</i>	9	0.32
Gadidae	1240	43.99	<i>Gadus morhua</i>	973	34.52
Gadidae			<i>Gadus morhua/Melanogrammus aeglefinus</i>	2	0.07

Family	NISP Family	% Family	Species	NISP Species	% Species
Gadidae			<i>Gadus morhua</i> / <i>Merlangius merlangus</i>	6	0.21
Gadidae			<i>Gadus morhua</i> / <i>Pollachius pollachius</i>	6	0.21
Gadidae			<i>Gadus morhua</i> / <i>Pollachius virens</i>	55	1.95
Gadidae			<i>Melanogrammus aeglefinus</i>	11	0.39
Gadidae			<i>Merlangius merlangus</i>	38	1.35
Gadidae			<i>Merlangius merlangus</i> / <i>Pollachius virens</i>	3	0.11
Gadidae			<i>Merlangius merlangus</i> / <i>Trisopterus luscus</i>	1	0.04
Gadidae			<i>Molva molva</i>	1	0.04
Gadidae			<i>Pollachius pollachius</i>	5	0.18
Gadidae			<i>Merlangius merlangus</i> / <i>Pollachius pollachius</i>	1	0.04
Gadidae			<i>Pollachius virens</i>	4	0.14
Gadidae			<i>Pollachius virens</i> / <i>Pollachius pollachius</i>	10	0.35
Gadidae			<i>Trisopterus luscus</i>	1	0.04
Gadidae			Unidentified	123	4.36
Labridae	1	0.04	Unidentified	1	0.04
Moronidae	21	0.74	<i>Dicentrarchus labrax</i>	21	0.75
Mugilidae	3	0.11	<i>Chelon ramada</i>	3	0.11
Phycidae	1	0.04	<i>Phycis blennoides</i>	1	0.04
Pleuronectidae	563	20.04	<i>Hippoglossus hippoglossus</i>	6	0.21
Pleuronectidae			<i>Limanda limanda</i> / <i>Microstomus kitt</i>	9	0.32

Family	NISP Family	% Family	Species	NISP Species	% Species
Pleuronectidae			<i>Platichthys flesus</i>	12	0.43
Pleuronectidae			<i>Platichthys flesus/Pleuronectes platessa</i>	185	6.56
Pleuronectidae			<i>Platichthys flesus/Pleuronectes platessa/Microstomus kitt</i>	126	4.47
Pleuronectidae			<i>Pleuronectes platessa</i>	89	3.16
Pleuronectidae			<i>Pleuronectes platessa/Limanda limanda</i>	1	0.04
Pleuronectidae			<i>Scophthalmus maximus</i>	1	0.04
Pleuronectidae			Unidentified	134	4.83
Rajidae	14	0.50	<i>Raja clavata</i>	12	0.43
Rajidae			Unidentified	2	0.07
Scombridae	490	17.38	<i>Scomber scombrus</i>	490	17.39
Scophthalmidae	1	0.04	<i>Scophthalmus maximus</i>	1	0.04
Serranidae	2	0.07	<i>Dicentrarchus labrax</i>	2	0.07
Soleidae	5	0.18	<i>Solea solea</i>	2	0.07
Soleidae			Unidentified	3	0.11
Sparidae	22	0.78	<i>Pagellus bogaraveo</i>	1	0.04
Sparidae			<i>Pagellus bogaraveo/Sparus aurata/SpondylIOSoma cantharus</i>	12	0.43
Sparidae			<i>SpondylIOSoma cantharus</i>	6	0.21
Sparidae			Unidentified	3	0.11
Triglidae	52	1.84	<i>Chelidonichthys cuculus/Chelidonichthys lucerna</i>	15	0.45
Triglidae			<i>Chelidonichthys lucerna</i>	32	1.14
Triglidae			Unidentified	5	0.18
Total	2817	100		2817	100

Table.A.3.4.b. NISP and relative frequencies of families and species identified at Lyminge from 1 mm sieving and flotation of soil subsamples.

Family	NISP Family	% Family	Species	NISP Species	% Species
Acipenseridae	1	0.07	<i>Acipenser sturio</i>	1	0.07
Anguillidae	210	14.21	<i>Anguilla anguilla</i>	209	14.14
Anguillidae			Unidentified	1	0.07
Belonidae	7	0.47	<i>Belone belone</i>	5	0.34
Belonidae			<i>Belone belone/Liza ramada</i>	2	0.14
Carangidae	64	4.33	<i>Trachurus trachurus</i>	64	4.33
Chondrichthyes	1	0.07	Unidentified	1	0.07
Clupeidae	221	14.95	<i>Alosa fallax</i>	3	0.20
Clupeidae			<i>Clupea harengus</i>	201	13.60
Clupeidae			<i>Clupea harengus/Sardina pilchardus</i>	1	0.07
Clupeidae			<i>Clupea harengus/Sprattus sprattus</i>	2	0.14
Clupeidae			<i>Sardina pilchardus</i>	7	0.47
Clupeidae			Unidentified	7	0.47
Cyprinidae	3	0.20	Unidentified	3	0.20
Esocidae	9	0.61	<i>Esox lucius</i>	9	0.61
Gadidae	302	20.43	<i>Gadus morhua</i>	96	6.50
Gadidae			<i>Gadus morhua/Pollachius pollachius</i>	1	0.07
Gadidae			<i>Gadus morhua/Pollachius virens</i>	5	0.34
Gadidae			<i>Merlangius merlangus</i>	115	7.78
Gadidae			<i>Merlangius merlangus/Pollachius virens</i>	1	0.07

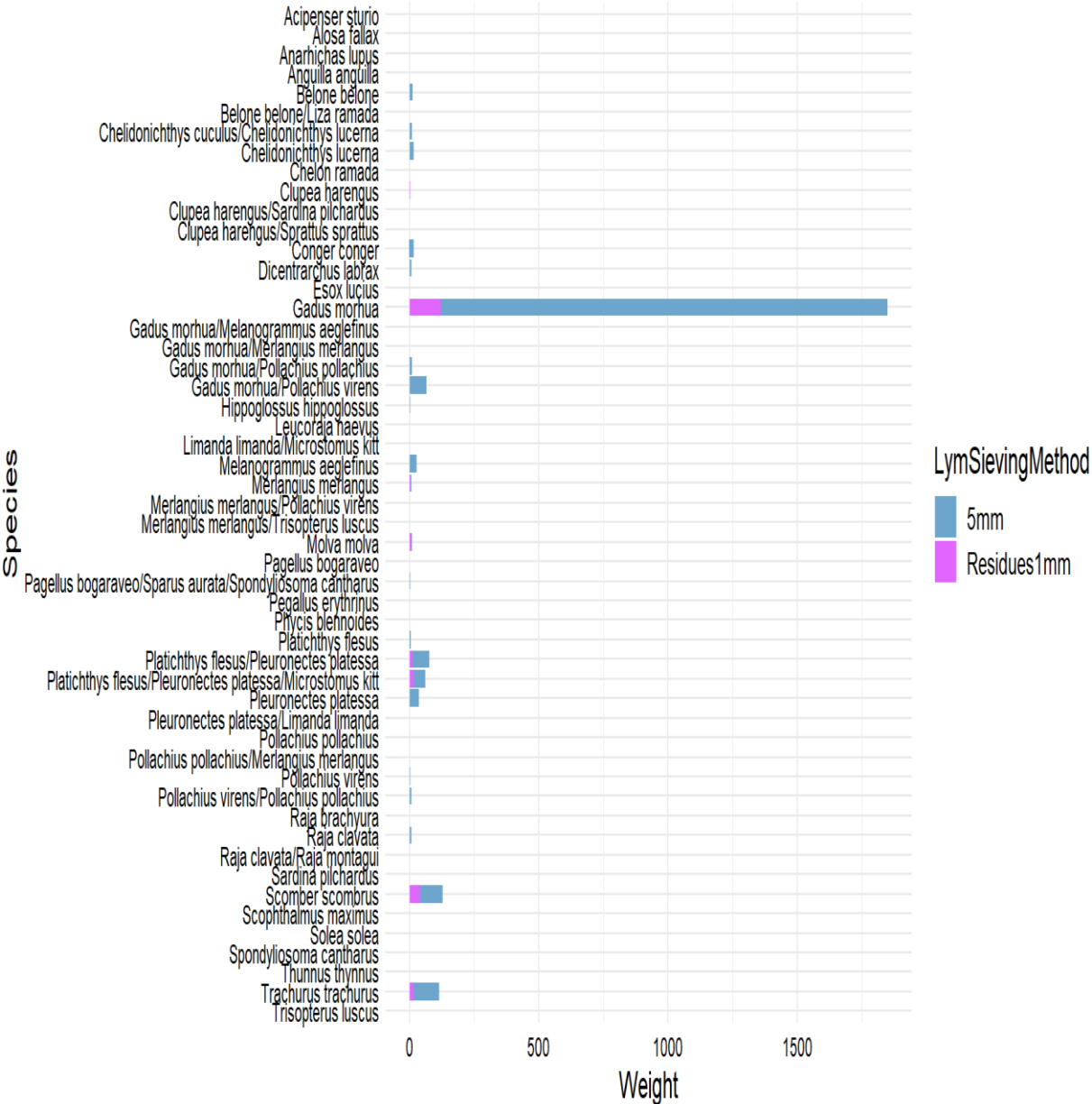
Family	NISP Family	% Family	Species	NISP Species	% Species
Gadidae			<i>Molva molva</i>	4	0.27
Gadidae			<i>Pollachius pollachius</i>	8	0.54
Gadidae			<i>Pollachius virens</i>	33	2.23
Gadidae			<i>Pollachius virens/Pollachius pollachius</i>	2	0.14
Gadidae			Unidentified	37	2.50
Moronidae	5	0.34	<i>Dicentrarchus labrax</i>	5	0.34
Mugilidae	1	0.07	<i>Chelon ramada</i>	1	0.07
Pleuronectidae	201	13.60	<i>Platichthys flesus/Pleuronectes platessa</i>	71	4.87
Pleuronectidae			<i>Platichthys flesus/Pleuronectes platessa/Microstomus kitt</i>	69	4.67
Pleuronectidae			<i>Pleuronectes platessa</i>	3	0.20
Pleuronectidae			Unidentified	58	3.86
Rajidae	19	1.29	<i>Leucoraja naevus</i>	1	0.07
Rajidae			<i>Raja brachyura</i>	1	0.07
Rajidae			<i>Raja clavata</i>	14	0.95
Rajidae			<i>Raja clavata/Raja montagui</i>	1	0.07
Rajidae			Unidentified	2	0.14
Scombridae	406	27.47	<i>Scomber scombrus</i>	404	27.33
Scombridae			<i>Thunnus thynnus</i>	1	0.07
Scombridae			Unidentified	1	0.07
Scophthalmidae	1	0.07	Unidentified	1	0.07
Soleidae	7	0.47	<i>Solea solea</i>	7	0.47
Sparidae	5	0.34	<i>Pagellus bogaraveo/Sparus aurata/Spondyliosoma cantharus</i>	4	0.27

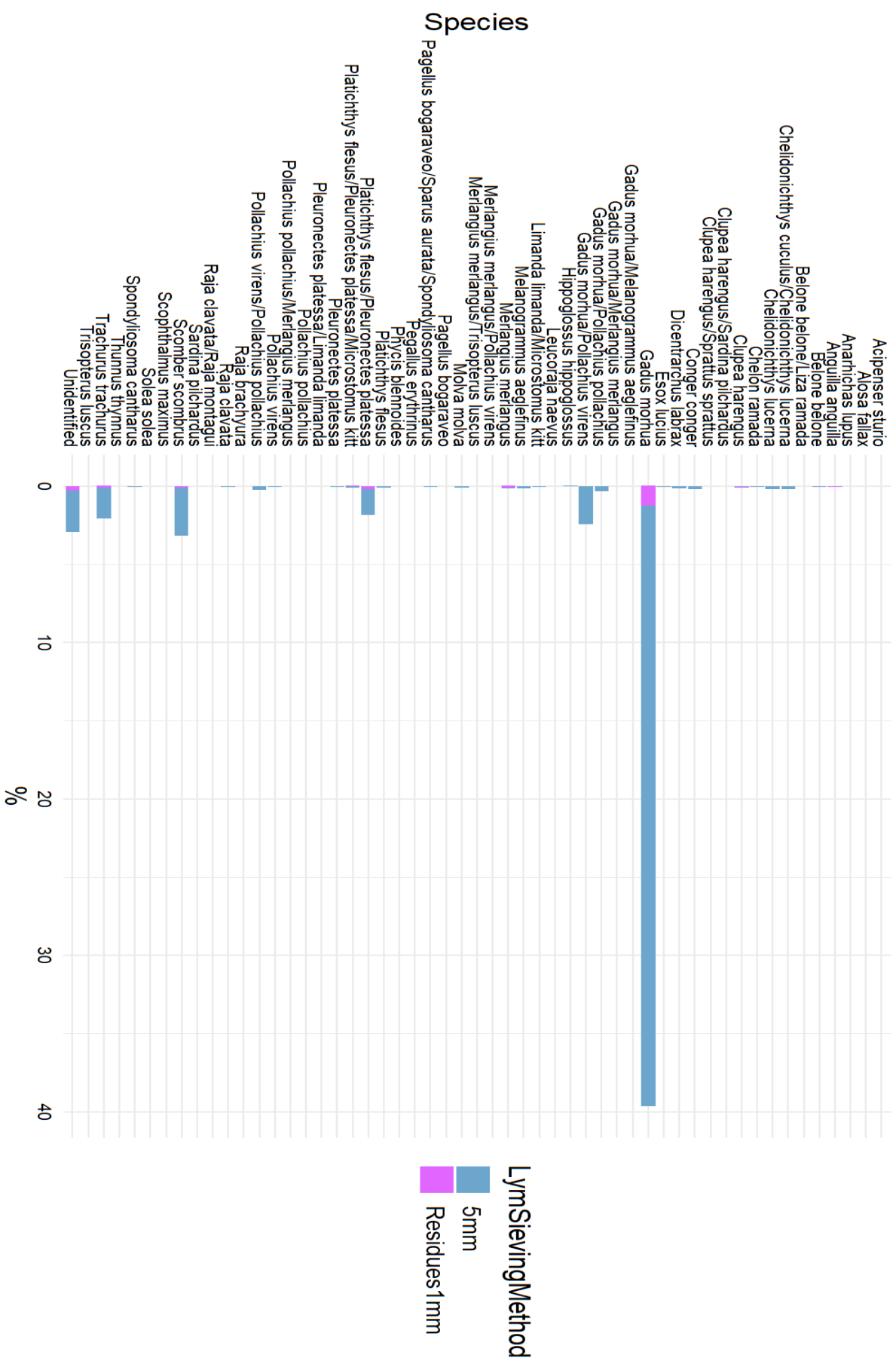
Family	NISP Family	% Family	Species	NISP Species	% Species
			<i>Pegallus erythrinus</i>	1	0.07
Triglidae	15	1.01	<i>Chelidonichthys cuculus/Chelidonicht hys lucerna</i>	9	0.61
Triglidae			<i>Chelidonichthys lucerna</i>	4	0.27
Triglidae			Unidentified	2	0.14
Grand Total	1478	100		1478	100

Appendix.3.5. Bar charts of weights and relative weights of identified fish species from Lyminge, listed by the two utilised sieving procedures

The identified species from Lyminge are displayed by: A. weight (grams); B. relative weight (marked as % of total weight). Plots coloured by sieving procedure (see Results Section 3.9.2; S.3.1).

A



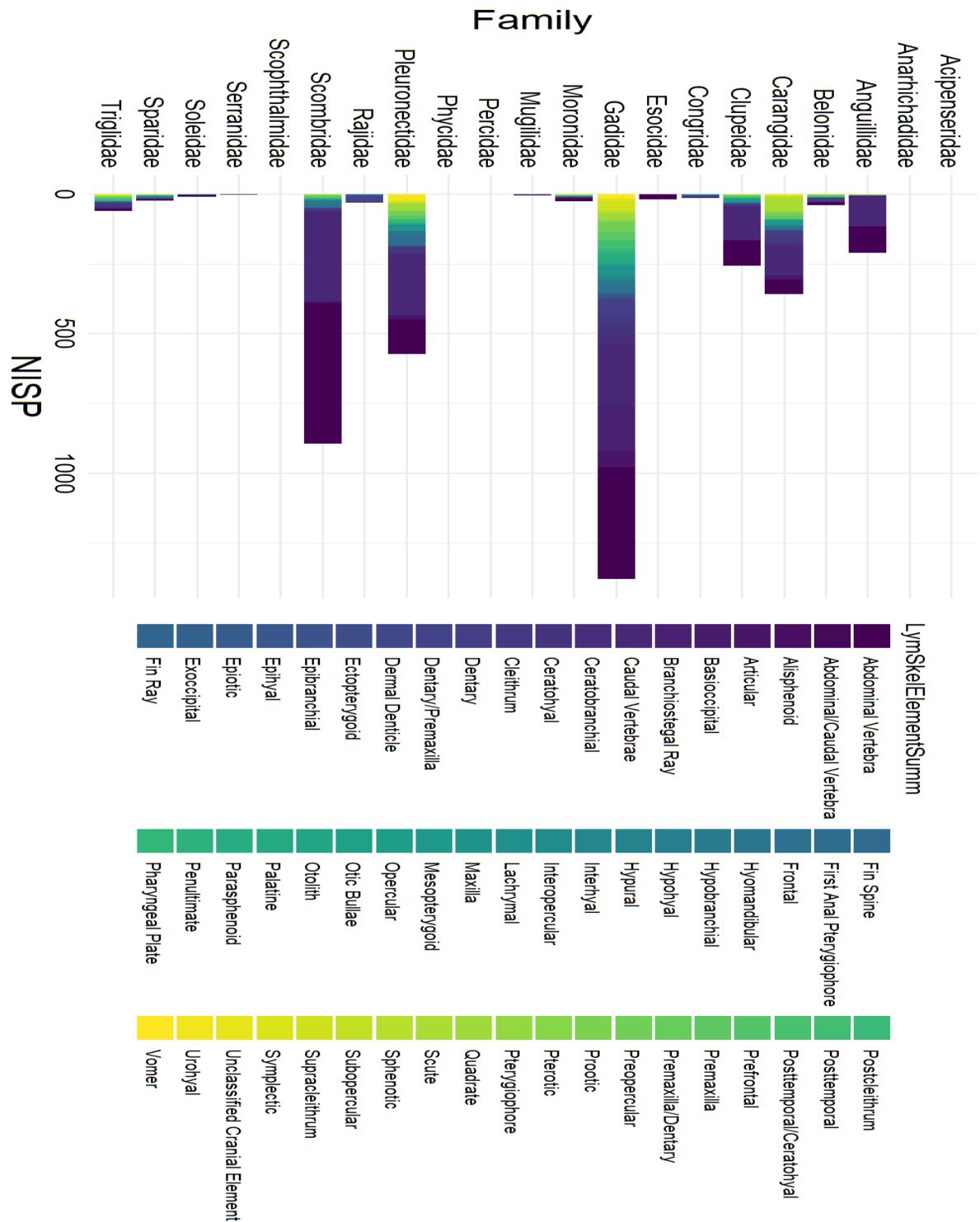


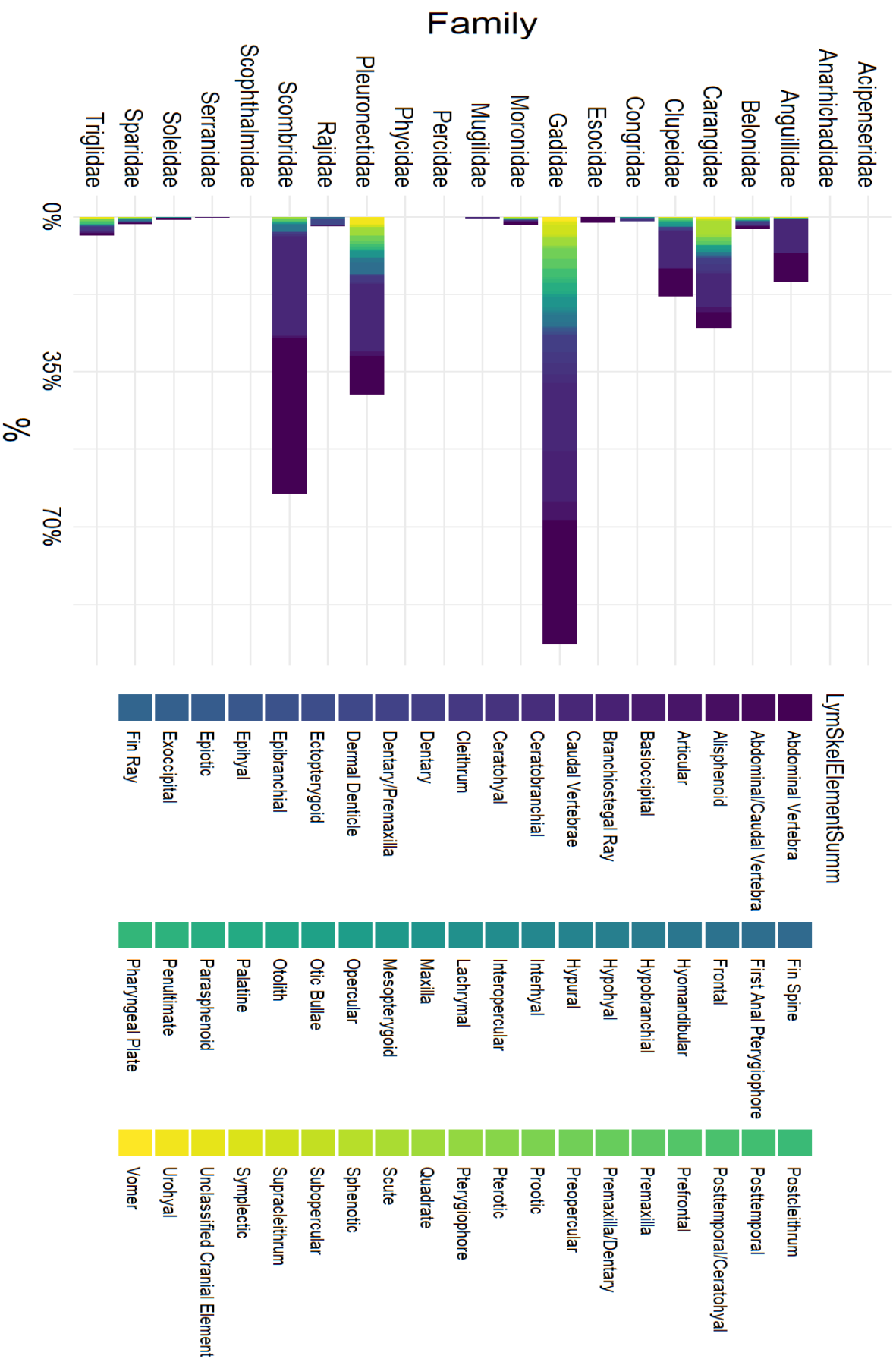
B

Appendix.3.6. Bar charts of NISP and relative frequency values of fish bones identified to taxonomic levels from Lyminge, by skeletal element

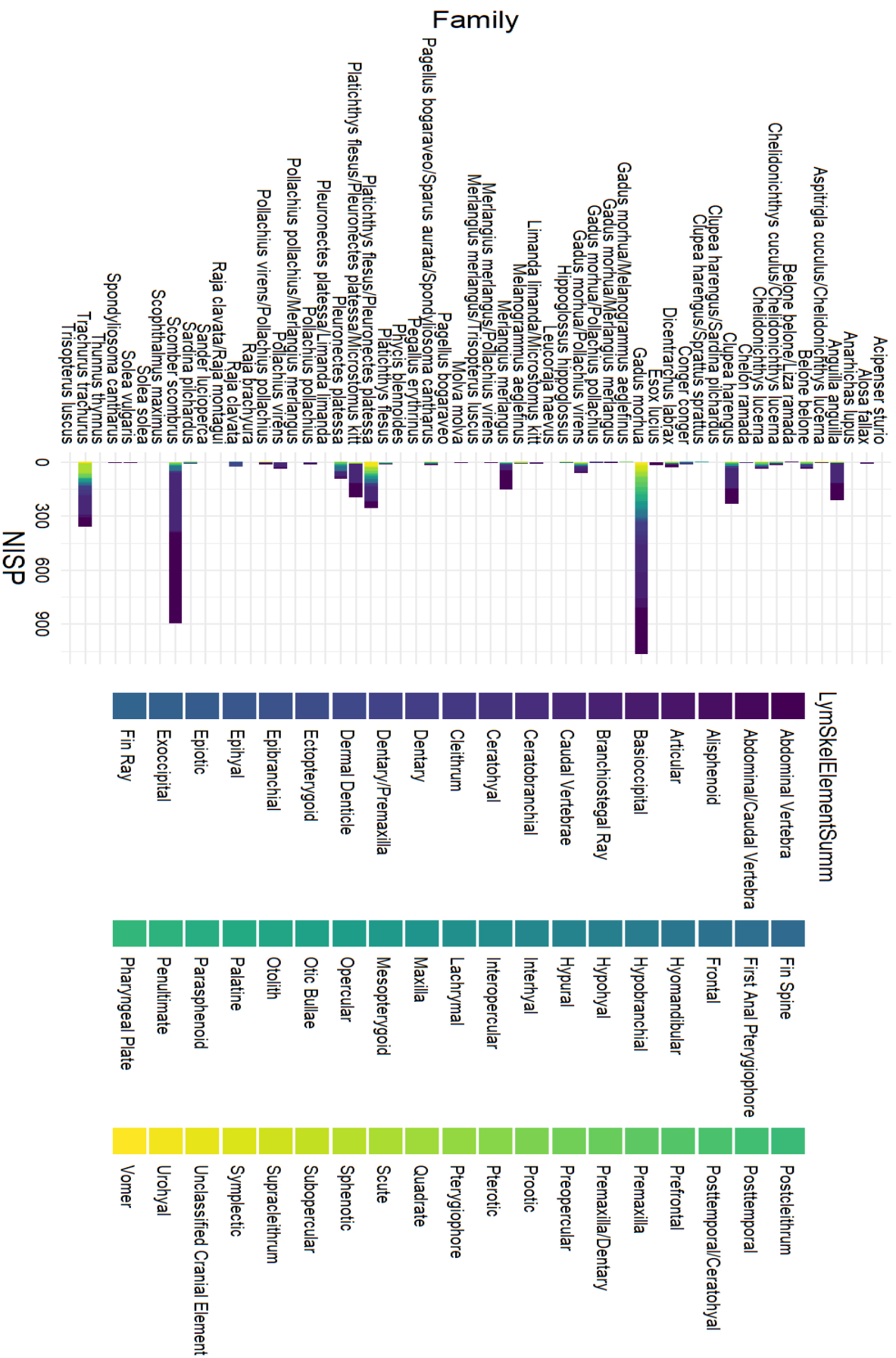
The identified skeletal elements from Lyminge are listed by: A. Family, as NISP; B. Family, as relative frequencies; C. Species, as NISP; D. Species, as relative frequencies. Relative frequencies marked as % of total NISP (S.3.1).

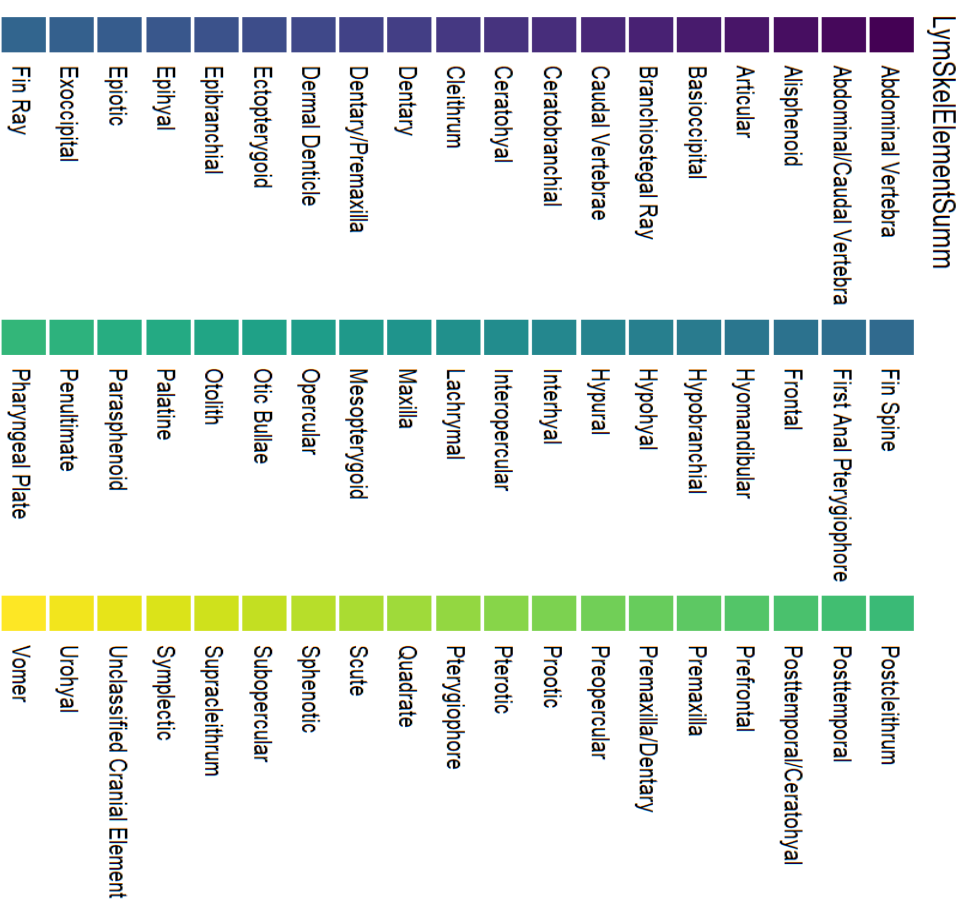
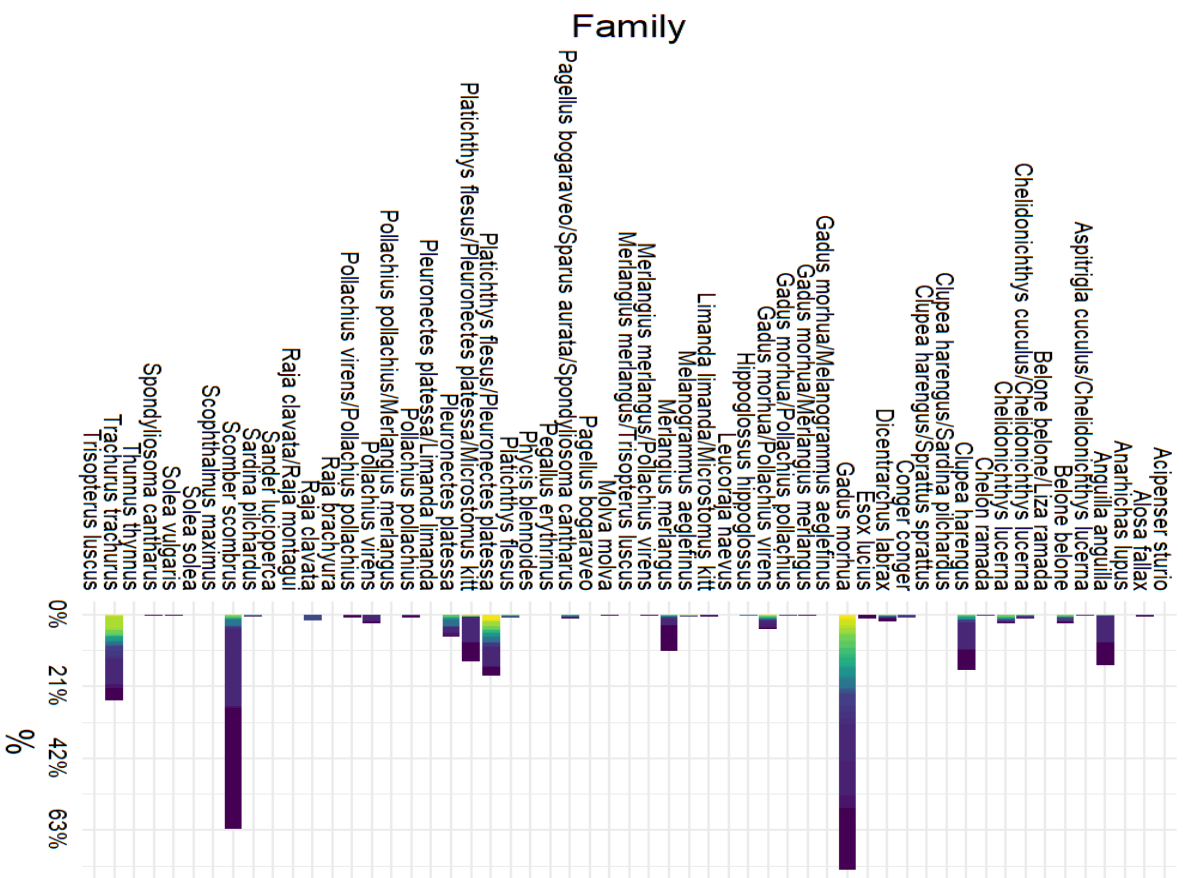
A





B



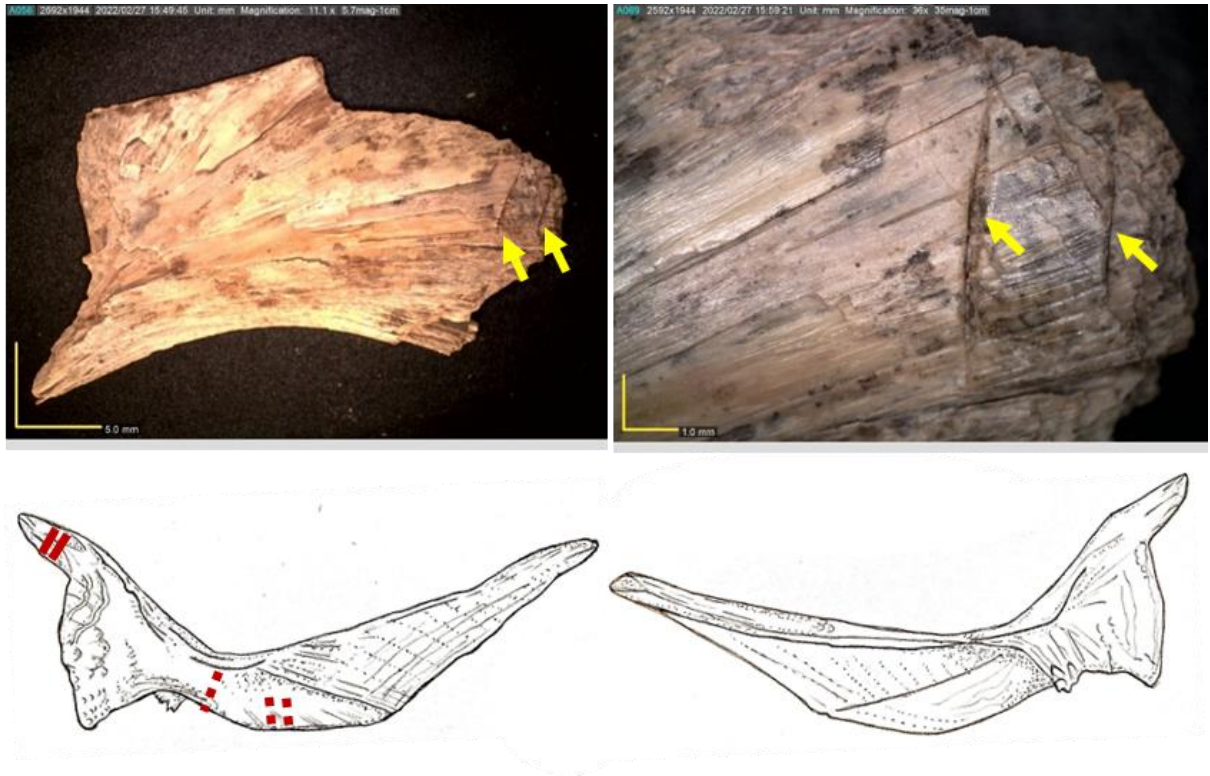


Appendix.3.7. Butchery marks observed on skeletal elements of Atlantic cod (*Gadus morhua*) from Lyminge

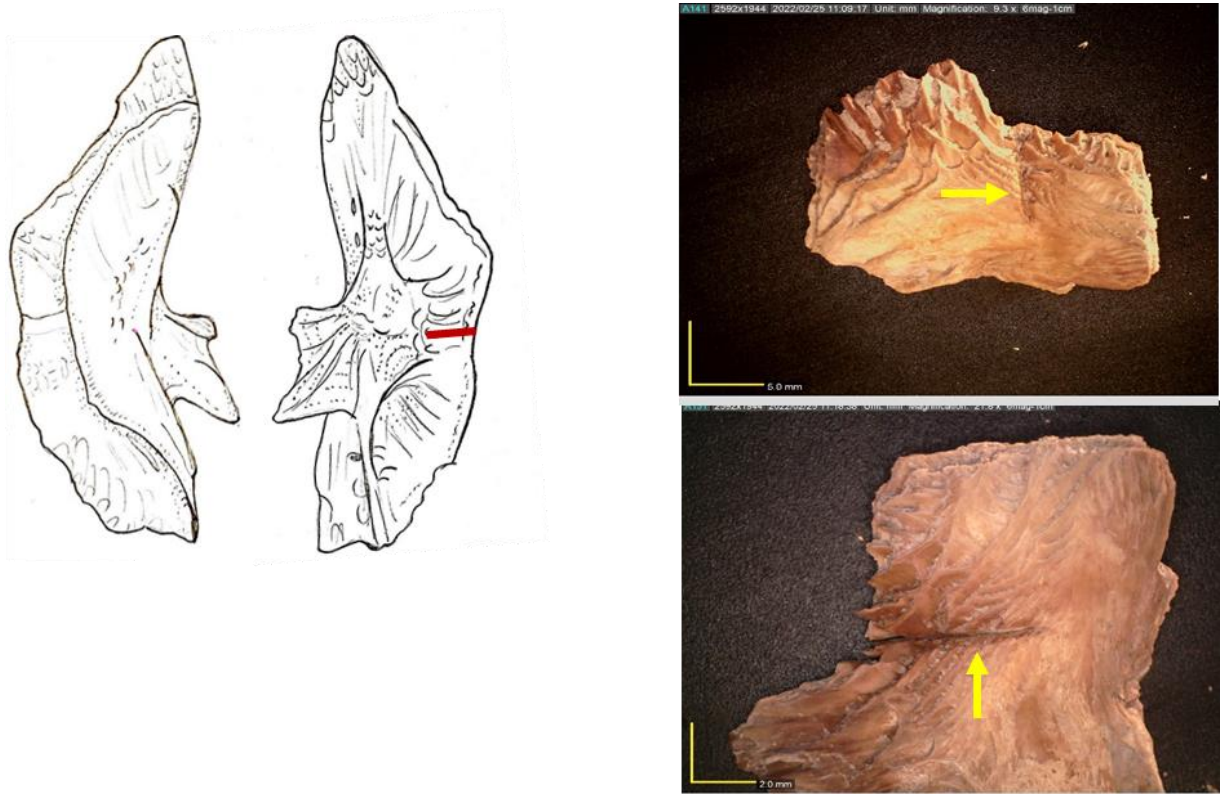
Butchery marks were observed on the following skeletal elements from Lyminge: A. Cleithrum; B. Preopercular; C. Hyomandibular; D. Supracleithrum; E. AV2. Photographs of each butchery mark and illustrations (after Cannon, 1989, Results Section) of the lateral and median sides of each element are displayed below. Butchery mark locations are marked by arrows in each photograph; scale in mm.

A. Cleithrum, n = 2. Photographs, from top to bottom: Specimen 1, horizontal butchery mark X2, right, lateral side. Specimen 2, vertical butchery mark, right lateral side; Specimen 2, vertical butchery mark X2, right lateral side. Illustrations display butchery marks as continuous lines for specimen 1 and as dotted lines for specimen 2. Photographs in right column are zoomed in from photographs in left column.





B. Preopercular, n = 1. Photographs of vertical butchery mark X1, right, medial side. Top photograph zoomed out, bottom photograph zoomed in. Illustrations display butchery mark as a continuous line.

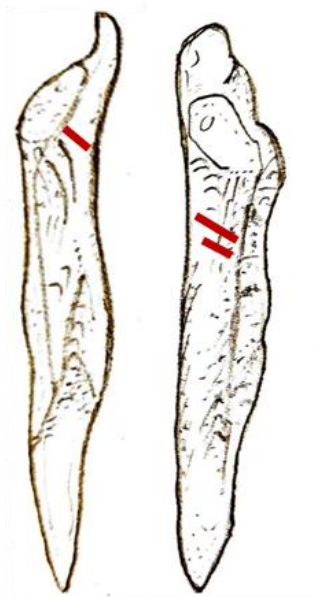
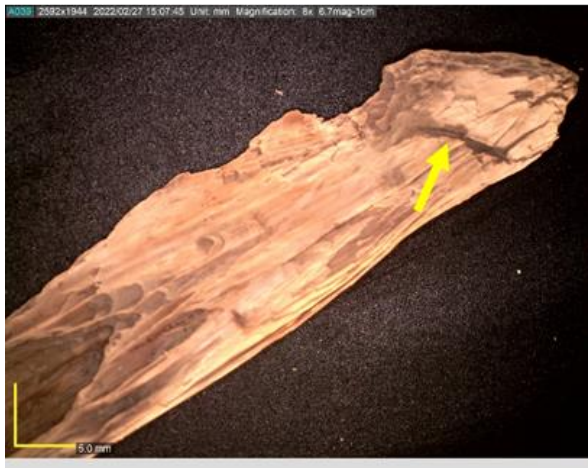


C. Hyomandibular, n = 1. Photographs of vertical butchery mark X1, left, lateral side. Illustrations display butchery mark as a continuous line.



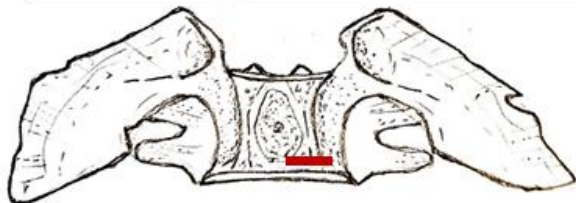
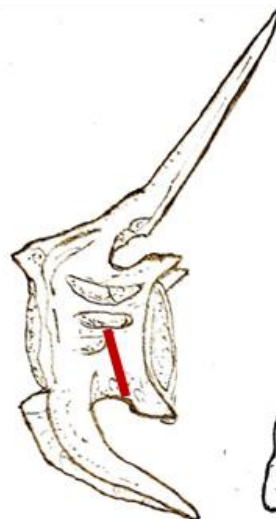
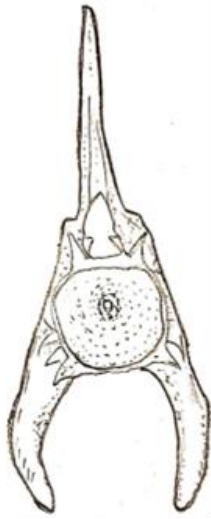
D. Supracleithrum, n = 1. Photographs, from top to bottom: horizontal butchery mark X2, left medial side; horizontal butchery mark X1, left lateral side. Photographs in right column are zoomed in from photographs in left column. Illustrations display butchery marks as continuous lines.





E. AV2, n = 1. Photographs, from top to bottom: vertical butchery mark X1, lateral side; horizontal butchery mark X1, ventral side. Photographs in right column are zoomed in from photographs in left column. Illustrations display butchery marks as continuous lines.





Appendix.3.8. NISPs and relative frequencies of identified species from Lyminge by bone colour

Bone colours indicative of burning include black, grey and white (see Results Section 3.9.5). Relative frequencies marked as % of total NISP of bones identified to species (n = 3,906).

Species	Common name	Beige NISP	% Beige	Black NISP	% Black	Brown NISP	% Brown	Grey NISP	% Grey	White NISP	% White
<i>Acipenser sturio</i>	European sea sturgeon					1	0.03				
<i>Alosa fallax</i>	Twaite shad	9	0.24								
<i>Anarhichas lupus</i>	Atlantic wolffish	1	0.03								
<i>Anguilla anguilla</i>	European eel	202	5.43	1	0.03	8	0.20				
<i>Belone belone</i>	Garfish	37	0.99								
<i>Belone belone/ Liza ramada</i>	Garfish/ Thinlip grey mullet	2	0.05								
<i>Chelidonichthys cuculus/ Chelidonichthys lucerna</i>	Red gurnard/ Tub gurnard	24	0.65								
<i>Chelidonichthys lucerna</i>	Tub gurnard	36	0.97								
<i>Chelon ramada</i>	Thinlip grey mullet	3	0.08			1	0.03				

Species	Common name	Beige NISP	% Beige	Black NSIP	% Black	Brown NISP	% Brown	Grey NISP	% Grey	White NISP	% White
<i>Clupea harengus</i>	Atlantic herring	191	5.14	6	0.15	29	0.74	3	0.08	4	0.10
<i>Clupea harengus/ Sardina pilchardus</i>	Atlantic herring/ European pilchard	1	0.03								
<i>Clupea harengus/ Sprattus sprattus</i>	Atlantic herring/ European sprat	3	0.08								
<i>Conger conger</i>	European conger	14	0.38								
<i>Dicentrarchus labrax</i>	European seabass	24	0.65			3	0.08			1	0.03
<i>Esox lucius</i>	Northern pike	18	0.48								
<i>Gadus morhua</i>	Atlantic cod	1052	28.29	14	0.36	2	0.05			1	0.03
<i>Gadus morhua/ Melanogrammus aeglefinus</i>	Atlantic cod/ Haddock	2	0.05								
<i>Gadus morhua/ Merlangius merlangus</i>	Atlantic cod/ Whiting	6	0.16								
<i>Gadus morhua/ Pollachius pollachius</i>	Atlantic cod/ Pollack	7	0.19								
<i>Gadus morhua/ Pollachius virens</i>	Atlantic cod/ Saithe	60	1.61								

Species	Common name	Beige NISP	% Beige	Black % NSIP	Black	Brown % NISP	Brown	Grey NISP	% Grey	White NISP	% White
<i>Hippoglossus hippoglossus</i>	Halibut	6	0.16								
<i>Leucoraja naevus</i>	Cuckoo ray	1	0.03								
<i>Limanda limanda/ Microstomus kitt</i>	Common dab/ Lemon sole	9	0.24								
<i>Melanogrammus aeglefinus</i>	Haddock	11	0.30								
<i>Merlangius merlangus</i>	Whiting	136	3.66			16	0.41			1	0.03
<i>Merlangius merlangus/ Pollachius virens</i>	Whiting/ Saithe	3	0.08			1	0.03				
<i>Merlangius merlangus/ Trisopterus luscus</i>	Whiting/ Pouting	1	0.03								
<i>Molva molva</i>	Common ling	5	0.13								
<i>Pagellus bogaraveo</i>	Blackspot seabream	1	0.03								
<i>Pagellus bogaraveo/ Sparus aurata/ Spondylusoma cantharus</i>	Blackspot seabream/ Gilthead seabream/ Black seabream	12	0.32	1	0.03	3	0.08				

Species	Common name	Beige NISP	% Beige	Black NSIP	% Black	Brown NISP	% Brown	Grey NISP	% Grey	White NISP	% White
<i>Pagellus erythrinus</i>	Common pandora	1	0.03								
<i>Phycis blennoides</i>	Greater fork beard	1	0.03								
<i>Platichthys flesus</i>	European flounder	9	0.24	3	0.08						
<i>Platichthys flesus/ Pleuronectes platessa</i>	European flounder/ European plaice	239	6.43	18	0.46						
<i>Platichthys flesus/ Pleuronectes platessa/ Microstomus kitt</i>	European flounder/ European plaice/ Lemon sole	186	5.00	2	0.05					7	0.18
<i>Pleuronectes platessa</i>	European plaice	92	2.47								
<i>Pleuronectes platessa/ Limanda limanda</i>	European plaice/ Common dab	1	0.03								
<i>Pollachius pollachius</i>	Pollack	11	0.30			2	0.05				
<i>Pollachius pollachius/ Merlangius merlangus</i>	Pollack/ Whiting	1	0.03								
<i>Pollachius virens</i>	Saithe	32	0.86	2	0.05	3	0.08				
<i>Pollachius virens/ Pollachius pollachius</i>	Saithe/ Pollack	11	0.30			1	0.03				

Species	Common name	Beige NISP	% Beige	Black % NSIP	Black	Brown % NISP	Brown	Grey % NISP	Grey	White % NISP	White
<i>Raja brachyura</i>	Blonde ray	1	0.03								
<i>Raja clavata</i>	Thornback ray	24	0.65			2		0.05			
<i>Raja clavata/ Raja montagui</i>	Thornback ray/ Spotted ray	1	0.03								
<i>Sander lucioperca</i>	Zander	1	0.03								
<i>Sardina pilchardus</i>	European pilchard	8	0.22			2		0.05			
<i>Scomber scombrus</i>	Atlantic mackerel	879	23.64	1	0.03	10		0.26	4	0.10	
<i>Scophthalmus maximus</i>	Turbot	2	0.05								
<i>Solea solea</i>	Common sole	9	0.24								
<i>Spondyllosoma cantharus</i>	Black seabream	6	0.16								
<i>Thunnus thynnus</i>	Atlantic bluefin tuna	1	0.03								
<i>Trachurus trachurus</i>	Atlantic horse mackerel	325	8.74	4	0.10	3		0.08		27	0.69

Species	Common name	Beige NISP	% Beige	Black NSIP	% Black	Brown NISP	% Brown	Grey NISP	% Grey	White NISP	% White
<i>Trisopterus luscus</i>	Pouting	1	0.03								
Total		3719	95.21	52	1.33	87	2.23	7	0.18	41	1.05